Wind Turbine Amplitude Modulation: Research to Improve Understanding as to its Cause and Effect

December 2013
Phase 1
Research

Contents

1. **Work Package A1** - An explanation for enhanced amplitude modulation of wind turbine noise, *National Aerospace Laboratory, NLR*

2. **Work Package A2** - Fundamental research into possible causes of amplitude modulation, *University of Southampton, ISVR*

3. **Work Package B1** - The measurement and definition of Amplitude Modulation, *University of Southampton, ISVR*

4. **Work Package B2** - Development of an AM dose–response relationship, *University of Salford, Acoustics Research Centre*

5. **Work Package C** - Collation and analysis of existing acoustic recordings, *Hoare Lea Acoustics*


7. **Work Package F** - Collation of work packages reports and final reporting, *Hoare Lea Acoustics*
Work Package A1
An explanation for enhanced amplitude modulation of wind turbine noise
National Aerospace Laboratory, NLR
Executive summary

An explanation for enhanced amplitude modulation of wind turbine noise

Problem area
Modern large wind turbines normally produce a swishing noise with a sound level variation of a few decibels. However, in some cases periods of increased swish or thumping are reported. At present the source mechanism for this Enhanced Amplitude Modulation (EAM) is not clear.

Description of work
In order to identify potential causes for EAM, a simulation study was performed into the effects of wind shear on the sound of a modern large wind turbine. For this purpose, an existing turbine noise prediction model was extended to include an azimuth-dependent blade source distribution. Furthermore, a stall noise module was implemented.

Results and conclusions
The simulation results show that, as long as the flow over the blades is attached, wind shear has practically no effect on amplitude modulation. However, strong wind shear can lead to local stall during the upper part of the revolution. This can yield noise characteristics which are very similar to those of EAM. Thus, it can be concluded that local stall is a plausible explanation for EAM. A sensitivity study was carried out to assess how critical the conditions for EAM are, and potential measures to prevent EAM are given. Apart from wind shear, other causes for a non-uniform inflow, such as yaw or topography, may also lead to local stall and EAM.

Applicability
The results from this study can be used to understand and reduce EAM, and to guide further research into this subject.
An explanation for enhanced amplitude modulation of wind turbine noise

S. Oerlemans
Summary

Modern large wind turbines normally produce a swishing noise with a sound level variation of a few decibels. However, in some cases periods of increased swish or thumping are reported, denoted as Enhanced Amplitude Modulation (EAM). In order to identify potential causes for EAM, a simulation study was performed into the effects of wind shear on the sound characteristics of a representative modern large wind turbine. First, the effect of wind shear on the local blade flow conditions was determined. It was found that, for certain turbine operation conditions, strong wind shear can lead to local stall during the upper part of the revolution. In order to determine the corresponding sound characteristics, an existing turbine noise prediction model was extended to include an azimuth-dependent blade source distribution. Furthermore, a stall noise module was implemented. The simulation results show that, as long as the flow over the blades is attached, wind shear has practically no effect on the amplitude modulation. However, if local stall occurs, the resulting noise characteristics can be very similar to those of EAM. Thus, it can be concluded that local stall is a plausible explanation for EAM. A sensitivity study showed that the characteristics of wind shear induced amplitude modulation mainly depend on the size of the stall region (which in turn depends on blade design, turbine control system, operation conditions and wind shear) and on the stall noise behaviour of the airfoils used on the blade. Only for certain combinations of these parameters EAM will occur. The most obvious measure to prevent EAM is to prevent local stall on the blades, which can be achieved in several ways. Apart from wind shear, non-uniform inflow conditions may also be caused by e.g. yaw (wind veer), topography, large-scale turbulence, or the wake of other turbines. These effects may lead to local stall and as a consequence to EAM.
Contents

1 Introduction 7

2 Characteristics of enhanced amplitude modulation 9
   2.1 Literature 9
   2.2 Analysis of sound sample 11

3 Wind turbine noise prediction method 12
   3.1 Simulation approach 12
   3.2 Wind shear and blade flow conditions 13
   3.3 Acoustic prediction method 15

4 Effect of wind shear on amplitude modulation 18
   4.1 No wind shear: normal swish 18
   4.2 Effect of wind shear for attached flow 19
   4.3 Effect of local stall 20
   4.4 Noise spectra 20
   4.5 Sensitivity study 21

5 Conclusion 22

References 24

Figures 26
Nomenclature

Latin

2-D  Two-dimensional
3-D  Three-dimensional
a   Induction factor
A   Spectral shape function
EAM Enhanced Amplitude Modulation
BPM Airfoil noise prediction method by Brooks, Pope, Marcolini [20]
C   Airfoil chord
D, D Directivity functions for high and low frequency, respectively
f   Frequency
L   Spanwise length of blade segment
m   Wind shear exponent
M   Mach number
SPL Sound Pressure Level
OASPL Overall Sound Pressure Level
r   Distance between source and observer
R   Rotor radius
Sr   Peak Strouhal number
St   Strouhal number $St = f \delta / U$
U   Flow speed
Uh  Wind speed at hub height
Ur  Rotational speed
Uw  Wind speed
Uz  Wind speed at height $z$
x, y, z Turbine coordinate system ($x$ in wind direction, $z$ vertical)
x', y', z' Airfoil coordinate system ($x'$ along chord, $y'$ along trailing edge)
z_h  Hub height

Greek

\( \alpha \)  Angle of attack
\( \alpha_s \)  Stall angle
\( \delta_p \)  Trailing edge boundary layer displacement thickness on pressure side
\( \delta_s \)  Trailing edge boundary layer displacement thickness on suction side
\( \zeta \)  Angle between blade flow velocity and source-observer line
\( \theta \)  Observer angle w.r.t. airfoil (see Figure 11)
\( \mu \)  
Sum of pitch angle and twist angle

\( \xi \)  
Observer position w.r.t. wind turbine (0° is downwind, see Figure 15)

\( \phi \)  
Observer angle w.r.t. airfoil (see Figure 11)

\( \psi \)  
Rotor azimuth angle (0° is 12 o’clock, see Figure 15)
1 Introduction

Wind is a clean, cheap, and inexhaustible source of energy. However, the noise from wind turbines constitutes an important hindrance for the widespread application of wind energy. The swishing character of the noise is often mentioned as an important factor explaining the relatively high annoyance, as compared to other sound sources of equal level (air or road traffic). Modern large wind turbines typically produce a swishing noise, i.e., a variation in the level of the broadband aerodynamic noise from the blades. This variation or modulation of the sound level occurs at the blade passing frequency, which is typically about 1 Hz. Normally, the peak-to-trough level variation (here denoted as ‘swish amplitude’) amounts to a few decibels. However, in some cases periods of increased swish or ‘thumping’ are reported, often referred to as Amplitude Modulation. Since normal swish is also an amplitude modulation of broadband blade noise, the term enhanced amplitude modulation or ‘EAM’ will be used in this report to denote increased swishing or thumping. The present study concerns a simulation study into potential causes for EAM. This study is part of a comprehensive research effort commissioned by RenewableUK [1,2]. The objective of this research effort is to identify the cause of EAM, and to develop an effective and reproducible measurement methodology and an associated dose-response relationship.

Normal blade swish can be explained as follows [3,4,5]. Under normal conditions (low wind shear), the blades produce a more or less constant amount of broadband noise during the complete revolution, which is caused by the turbulent airflow over the trailing edge of the blade (trailing edge noise). Due to directivity and convective amplification, this sound radiates mainly in the direction in which the blade is moving. In other words: you mainly hear the blade when it is coming towards you. For a nearby observer on the ground this means that most of the noise is produced when the blade moves downwards (roughly in the horizontal position for an upwind or downwind observer). Each time a blade passes this position, a swish is emitted. By the time the sound reaches the observer on the ground, the blades have already turned further. Therefore, it is sometimes suggested that the sound is produced when the blades pass the tower. However, acoustic source location measurements clearly demonstrate that the sound is produced around the 3 o’clock position (Figure 1).

The characteristics of normal swish can be analysed using a semi-analytical, semi-empirical wind turbine noise prediction method [5]. This frequency-domain prediction code only needs the blade geometry (airfoils, chord and twist distribution) and turbine operation conditions (wind speed, RPM, blade pitch) as input, and calculates the trailing edge noise from the blades. The effects of atmospheric turbulence, wind shear, and yaw are neglected, i.e., stationary and uniform inflow conditions are assumed. The prediction method was validated using acoustic data measured on a large circle around the turbine (radius 1.3 rotor diameters).
Good agreement was found between predictions and experiment, not only in terms of sound levels and spectra, but also with regard to turbine noise directivity and swish [5]. Calculated noise footprints show that, for observers more than a few rotor diameters away from the turbine, swish amplitudes up to about 5 dB may be expected in cross-wind directions, while in the up- and downwind direction no swish should be perceived (Figure 2). Close to the turbine, substantial swish (2-6 dB) is perceived in all directions. Similar trends were found using an alternative time-domain noise prediction method [6]. Note that in practice the perceived swish may reduce at large distance, due to a combination of the following factors: (1) inefficient sound propagation in cross-wind direction, (2) atmospheric absorption of high frequencies, and (3) the maximum sound level is below the background noise.

Thus, under typical conditions, trailing edge noise is the dominant noise source for modern large wind turbines, and normal swish can be explained using trailing edge noise directivity and convective amplification. However, in the case of EAM the reported noise characteristics are different (see Chapter 2): the variation in sound level is larger than 6 dB, and the level variations are also perceived at large distance, in upwind or downwind direction. In addition, there appears to be a change in the character of the noise, which becomes more impulsive and/or has increased low-frequency content. Several potential causes for EAM have been suggested, including wind shear, stall, yaw error, blade-tower interaction, inflow turbulence, and interference between different turbines. However, at present the mechanism is still not clear.

In this study, simulations will be carried out to investigate whether EAM can be explained by a non-uniform inflow. To facilitate the simulations, the existing prediction method [5] will be extended to include an azimuth-dependent blade noise source strength (azimuth is the angular position of the blade in the rotor plane). We will here focus on wind shear, but in practice non-uniform inflow conditions may also be caused by e.g. yaw, topography, large-scale turbulence or the wake of other turbines. Note that large-scale turbulence will only cause brief periods of non-uniform inflow. Wind shear results in an increased angle of attack during the upper part of the revolution and a lower angle of attack during the lower part of the revolution (Figure 3). A higher angle of attack leads to a thicker or even separated suction side boundary layer, which in turn yields a higher level and lower frequency of the trailing edge noise. Figure 3 also illustrates the effect of yaw (i.e., the deviation between the wind speed direction and the normal to the rotor plane). Yaw may occur due to wind veer - the variation in wind direction with height. Wind veer can reach values of 30° to 40° in the rotor plane of a wind turbine [7]. However, in practice wind veer is expected to have a smaller effect on the local angle of attack than wind shear. This is because wind shear directly affects the angle of attack through $U_\alpha$, while yaw modifies $U_\alpha$ only by the cosine of the yaw
angle. For example, for \( U_r/U_w = 7 \) a yaw angle of 20° reduces the angle of attack by at most 0.8°, while a change in wind speed of 20% can change the angle of attack by ±1.6°.

The structure of this report is as follows. In Chapter 2, we will first briefly review the characteristics of EAM, as guidance for the simulations. Next, the modified wind turbine noise prediction method is described in Chapter 3. The results of the simulations are presented and discussed in Chapter 4. Finally, the conclusions of this study are summarized in Chapter 5.

2 Characteristics of enhanced amplitude modulation

As mentioned above, normal swish, due to trailing edge noise directivity and convective amplification, causes peak-to-trough swish amplitudes up to 6 dB. For observers close to the turbine (less than two diameters away), substantial swish occurs in all directions, while at large distance (more than three diameters away) swish only occurs in cross-wind directions. In this chapter we will search the available literature for deviations from this pattern, since we are interested in EAM, which is by definition more ‘severe’ than normal swish. Thus, although the characteristics of EAM are unclear at this stage, EAM is here defined as an amplitude modulation which is stronger than the modulation predicted by the standard swish model described above*. Besides the noise characteristics, we will also try to find some clues about potential causes of EAM. In Section 2.1, we will briefly review the available literature. In Section 2.2, a sound sample will be analysed.

2.1 Literature

Extensive reviews of research into amplitude modulation of wind turbine noise were given by Moorhouse at al. [8], Bowdler [9] and Bullmore et al. [2]. In the following a short, more or less chronological, review will be given of the relevant observations.

Dunbabin [10] measured blade swish from a 34-m diameter pitch-controlled turbine using microphones on a 60-m diameter circle around the turbine. For constant conditions (yaw, power, pitch, wind speed), typical swish amplitudes of about 5 dB were found, but occasionally values of 10 dB were observed (in the 1 kHz and 2 kHz octave bands). Since the swishes did not occur at the same time on all microphones, it was concluded that the modulation was not due the blades passing the tower. These results are well in line with the normal swish mechanism described above, except for the occasional 10-dB modulations, for which no explanation was given.

* The present definition of EAM is only intended to distinguish the different source mechanisms. It should not be interpreted as being a ‘threshold’ for response to amplitude modulation.

COMPANY CONFIDENTIAL
Van den Berg [11] measured the sound from a wind farm with seventeen 70-m diameter, pitch-controlled wind turbines. The measurement position was 750 m from the nearest turbine. The variation in A-weighted overall sound level was typically 2-3 dB, but during short periods values of 4-6 dB were measured. Due to the spatial extent of the wind farm, for some turbines the microphone was located in the downwind direction, but for other turbines it was located almost in the cross-wind direction. Therefore, the measured level variations may be partly explained by normal swish. Van den Berg investigated two other mechanisms to explain the modulation. First, he deduced that for extreme wind shear the trailing edge noise level may vary by up to 5 dB during one revolution, due to the change in angle of attack as explained above. However, it should be noted that due to summation of the noise from three blades, the effective sound level variation will be much smaller than this 5 dB. This can be illustrated by the fact that in Figure 1 the difference in source level between the upward and downward movement is about 12 dB, while the effective swish amplitude measured at the same location is only 2.5 dB [4]. This is also confirmed by the simulations by Boorsma et al. [12], who found a negligible influence of a standard wind profile on the (calculated) perceived trailing edge noise level variation. Figure 1 also illustrates that, at least in these measurements (unstable atmosphere), wind shear was not causing the swish, because then the source maximum should have been located around 12 o’clock.

The second mechanism investigated by van den Berg is synchronous running of different turbines. However, as noted before [9], such interaction between turbines cannot increase the level variation: if all turbines radiate swishes in phase (for a given observer position), the perceived modulation is the same as for a single turbine. If they are not in phase the level variation will be less. In summary, the observations by van den Berg may be explained by a combination of normal swish and extreme wind shear. The present study should give more insight into this possibility.

Moorhouse et al. [8] analyse EAM characteristics on the basis of complaints from residents for different sites. They mention variations in A-weighted sound levels of 3-5 dB and conclude that EAM occurs for specific wind directions, which occur between 7% and 25% of the time (for the four EAM sites analysed in detail). If for these wind directions the observers are located in the cross-wind direction with respect to the turbine(s), these results can be explained by normal swish. If the observers are in the upwind or downwind direction, another mechanism must be responsible for the level variations.

Di Napoli [13] measured the noise from a 1-MW pitch-controlled wind turbine on a downwind position at large distance. He reports overall level variations up to 5 dB, which were typically measured during periods of varying wind speed and rotational speed. In view of the downwind measurement position, these variations cannot be explained by normal swish. They may be related to off-design flow conditions on the blade (e.g. separated flow or stall), due to
the varying wind conditions. The effect of stall (due to strong wind shear) on the radiated noise will also be investigated in the present study.

Stigwood [14] reports level variations up to about 8 dB, both close to a single turbine and at large distance from a wind farm. These large variations cannot be explained by normal swish, and it is suggested that they are related to strong wind shear. He also notes that in case of EAM there is more low-frequency content in the sound. This could point to an increased boundary layer thickness at the trailing edge or even separated flow.

Vos et al. [15] measured the noise from a wind farm with seventeen 80-m diameter pitch-controlled turbines at distances between 200 m and 850 m. The sound level variations were 1-2 dB in 79% of the cases, 2-3 dB in 18% of the cases, and 3-4 dB in 1% of the cases. These findings appear to be in line with the characteristics of normal swish.

2.2 Analysis of sound sample

The characteristics of EAM are further investigated here by analysing a sound recording of about 25 s made by Bowdler [16]. It was measured about 50 m upwind from a 93-m diameter pitch-controlled wind turbine. The sample is particularly interesting because it contains the transition from normal swish to ‘thump’ (EAM). From subjective listening the transition occurs between 11 s and 13 s after the start of the sample. The complete sample sounds ‘aerodynamic’, i.e., the sound does not appear to be mechanical in nature.

The time history of the A-weighted overall sound level is shown in Figure 4. During the swish period (until 11 s) the average peak-to-trough level variation is 5.2 dB, which can be understood from the normal swish characteristics. However, during the EAM period (from 13 s onwards), the average level variation is 7.7 dB. If we look at the time difference between the minima and maxima (Figure 5), the RPM does not appear to be changing significantly during the change from swish to EAM. Furthermore, for both periods the average rise time (trough-to-peak) differs less than 10% from the average fall time (peak-to-trough), indicating that the modulations are not strongly asymmetric.

However, there appears to be a slight change in the phase of the swishes: whereas the time difference between consecutive minima and maxima is scattered around an average value of about 0.65 s in both periods, during the transition (around 12 s) it reaches 0.93 s. In the case of normal swish such a phase shift occurs when, due to a changing wind direction, the right hand side of the rotor plane (the descending blades) moves away from the upwind observer [5]. It is not clear if this was the case during the present measurement.

Finally, if we look at the average 1/3-octave band spectra for the swish period and the EAM period (Figure 6), we see that both have a broadband character, but that the EAM sound has much more low-frequency content. This is in line with the observations by Stigwood [14]
mentioned above, and suggests an increased boundary layer thickness or even separated flow, possibly due to an increased wind speed.

3 Wind turbine noise prediction method

Based on the EAM characteristics described in the previous chapter, we will now define the approach for the simulations (Section 3.1). The assumed wind shear characteristics and resulting blade flow conditions are discussed in Section 3.2. The acoustic prediction method is then described in Section 3.3.

3.1 Simulation approach

In the previous chapter we have seen that EAM is characterised by peak-to-trough level variations of more than 6 dB, and/or a substantial level variation at large distance in upwind or downwind direction. These observations cannot be explained by normal swish. As mentioned before, due to summation of the noise from three blades, we need a large variation in acoustic source strength during the revolution of the blade to explain these observations. As explained at the end of Chapter 1, trailing edge noise levels may be affected by variations in wind speed (shear) or wind direction (veer) over the rotor plane, or a combination of both. In the present study we will focus on wind shear, because the effect on angle of attack is expected to be stronger. Note that wind speed variations may also have other causes, such as large-scale atmospheric turbulence, topography, or the wake of other turbines. Wind shear will cause variations in angle of attack as a function of rotor azimuth, which will affect the trailing edge noise levels. However, as discussed in the previous chapter these noise level variations are probably too small to explain EAM. It is therefore also interesting to investigate whether stall may occur during part of the revolution (Figure 7). For stall-control wind turbines it is known that stall results in more noise [17]. For airfoils, the available literature suggests that stall results in a sudden increase of low-frequency noise [18,19,20,21]. This seems to be in line with the observations described in the previous chapter.

The noise simulations will be carried out for a representative large modern wind turbine with a tower height and rotor diameter of about 100 m. The turbine is pitch-controlled and has a rated power in the range of 2 MW. Based on the above considerations, the approach for the simulations is as follows. First, we will investigate which (extreme) wind shear conditions may occur in practice, and calculate the resulting angles of attack as a function of blade azimuth. This will enable us to assess whether local stall may occur. We will then calculate the trailing edge noise and/or stall noise for each blade segment, again as a function of blade azimuth. Finally, the noise from the three blades will be added and the total noise level will be computed.
for different observer positions around the turbine, to estimate the perceived noise level variations. This will allow us to assess whether wind shear may explain the observed EAM characteristics.

The objective of this study is not to investigate in detail how and when stall occurs, or what the exact stall noise characteristics are. Rather, the goal is to assess (1) whether strong wind shear may lead to stall, and (2) if stall can lead to EAM. For this reason it is not very critical which turbine is used for the simulations, as long as it is representative for a large modern turbine. It should be noted that the effects of wind shear are modelled using engineering methods, which have not been validated by experiments yet.

3.2 Wind shear and blade flow conditions

In order to characterise the atmospheric wind shear we will apply the power law, which is used by many wind energy researchers [17]:

$$\frac{U_v(z)}{U_v(z_h)} = \left( \frac{z}{z_h} \right)^m. \quad (1)$$

In this equation, $U_v$ is the wind speed, $m$ is the wind shear exponent, $z$ is the height, and $z_h$ is a reference height, for which here the hub height is taken. The wind shear exponent is a highly variable quantity. A low value indicates an unstable atmosphere with small variations in wind speed as a function of height, a high value indicates a stable atmosphere with high wind shear. Van den Berg [11] reports values for $m$ between about 0.1 (unstable) and 0.6 (very stable) for a flat site in The Netherlands. The occurrence of these extreme values is a few percents of the time. Bowdler [7] showed that the wind shear exponent decreases with increasing wind speed. For a flat site in the UK, he found average values of 0.20 (daytime) and 0.43 (nighttime). In this study we will use values for $m$ of 0 (no wind shear), 0.3 (stable), and 0.6 (very stable). The corresponding normalised wind speed in the rotor plane $\frac{U_v}{U_h}$, with $U_h$ the wind speed at hub height, is shown in Figure 8.

In order to simulate the ‘worst case’ situation, we should use a (hub height) wind speed in the range where the turbine is most susceptible to stall, i.e., where the angles of attack are highest. This depends on the control system of the turbine, i.e., the variation of RPM and blade pitch angle as a function of wind speed. Variable-speed turbines typically increase the RPM (by adjusting generator torque) up to some wind speed, after which it remains constant. The pitch angle typically remains constant up to a certain wind speed, after which it is increased to control power. As illustrated in Figure 3, the angle of attack increases with increasing wind speed, but decreases with increasing RPM and increasing pitch angle. As a result the highest angles of attack, and therefore the highest susceptibility to stall, will occur at some intermediate wind
speed. The present simulations were done at a hub height wind speed of about 11 m/s, using the actual control settings of the present turbine.

For the aerodynamic and acoustic analysis the blade is divided into radial segments with a spanwise extent of about 1 m. As argued above, a full computation of the complex 3-D flow field around a rotating wind turbine blade in the presence of wind shear is beyond the scope of the present study. Therefore, we will assume local 2-D flow conditions for each blade segment. To assess whether stall can occur, we should check if the local angle of attack exceeds the stall angle $\alpha_{st}$ for the given airfoil. We will focus on the outer 40% of the blade, where all the noise is produced (aerodynamic noise is proportional to the 5th or 6th power of the local flow velocity). The angle of attack on each segment is calculated using the following equation:

$$\alpha = \tan^{-1}\left(\frac{(1-a)U_z}{U_r}\right) - \mu,$$

(2)

where $U_z$ is the height-dependent wind speed, $U_r$ the rotational speed of the blade element, and $\mu$ the sum of the blade pitch and the local twist of the blade segment. The induction factor $a$ accounts for the fact that the wind is slowed down by the rotor. For an ideal rotor $a$ equals 1/3, but we will here use a slightly lower value $a_0$, because for a uniform inflow the resulting angles of attack on the outer 40% of the blade agree within 0.1° with those calculated using a more advanced blade element momentum method [22]. To account for induced downwash due to the tip vortex, the angle of attack for the outer blade element is reduced by 1°.

If for a given blade segment stall occurs during part of the revolution, the local lift production decreases. As a result the local induction factor decreases and the angle of attack calculated using Eq. (2) increases. For a typical airfoil, stall results in a lift reduction of about 25% to 50%. Assuming that the lift is proportional to $(1-a)^2$ [17], the local induction factor will reduce by about 50% in the case of stall. Thus, the flow state on a given blade segment depends on the local wind speed as follows: for low wind speeds the flow is always attached and for high wind speeds the flow is always stalled. For intermediate wind speeds two solutions exist: the flow may be either attached ($\alpha < \alpha_{st}$ for $a = a_0$) or stalled ($\alpha > \alpha_{st}$ for $a = a_0/2$).

The locations in the rotor plane where the angle of attack may exceed the stall angle are shown in Figure 9 for two values of the wind shear coefficient. The plots show that stall can occur for a substantial part of the rotor plane. As expected the stall region increases with increasing shear factor. It should be noted that these calculations were done using the ‘stall value’ $a = a_0/2$ for the induction factor. If attached flow is assumed, with $a = a_0$, the angle of attack is always smaller than $\alpha_{st}$ for the conditions in Figure 9. This means that both flow states (attached flow and stalled flow) are possible for the indicated locations. In the following we will
assess both situations. Stall hysteresis or dynamic stall effects (delay of stall due to rapid $\alpha$ increase and vice versa) are not taken into account.

In order to calculate the trailing edge noise, we need to know the boundary layer displacement thickness at the trailing edge of each blade segment. For the present conditions the Reynolds number on the outer 40% of the blade ranges between about 3 and 6 millions, and the angle of attack between $\alpha_- - 5$ and $\alpha_+ + 2$. For these conditions the dependence on Reynolds number is small, and we can estimate the trailing edge boundary layer thickness on the suction and pressure side (for attached flow) using the relations shown in Figure 10, where $\delta^*$ is the displacement thickness, $C$ is the airfoil chord and $\alpha$ the angle of attack. These approximations are based on calculations with the RFOIL airfoil design and analysis code [23] for the present airfoil.

3.3 Acoustic prediction method
This section describes the acoustic prediction method for attached flow and stalled flow. Furthermore, it is explained how the resulting blade noise spectra are transferred to the wind turbine noise footprint.

3.3.1 Trailing edge noise for attached flow
For attached flow, the trailing edge noise from each blade segment is calculated with the method described and validated in Ref. 5. Using the local Reynolds number, angle of attack and boundary layer displacement thickness from the previous section as input, the source spectrum for each radial blade segment is calculated using the 2D semi-empirical trailing edge noise prediction code developed by Brooks, Pope and Marcolini [20]. In this code, which is based on acoustic and aerodynamic wind tunnel measurements on NACA0012 airfoils, the total trailing edge source strength due to the turbulent boundary layer is the sum of three contributions of the following form:

$$SPL_i = 10 \log \left( \frac{\delta^* M^3 L}{r^2} \right) + A \left( \frac{St}{Sr} \right) + K, \quad (3)$$

where $\delta^*$ is the displacement thickness, $M$ the Mach number, $L$ the span of the blade segment, $r$ the distance to the observer, and $K$ an empirical constant which depends on the Mach and Reynolds numbers. The function $A$ describes the spectral shape as a function of the ratio between the Strouhal number $St = f \delta^* / U$ (with $U$ the local flow speed) and the empirical peak Strouhal number $Sr$. The three contributions (here denoted by the index $i$) are the pressure side boundary layer, the suction side boundary layer, and an additional contribution to account for nonzero angle of attack. Eq. (3) basically states that trailing edge noise is
proportional to the boundary layer thickness (which is a measure for the turbulence correlation scale) and the fifth power of the flow speed. The boundary layer thickness for the different blade segments of the present wind turbine blade is calculated using the approximation described in the previous section. To account for directivity and convective amplification a smoothed version of the trailing edge noise directivity function is used [5]:

$$D_s = \frac{2 \sin^2(\theta/2) \sin^2 \phi}{(1 - M \cos \zeta)^s}, \quad (4)$$

where the subscript $s$ indicates the smoothing, $\theta$ and $\phi$ are defined in Figure 11, $\zeta$ is the angle between the blade flow velocity and the source-observer line, and $M$ is the Mach number. The numerator in Eq. (4) describes the trailing edge noise directivity, and indicates that the noise is mainly radiated towards of the leading edge. The characteristics of this function are shown in Figure 12. The denominator represents the convective amplification factor for trailing edge noise, and indicates that the source amplitude increases when the source is moving towards the observer. The Doppler frequency shift is accounted for by calculating for each source frequency the Doppler-shifted frequency at the observer position, and redistributing the acoustic energy over the appropriate frequency bands.

### 3.3.2 Stall noise

For stalled flow, the prediction method should reflect the characteristics mentioned in literature [18,19,21]: a sudden increase in noise accompanied by a shift to lower frequencies. Such a noise increase, occurring only for part of the revolution, may explain the EAM observations mentioned above (level variations exceeding 6 dB and/or a substantial level variation at large distance in upwind or downwind direction). The increase in sound level for stalled flow can be physically understood from the larger turbulence length scales, the larger coherence length, and the higher turbulence intensity (as compared to attached flow). In Ref. [19] stall was found to result in a 10 dB increase in broadband noise. In Ref. [18] the noise increase due to stall appeared to be somewhat lower than 10 dB, but in Ref. [21] noise increases up to 20 dB (light stall) or 30 dB (deep stall) were found in a certain frequency range. All in all, it seems reasonable to assume an increase of 10 dB in overall sound level, although the actual value may depend on the airfoil. Thus, the prediction method should exhibit a sudden noise increase of about 10 dB when stall occurs.

The shift to lower frequencies for stall noise can be physically understood from the larger turbulence length scales. In Ref. [21] the front projection of the airfoil ($C \sin \alpha$) was used as the relevant length scale, and the stall noise spectrum was found to peak at a Strouhal number of about 0.3. For attached flow (see previous section), the trailing edge noise spectrum
peaks at a Strouhal number $St = f \delta^* / U$ of about 0.15. Since for the present conditions the attached boundary layer thickness $\delta^*$ is about four times smaller than $C \sin \alpha$, this implies that the peak frequency is roughly halved when stall occurs. This change in peak frequency should be captured by the prediction method.

The Brooks, Pope and Marcolini or ‘BPM’ model [20], which is used in the present study to calculate the trailing edge noise for attached flow (see previous section), also contains a module for noise from a stalled airfoil. In this module Eq. (3) is still used, but for $\alpha > \alpha_n$, only the $i = 3$ term is retained, and the width of the noise spectrum is increased. The peak level and frequency are controlled by the displacement thickness $\delta^*$ of the stalled flow. In order to capture the desired characteristics for stall noise, for the present application the BPM module is implemented in the following way. First, it is assumed that $\delta^*$ increases by a factor of two when stall occurs. This yields the desired reduction in peak frequency by a factor of two, as argued above, and an increase in level of about 3 dB. Second, 7 dB is added to the spectral levels calculated using the BPM code, in order to obtain the desired 10 dB overall noise increase. The resulting blade noise spectra as a function of angle of attack, for an airfoil on the outer part of the blade, are shown in Figure 13 and Figure 14. For $\alpha < \alpha_n$ (attached flow), the spectrum consists of two ‘humps’ representing the contributions from the suction and pressure side of the airfoil. As expected, the low-frequency (suction side) hump increases in level and decreases in frequency for increasing angle of attack. At the stall angle, the width of the spectrum can be seen to increase. Moreover, the peak frequency is reduced and the level increases substantially. As a result, the overall sound level increases by about 10 dB at the stall angle (Figure 14).

As explained above, the dominant frequencies for stall noise are lower than for trailing edge noise, due to the larger turbulence length scale. As a result the acoustic wavelength becomes of the same order as the airfoil chord. Thus, for stall noise the directivity function of a compact dipole is used:

$$D_d = \frac{\sin^2 \theta \sin^2 \phi}{(1 - M \cos \zeta)^2}.$$  \hfill (5)

This function corresponds to the low-frequency directivity function used for stall noise in the BPM model. The numerator indicates that the noise is mainly radiated in the direction perpendicular to the plane of the airfoil. The characteristics of this function are shown in Figure 12. The denominator is the same as for the trailing edge noise directivity function in Eq. (4), and indicates that the source amplitude increases when the source is moving towards the observer. The Doppler frequency shift is calculated in the same way as for trailing edge noise.
3.3.3 Noise footprints
The time-dependent noise footprints of the turbine are calculated in the same way as described in Ref. [5], except that the blade noise source strength now depends on azimuth. Three blades are modeled at 120° from each other and the azimuth-dependent radial source distribution for each blade is calculated as described in the previous sections. For each rotor azimuth the contribution of each blade segment to the sound level at a certain observer position is calculated, using the directivity functions of Eqs. (4) and (5). Note that for a given arrival time, the emission time (i.e., emission azimuth) is generally different for the different blade elements. By plotting the total sound level at different observer positions for a fixed observer time, the instantaneous noise footprint is obtained. It should be noted that the prediction model focuses on the sources of wind turbine noise, which means that propagation effects, such as sound refraction due to wind shear, are not included.

4 Effect of wind shear on amplitude modulation
In this chapter the results of the simulations will be presented and discussed. In order to assess the effect of wind shear on amplitude modulation, simulations were carried out for the following five cases:

1. No wind shear \((m = 0)\), attached flow;
2. Stable atmosphere \((m = 0.3)\), attached flow;
3. Very stable atmosphere \((m = 0.6)\), attached flow;
4. Stable atmosphere \((m = 0.3)\), local stall;
5. Very stable atmosphere \((m = 0.6)\), local stall.

As explained in Section 3.2, for the cases with wind shear both attached and stalled flow may occur for the locations indicated in Figure 9. Therefore both situations are simulated. The structure of this chapter is as follows. First, the simulation results for the reference case (no wind shear) are presented in Section 4.1. Next, in Section 4.2 the effect of wind shear on amplitude modulation will be assessed for attached flow (Cases 2-3). Then, in Section 4.3 the effect of local stall will be investigated (Cases 4-5). Finally, the sensitivity of the simulation results to different model parameters will be studied in Section 4.5. The rotor azimuth angle \(\psi\) and the observer angle \(\xi\) are defined in Figure 15. We will focus on the results at large distance, because these are most relevant for noise pollution.

4.1 No wind shear: normal swish
As a 'normal swish' reference, the simulation results for Case 1 (no wind shear) are presented in Figure 16. The upper row shows instantaneous turbine noise footprints (top view) for four
different rotor azimuth angles, up to a distance of ten times the rotor diameter. The turbine is located at the center of the footprint, and the wind goes from left to right. The rotor azimuth (as seen from an upwind position) at observer time is indicated in the upper right corner of each footprint. In order to limit the range of the dB scale and show the level variations more clearly, the sound levels are normalized using the horizontal distance $r_h$ to the turbine:

$$SPL_{norm} = SPL + 20 \log r_h.$$ In this way the levels at a given distance can still be directly compared. The sound levels are integrated between 100 Hz and 5 kHz and are given in dBA. The footprints show two waves of increased sound level, one in each cross-wind direction, which start close to the turbine at $\psi = 90^\circ$ and propagate outward with the speed of sound. The wave on the side of the descending blade is generated when the blade is around 1 o’clock, while the wave on the side of the ascending blade is generated when the blade is around 6 o’clock. After $\psi = 180^\circ$ the cycle repeats and both waves can be seen to propagate further to the edge of the footprints.

Due to the passage of these sound waves from the blades, the noise levels in the crosswind directions vary significantly, while in the upwind and downwind directions the levels are practically constant at large distances. This is illustrated in the middle row of Figure 16, which shows the average and swish (level variation) footprints for a complete revolution. Note that these footprints are very similar to those in Figure 2, which suggests that the general pattern does not depend strongly on turbine or operation details. The footprints in Figure 16 show that for both cross-wind directions, the average level is lower than in the up- and downwind directions, but the variation in level is larger. The patterns do not change significantly beyond a distance of a few rotor diameters. The sound characteristics at large distance, which are most relevant for noise annoyance, are quantified in the lower row of Figure 16. Note that in the time histories, the vertical ticks are spaced at 6 dB. It can be seen that even at a large distance, trailing edge noise directivity and convective amplification may cause swish amplitudes up to about 5 dB in the cross-wind directions. In the upwind and downwind directions the swish is practically zero. The slightly higher level in the upwind direction is due to the fact that the blade flow vector $U$ is tilted towards the downwind direction (Figure 3), which affects the convective amplification factor in the denominator of Eq. (4).

### 4.2 Effect of wind shear for attached flow

The results for Cases 2 and 3 ($m = 0.3$ and $m = 0.6$, attached flow) are presented in Figure 17 and Figure 18. In general the sound characteristics are very similar to those for Case 1, except that the waves on the side of the descending blade have a slightly higher level than those on the side of the ascending blade. This is because the blades produce more noise around 12 o’clock than around 6 o’clock, due to the higher wind speed at larger height. However, the swish is still not higher than about 5 dB in the cross-wind directions, and practically zero in the upwind and downwind directions.
downwind directions. Thus, it appears that EAM cannot be explained by wind shear, as long as the flow is still attached and no stall occurs.

4.3 Effect of local stall
The results for Cases 4 and 5 ($m = 0.3$ and $m = 0.6$, local stall) are presented in Figure 19 and Figure 20. The stall locations for both cases are shown in Figure 9. The sound characteristics clearly differ from the cases without stall. Most of the noise is produced during the upper part of the revolution, where stall occurs. Due to the different directivity function for stall noise, sound waves are radiated in the upwind and downwind directions. Due to the convective amplification factor in the denominator of Eq. (5), the noise level on the side of the descending blade is slightly higher than on the side of the ascending blade. For $m = 0.3$, where the stall region is smaller than for $m = 0.6$, the sudden noise increase during part of the revolution causes substantial amplitude modulation (about 3 dB) in the upwind and downwind directions at large distance (see Figure 21). This modulation is not found for the cases without stall and seems to be in line with the EAM observations described in Chapter 2. Moreover, closer to the turbine amplitude modulations exceeding 6 dB are observed in the cross-wind direction (Figure 22). These high modulation amplitudes are not found for the cases without stall. In Figure 20, the time history for $\zeta = 270^\circ$ shows a complex modulation pattern. This is probably due to different blades sequentially leaving and entering the stall region. Note that the average level in this cross-wind direction is much lower than in other directions.

The above results show that local stall can yield noise characteristics which are very similar to the EAM characteristics mentioned in Chapter 2: substantial swish at large distance in upwind and downwind directions, level variations exceeding 6 dB, and more low-frequency content. Thus, local stall is a plausible explanation for EAM. In Section 4.5 a sensitivity study will be carried out to investigate how critical the conditions for EAM are.

4.4 Noise spectra
The noise spectra for Cases 1-5, as perceived at large distance in upwind and downwind directions and averaged over a complete revolution, are presented in Figure 23 (normalised absolute levels). It can be seen that, as long as the flow remains attached, wind shear has almost no effect on the average spectra. This is because the small increase in angle of attack for the upper part of the revolution (about 1.5° at most) is compensated by a reduction in angle of attack for the lower part of the revolution. The noise increase in case of local stall (Cases 4 and 5) is clearly visible. Although the peak frequency remains practically the same as for attached flow (due to A-weighting, see Figure 13), the largest noise increase occurs at the lower frequencies.
The corresponding spectra for the cross-wind directions are shown in Figure 24. It should be noted that the average sound level in the cross-wind directions is much lower than in the upwind and downwind directions (see Figure 16 to Figure 20). For $\xi = 90^\circ$ most of the perceived noise is produced around 6 o’clock. For attached flow (Cases 1-3) the noise level reduces with increasing shear factor, because the wind speed at 6 o’clock reduces and as a result the angle of attack and boundary layer thickness reduce as well. Local stall (Cases 4 and 5) results in a slight noise increase with respect to the corresponding attached flow cases. For $\xi = 270^\circ$ most of the perceived noise is produced around 1 o’clock. Now the noise level for attached flow increases with increasing shear factor, due to the increased wind speed at 1 o’clock. Interestingly, the perceived levels decrease in case of local stall. This is because the trailing edge noise which was radiated from around 1 o’clock in the attached flow cases, is now replaced by stall noise, which is radiated mainly in the upwind and downwind directions.

Instantaneous spectra for the downstream observer position are shown in Figure 25. It can be seen that the modulation has a broader spectrum in the peak than in the trough. This is because the peak is dominated by stall noise and the trough by trailing edge noise from the attached flow. The average noise spectra for observer positions close to the turbine (at one rotor diameter) are similar to those at large distance (Figure 26). The effect of local stall is less pronounced than at large distance (Figure 23), because close to the turbine most of the noise is produced around the 3 o’clock position, where trailing edge noise is dominant.

4.5 Sensitivity study

In this section we will investigate the sensitivity of the simulation results to different model parameters. Throughout this section, Case 4 ($m = 0.3$, local stall) will be used as a reference, since this case showed the largest modulation in upwind and downwind directions at large distance. We will focus on the modulation amplitude at large distance. The effect of the wind shear exponent $m$ is shown in Figure 27. The general trend is the same for different values of $m$, but the highest modulation amplitude in upwind and downwind direction (about 4 dB) is found for $m = 0.4$. For smaller $m$ the smaller stall region results in less noise increase and therefore less modulation, while for higher $m$ the larger stall region gives less modulation due to the summation of the noise from the three blades.

The effect of the blade pitch angle is shown in Figure 28. It can be seen that for a small decrease in pitch angle (larger angle of attack) the characteristics remain similar to the reference case. However, if the pitch angle is increased, the stall region becomes smaller and the modulation amplitude becomes similar to that for attached flow (see Figure 17). Thus, the effect of blade pitch on amplitude modulation is mainly determined by the size of the stall region.

Finally, the influence of the stall noise level increase is investigated. As explained in Section 3.3.2, the prediction model assumes a noise increase of about 10 dB when stall occurs.
(see Figure 13 and Figure 14). It was already mentioned that the level increases reported in literature vary, and that the actual value may depend on the airfoil. The effect of a 3 dB change in this stall noise level increase is shown in Figure 29. As expected, the modulation amplitude increases with increasing stall noise level increase, although the trends remain similar. Thus, the magnitude of the modulation amplitude strongly depends on the stall noise level increase of the airfoil. This means that, in order to predict an accurate quantitative value of the amplitude modulation for a given turbine, detailed information about the stall noise behaviour of the relevant airfoils is needed.

In summary, it can be concluded that the characteristics of wind shear induced amplitude modulation mainly depend on the size of the stall region (which in turn depends on blade design, turbine control system, operation conditions and wind shear) and on the stall noise behaviour of the airfoils used on the blade.

5 Conclusion

Modern large wind turbines normally produce a swishing noise with a sound level variation of a few decibels. However, in some cases periods of increased swish or thumping are reported, here denoted as Enhanced Amplitude Modulation (EAM). The characteristics of EAM were investigated by means of a literature study and by analysis of a sound sample. It was concluded that EAM can be characterised by sound level variations of more than 6 dB and/or substantial level variations at large distance in upwind or downwind direction, often accompanied by more low-frequency content in the sound.

In order to identify potential causes for EAM, a simulation study was performed into the effects of wind shear on the sound characteristics of a representative modern large wind turbine. First, the effect of wind shear on the local blade flow conditions was determined. It was found that, for certain operation conditions (where the blades are most susceptible to stall), strong wind shear can lead to local stall during the upper part of the revolution. Next, in order to determine the corresponding sound characteristics, an existing turbine noise prediction model was extended to include an azimuth-dependent blade source distribution. Furthermore, a stall noise module was implemented. It should be noted that the effects of wind shear were modelled using engineering methods, which have not been validated by experiments yet. The simulation results show that, as long as the flow over the blades is attached, wind shear has practically no effect on the amplitude modulation. However, if local stall occurs, the resulting noise characteristics can be very similar to the EAM characteristics mentioned above, depending on the size of the stall region. Thus, it can be concluded that local stall is a plausible explanation for EAM.
In order to assess how critical the conditions for EAM are, a sensitivity study was carried out. This study showed that the occurrence of EAM for this specific turbine strongly depends on wind shear, blade pitch, and the assumed stall noise level increase. More generally, it can be concluded that the characteristics of wind shear induced amplitude modulation mainly depend on the size of the stall region (which in turn depends on blade design, turbine control system, operation conditions and wind shear) and on the stall noise behaviour of the airfoils used on the blade. Only for certain combinations of these parameters EAM will occur. The most obvious measure to prevent EAM is to prevent local stall on the blades. An increase in the stall margin may be achieved by operating the blades at a lower angle of attack or by using airfoils with a high stall angle. A practical implementation for existing turbines may be to increase the blade pitch angle in case of strong wind shear.

Finally, it should be noted that, apart from wind shear, (temporary) non-uniform inflow conditions may also be caused by e.g. yaw (wind veer), topography, large-scale turbulence, or the wake of other turbines. These effects may lead to local stall and as a consequence to EAM. Thus, for future experimental research into EAM, it is recommended to focus not only on the sound characteristics, but to monitor as much as possible also the turbine operation parameters and meteorological conditions. A convenient method for detecting local stall could be the use of stall-flags [24,25].
References


† Part of: S. Oerlemans, Detection of aeroacoustic sound sources on aircraft and wind turbines, PhD thesis University of Twente, The Netherlands, 2009 (http://doc.utwente.nl/67363/).
[16] www.dickbowdler.co.uk.


Figures

Figure 1: Noise source distribution in the rotor plane of a modern large wind turbine, measured about one rotor diameter upwind from the turbine. The source distribution is averaged over many revolutions. The range of the colour scale is 12 dB. Practically all noise is produced by the outer part of the blades (not the very tip) during the downward part of the revolution.

Figure 2: Footprints of the average sound level (left) and the sound level variation (right) during a revolution [5]. The turbine is located at the centre of the plot (top view), and the wind goes from left to right. The radius of the plotted area equals 10 rotor diameters. The figure shows that, for an observer more than a few rotor diameters away, the average levels are highest in the upwind and downwind directions, but the variations in level are largest in the cross-wind directions. Close to the turbine, substantial swish is perceived in all directions.
**Figure 3:** Airfoil with definition of flow angles. $U_w$ is the wind speed, $U_r$ is the rotational speed, $\mu$ is the pitch angle and $\alpha$ is the angle of attack. $F$ is the force on the blade. Close to the blade tip $U_r$ is usually roughly seven times higher than $U_w$. An increase in wind speed leads to a higher angle of attack.

**Figure 4:** Time history of A-weighted overall sound level as a function of time (absolute levels not meaningful). The transition between normal swish and EAM occurs between 11 s and 13 s. The crosses indicate the instantaneous levels (averaged over 0.23 s), the squares indicate the maxima and minima.
Figure 5: Number of maxima and minima as a function of time (left axis). The blue markers (right axis) indicate the time difference between consecutive minima and maxima.

Figure 6: Average spectra for swish period and EAM period (absolute levels not meaningful). The EAM sound has much more low-frequency content than the swishing sound.
Figure 7: Mechanisms of normal trailing edge noise (left) and stall noise (right) [20]. The larger turbulence length scale for stalled flow results in increased low-frequency noise.

Figure 8: Wind profile in rotor plane for different values of the wind shear factor $m$.

Figure 9: Locations in the rotor plane where stall can occur, for a wind shear factor of 0.3 (left) and 0.6 (right). The circles indicate the outer 40% of the blade.
Figure 10: Normalised trailing edge boundary layer displacement thickness as a function of angle of attack, for suction side and pressure side (multiplied by 10). The tick marks on the horizontal axis are spaced at 1°.

Figure 11: Definition of angles between observer and trailing edge source.
Figure 12: Directivity functions for trailing edge noise (left) and stall noise (right). The source is located at the centre of the sphere. The flow is in the x'-direction and the trailing edge runs along the y'-axis. The range of the color scale is 12 dB.

Figure 13: Source spectra for blade section in dB (left) and dBA (right) as a function of relative angle of attack (0° corresponds to the stall angle). The lines for 0° and 2° are practically on top of each other.
Figure 14: Overall sound level for blade section as a function of angle of attack. The tick marks on the horizontal axis are spaced at 1°.

Figure 15: Definition of rotor azimuth angle $\psi$ and observer angle $\zeta$. 
Figure 16: Simulation results for Case 1 (m=0, attached flow). Upper row: instantaneous noise footprints. Middle row: average and swish footprint. Lower row: time histories and directivity at large distance (10 rotor diameters from turbine).
Figure 17: Simulation results for Case 2 (m=0.3, attached flow). Upper row: instantaneous noise footprints. Middle row: average and swish footprint. Lower row: time histories and directivity at large distance (10 rotor diameters from turbine).
Figure 18: Simulation results for Case 3 (m=0.6, attached flow). Upper row: instantaneous noise footprints. Middle row: average and swish footprint. Lower row: time histories and directivity at large distance (10 rotor diameters from turbine).
Figure 19: Simulation results for Case 4 (m=0.3, local stall). Upper row: instantaneous noise footprints. Middle row: average and swish footprint. Lower row: time histories and directivity at large distance (10 rotor diameters from turbine).
Figure 20: Simulation results for Case 5 (m=0.6, local stall). Upper row: instantaneous noise footprints. Middle row: average and swish footprint. Lower row: time histories and directivity at large distance (10 rotor diameters from turbine).
Figure 21: Modulation amplitude at large distance (10 rotor diameters from turbine).

Figure 22: Modulation amplitude at one rotor diameter from turbine.
Figure 23: Average spectra for different cases, perceived at large distance (10 rotor diameters from turbine) on a downwind (left) and upwind (right) position.

Figure 24: Average spectra for different cases, perceived at large distance (10 rotor diameters from turbine) on both cross-wind positions.
Figure 25: Instantaneous spectra for Case 4, perceived at large distance (10 rotor diameters from turbine) on the downwind position. The blue and red lines correspond to the peak and trough of the modulation (see also Figure 19).

Figure 26: Average spectra for different cases, perceived at one rotor diameter from the turbine on a downwind (left) and upwind (right) position.
Figure 27: Effect of wind shear exponent on modulation amplitude at large distance (10 rotor diameters from turbine).

Figure 28: Effect of blade pitch angle on modulation amplitude at large distance (10 rotor diameters from turbine).
Figure 29: Effect of stall noise level increase on modulation amplitude at large distance (10 rotor diameters from turbine).
Work Package A2

Fundamental research into possible causes of amplitude modulation

University of Southampton, ISVR
Consultancy Report
Ref: 8630-R01

Submitted to: RenewableUK

Prepared by: Dr M G Smith
Manager/Principal Consultant

Wind Turbine Amplitude Modulation: Research to Improve Understanding as to its Cause & Effect

Work Package A2 (WPA2) - Fundamental Research into Possible Causes of Amplitude Modulation

March 2012

8630-R01
Contents

1. Summary ................................................................................................................................ 1

2. Introduction ............................................................................................................................. 1

3. Background theory and models ............................................................................................... 4
   3.1 Basic theory for aerodynamic noise from aerofoils ............................................................. 4
   3.2 Semi-empirical models of wind turbine noise ....................................................................... 5
       3.2.1 Inflow turbulence noise .................................................................................................. 7
       3.2.2 Turbulent boundary layer – trailing edge interaction noise ........................................ 8
       3.2.3 Stall noise ..................................................................................................................... 9
       3.2.4 Doppler shift ............................................................................................................... 9
       3.2.5 Propagation effects ..................................................................................................... 10
       3.2.6 Other aerodynamic and aeroelastic effects ................................................................. 11
   3.3 A model of Normal AM ...................................................................................................... 12

4. Potential sources of Other AM .............................................................................................. 14
   4.1 Source mechanisms ............................................................................................................. 14
       4.1.1 Effect of wind shear .................................................................................................... 15
       4.1.2 Effect of other steady flow characteristics on localised blade stall ....................... 17
       4.1.3 Effect of non-uniform unsteady flow ......................................................................... 19
   4.2 Propagation in non-uniform flow .................................................................................... 20

5. Assessment of factors contributing to Other AM .................................................................. 23
   5.1 Local blade stall due to non-uniform inflow ................................................................... 23
   5.2 Non-uniform inflow turbulence ...................................................................................... 24

6. Conclusions ............................................................................................................................ 26

7. Acknowledgment .................................................................................................................. 28

8. References ............................................................................................................................. 29

Table 1. Sources of Normal AM in Uniform Steady Flow .......................................................... 31

Table 2. Sources of AM in steady flow with wind shear or other wind speed variations .......... 32

Table 3. Sources of AM in unsteady flow, with or without wind shear .................................... 34

Figures ....................................................................................................................................... 35
1. **Summary**

The noise produced by wind turbines is inherently periodically time varying in level, an effect known as amplitude modulation (AM). Normal AM is caused by the directivity of the dominant noise sources of the rotating blades (at the trailing edge) combined with their changing position and orientation. This normal AM is most pronounced in cross-wind directions.

In some circumstances the character and spatial distribution of the amplitude modulation is altered, with a shift to lower frequencies, an increase in modulation depth and high levels of AM occurring at large distances upwind or downwind. These characteristics cannot be explained by current models of Normal AM. This report provides a review of possible causes of ‘Other AM’.

Two source mechanisms that could play a part in the observed shift to lower frequencies have been identified as: a) stalled or detached flow over part of the blade; b) high levels of inflow turbulence. When these sources mechanisms occur there is also a change in directivity of the noise emissions compared with the directivity of trailing edge noise, with increased levels expected in directions orthogonal to the rotor plane.

However, these conditions alone cannot explain Other AM. A key additional condition that is necessary for high levels of AM to occur at large distances downwind is that the flow into the rotor is non-uniform. Either:

- The wind profile is non-uniform, for example due to a vertical or lateral variation in wind speed or a spatial variation of the angle of the wind onto the rotor. Significantly different AM characteristics are then predicted when local stall occurs due to the time-varying source. High vertical wind gradients (wind shear) or local wind gusts could provide the meteorological conditions for this to happen.
- The turbulence entering the rotor disk is non-uniform, causing time-varying levels of inflow turbulence noise as each blade enters the region of high
turbulence. Non-uniform turbulence could occur under certain meteorological conditions or when there are obstructions upwind of the wind turbine.

The potential role of propagation effects has also been investigated. Wind shear causes a number of effects in the upwind and downwind directions which may combine with the above source effects to enhance Other AM. Atmospheric attenuation causes a shift towards lower frequencies at large distances, which would compound any shift to low frequencies at source. The effects of the moving source would also tend to shift the spectrum to lower frequencies compared with nearfield locations. Ground reflection effects could also increase the level of AM by a small amount.

The way in which these various mechanisms and factors combine to produce the particular features of Other AM at large distances needs to be confirmed by additional data gathering.
2. **Introduction**

The work presented in this report is part of project funded by RenewableUK and entitled ‘Wind Turbine Amplitude Modulation: Research to Improve Understanding as to its Cause & Effect’. The project comprises a total of six separate work packages. The outcome results of each of the work packages have separately resulted in their own dedicated final reports. A seventh work package, WPF, has produced an overarching final report in which the key findings across the separate work packages have been collated and discussed.

This is the final report of Work Package WPB2: ‘Fundamental Research into Possible Causes of Amplitude Modulation’.

Wind turbine aerodynamic noise, by which is meant the noise produced by the rotating wind turbine blades, includes a steady component as well as, in some circumstances, a periodically fluctuating, or amplitude modulated (AM), component. However, AM may take different forms. One form of AM, commonly referred to as ‘blade swish’, is an inherent feature of the operation of all wind turbines. It can be explained by well understood mechanisms, it being the result of the directivity characteristics of the noise created by the air flowing over a turbine blade as it rotates. Because this type of AM is an inherent feature of the operation of wind turbines, whose origin can be explained and modelled, the present project adopts as its definition the term ‘normal amplitude modulation’ (NAM). The key driver for the project, however, is the recognition that some AM exhibits characteristics that fall outside those expected of NAM. Such characteristics include a greater depth of modulation, different directivity patterns or a changed noise character. For this reason the present project adopts as its definition the term ‘other amplitude modulation’, or ‘OAM’, for all observations of AM that lie outside that expected of NAM.

In recent years public concern has grown about the potential annoyance from wind turbine OAM noise. This concern has resulted in an increased interest to establish how AM, and in particular OAM, occurs, how it can be better defined and measured, and how it is generally perceived and responded to. It is the answers to these questions that the present project seeks to address.
The environmental noise impact of wind turbine generators has to be assessed when planning new installations and methodologies have been developed for this purpose. However, one characteristic of the aerodynamic noise from wind turbines which has thus far been less amenable to prediction and assessment is amplitude modulation (AM), the variation in noise level occurring periodically in time at the blade-passing frequency of the turbine rotor (0.75 Hz for a 3-bladed rotor spinning at 15 rpm, which is typical for modern turbines). This characteristic is often termed ‘blade swish’ and in most cases is only audible close to the turbine and is not expected to be detectable to any significant extent at distances greater than around 400-500 metres.

This ‘Normal’ amplitude modulation (NAM) is caused by the directivity of the dominant aerodynamic noise source (on modern turbines this is usually considered to be so-called trailing edge noise, discussed in Section 3.2.2) combined with the time-varying position and orientation of the rotating blades. For typical large wind turbines, Normal AM tends to be dominated by frequencies in the 400 – 1000 Hz range and is most pronounced in the near/mid-field in cross-wind directions; it reduces significantly with distance, especially in the downwind or upwind directions, and should be negligible at large distances when the observer is close to the axis of the turbine (which is generally closely aligned with the wind direction).

In some circumstances, as outlined in the Work Package C report for this study [1], it has been observed that the level and character of the amplitude modulation is altered, with an increase in low frequency noise content, an increase in modulation depth and a change in the spatial distribution of the observed effect. In specific cases, high levels of AM have been observed at large distances downwind or upwind of a number of installations. These instances cannot be explained by the current standard models of ‘Normal’ AM, and so are called ‘Other’ AM (OAM).

This report provides a review of possible mechanisms that could be causing this change. Basic background theory to the standard models of wind turbine noise and Normal AM are discussed in Section 3, and then potential sources of Other AM are discussed in Section 4. Section 5 provides an assessment of what the AM characteristics might be for each of these alternative mechanisms so that existing
databases of wind turbine noise data can be matched against these criteria and new data can be gathered.

From the data identified in the Work Package C report [1] as showing Other AM, the data acquired by D. Bowdler is used here as an illustrative example. The spectrogram of this recording is presented in Figure 1b), showing 7 seconds of Normal AM data followed by a transition to a period of Other AM. The average spectra associated with the sections of Normal AM and Other AM are plotted in figure 1a). This sample will be referenced in this report to illustrate some of the potential effects discussed. It must be borne in mind however that this data, which was gathered in the near-field of a turbine, is not necessarily representative of either what would have been measured on this wind turbine in the far-field (as discussed in various sections below), or of Other AM in general. It does suggest, however, that changes at source may occur in some conditions, so that propagation effects alone do not explain Other AM.
3. Background theory and models

3.1 Basic theory for aerodynamic noise from aerofoils

Aerodynamic noise source mechanisms have been the subject of extensive research over the past 60 years because of their importance in aircraft engines. Following the fundamental work by Lighthill on noise generated by turbulence in high speed jets [2], Curle extended the theory to show how turbulence interacting with a solid body increases the efficiency of the noise source [3], and Ffowcs-Williams and Hall [4] went on to demonstrate that the efficiency of noise generation was further increased when the turbulence interacts with a sharp edge.

The aerodynamic noise produced by wind turbine blades as they rotate is caused by the interaction of the blades with turbulence in the flow. Some turbulence is present in the wind and this causes so-called ‘inflow turbulence noise’. However, turbulence is also generated by the boundary layer of the flow over the blades, and this is the origin of a number of ‘self-noise’ mechanisms which would be produced by the turbine even in a uniform and non-turbulent flow. These mechanisms are illustrated in figure 2 which is discussed in the next section.

The noise source mechanisms are essentially linked to the steady aerodynamics of the turbine, outlined in figure 3, through which power is extracted from the wind by utilising the lift force $F$ to turn the rotor. The velocity of the blade $U_r$ and the wind vector $U_w$ combine to create a resultant flow vector $U$ over the blade. Since local blade velocity increases with radius, the blades are twisted and pitched by a radially varying angle $\mu$ so as to give an angle of incidence or attack $\alpha$ that maximises the lift force. Most modern large turbines are of the variable speed, pitch-regulated type, with the speed and blade pitch angle being adjusted to optimise power output from the turbine. In older turbines, power regulation was implemented through (active or passive) stalling of the blades, which increased overall noise levels at high wind speeds, but this is unlikely to increase AM levels and will not be considered in further detail in this study.
The dominant self-noise mechanism when dealing with an A-weighted spectrum of wind turbine noise is generally considered to be trailing-edge noise [10], in which the turbulent boundary layer of the flow over the blade is convected past the sharp trailing edge. The theory of Ffowcs-Williams and Hall thus provides a basis for most models of aerofoil trailing edge noise. Their work was refined into a more useable model by Amiet [5], who also included the directivity effects associated with a finite chord blade.

The currently accepted model of inflow turbulence noise on aerofoils was produced by Amiet [6] who describes how the unsteady flow causes a time varying angle of attack, with noise being generated by the resulting fluctuating lift forces acting on the blade. The spectrum of noise is controlled by the turbulence intensity spectrum and, since this normally rolls off rapidly at high frequency, inflow turbulence noise is generally only believed to be significant at frequencies below the peak of a typical A-weighted wind turbine noise spectrum.

Although trailing edge noise is currently considered to be the dominant source with respect to A-weighted overall levels on most wind turbines, the relative importance of inflow noise is still not clear and is probably site specific [15, 16], depending on local levels of turbulence in the wind.

3.2 Semi-empirical models of wind turbine noise

Whilst the basic research publications discussed in the previous section define the fundamental physics for each source, most prediction models are semi-empirical and combine basic scaling laws with empirical constants derived from measured data.

The paper by Hubbard and Shepherd [7] provides an excellent review covering both source mechanisms and propagation effects which, although published in 1991, is still generally relevant today. The main progress since that time has been in detailed modelling of the various effects rather than in developing fundamentally new theory. Of the many contributions reviewed, the paper by Grossveld [8] is useful in providing a predicted noise source breakdown for the 1.5 MW MOD-2 wind turbine; this model
suggests a major contribution from low frequency inflow turbulence noise, although this on-axis source breakdown was not validated.

Since these early models were developed, Brooks, Pope and Marcolini [9] (BPM) produced an extensive database of experimental data on the self-noise of aerofoils, and derived a semi-empirical prediction method for the five self-noise mechanisms identified in the study, which are illustrated in figure 2:

- Boundary-layer turbulence passing the trailing edge. This is the dominant source on wind turbines under normal operating conditions.
- Separated-boundary layer / stalled-aerofoil flow. This is a potentially major source in particular conditions and is discussed in detail in later sections.
- Vortex shedding due to laminar-boundary-layer instabilities. This is unlikely to contribute to wind turbine noise as the flow regime does not apply.
- Vortex shedding from the blunt trailing edge of the blade. This is a known feature of wind turbines, but generally occurs at high frequencies and so is not relevant to amplitude modulation of lower frequency noise as is required to explain Other AM.
- The turbulent vortex flow existing near the tips of lifting blades. This is normally a relatively high frequency problem, and has also been largely controlled by careful tip design on modern machines.

The BPM semi-empirical model may be used to predict the peak far-field 1/3 octave band self-noise spectrum for a uniform aerofoil in a steady uniform flow, but gives no information about the directivity of the noise with respect to the coordinates of the blade element.

It is apparent therefore that three sources need to be considered as being potentially relevant to the problem of Other AM: inflow turbulence noise; turbulent boundary layer – trailing edge noise; separated boundary layer and stall noise. The prediction models for each of these sources have three common elements:

- A function defining a source spectrum shape $A(St)$, where $St$ is a non-dimensional frequency known as the Strouhal number for that source.
- A function $D(\theta,\phi)$ which defines the directivity of the source in terms of the polar and azimuthal radiation angles, $\theta$ and $\phi$, relative to the coordinate system of the blade element.
- A scaling term to account for the dimensions of the blade and the characteristics of the flow.

3.2.1 Inflow turbulence noise

Prediction models of inflow turbulence noise based on Amiet [6] thus have the general form:

\[
L_i(f) = 10\log_{10} \left( \frac{\sigma^2 L d U^5}{R^2} A_1(S_{1t}) D_1(\theta, \phi) C(M, \zeta) \right)
\]

Here \( L_i(f) \) is the 1/3 octave band spectrum at centre frequency \( f \). The parameters \( \sigma^2 \) and \( L \) are related to the intensity and length scale of the turbulence in the wind, \( U \) is flow velocity over the blade, \( d \) is the span of the blade element and \( R \) is the observer distance. The function \( A_1(S_{1t}) \) is derived from the lift function of the blade, which defines the lift force as a function of the angle of attack, and is a function of the Strouhal number \( S_{1t} = fb/U \), where \( b \) is the blade chord. The directivity function is the dipole radiation pattern:

\[
D_1(\theta, \phi) = \sin^2(\theta)\sin^2(\phi)
\]

the polar component of which is plotted in figure 4a), and is dominant perpendicular to the blade.

\( C(M, \zeta) \) is called the convective amplification factor, which increases the intensity of the sound when the source is moving towards the observer:

\[
C(M, \zeta) = \frac{1}{(1 - M\cos(\zeta))^2}
\]

Here \( M \) is the relative Mach number of the source and receiver, and \( \zeta \) is the angle between them relative to the direction of motion.

From this simplified outline model it is apparent that for a given wind turbine, for which the flow velocity over the blade is primarily controlled by the tip speed of the rotor rather than the wind speed, the main variability with wind conditions will come from the intensity and length scale of the turbulence, and the variation of the lift function of the blade with angle of attack.
3.2.2 Turbulent boundary layer – trailing edge interaction noise

For trailing edge noise the models of Grossveld and of Brooks, Pope and Marcolini can be written in a similar form:

$$L_2(f) = 10 \log_{10} \left( \frac{\delta^* dU^5}{R^2} A_2(S_{t_2})D_2(\theta,\phi)C(M,M') \right)$$

(4)

Here $\delta^*$ is the thickness of the boundary layer at the trailing edge of the blade. The spectrum shape $A_2(S_{t_2})$ is derived from test data (full scale wind turbine data for Grossveld and model scale aerofoil data for BPM), and is a function of the Strouhal number of the boundary layer $S_{t_2} = f \delta^*/U$.

The directivity function at high frequencies and for large chords ($b/\lambda >>1$) is the cardioid radiation pattern plotted in figure 4d):

$$D_2(\theta,\phi) = \sin^2(\theta/2)\sin^2(\phi)$$

(5)

At lower frequencies the directivity is a function of the chord to wavelength ratio as shown in figures 4b) and 4c). The most typical directivity for trailing edge noise from a wind turbine is with $b/\lambda = 1$, for example if $b= 0.5\text{m}$ then $\lambda = 0.5\text{m}$ and this corresponds to a frequency of 680Hz. The peak of the directivity function occurs at about 30° to the blade, although this will be shifted to slightly lower angles by the effect of convective amplification. The blade twist also needs to be taken into consideration when considering the peak noise radiation angle with respect to the global wind turbine – observer geometry, and the twist varies with radial position of the blade element under consideration.

From this outline model of trailing edge noise it is apparent that the most important parameter that varies when wind conditions change is the boundary layer thickness. For example, from figure 2 it is apparent that a higher wind speed leads to an increased angle of attack (assuming that there is no change of blade pitch due to the wind turbine control algorithm), as a result of which the boundary layer thickness will also be increased. This both increases the (unweighted) sound power of the source defined by Eq (4) and lowers the peak frequency of the spectrum defined by the peak Strouhal number.
3.2.3 Stall noise

For stall noise, the Brooks, Pope and Marcolini model can be written in the same form as the trailing edge noise:

\[ L_s(f) = 10 \log_{10} \left( \frac{\delta^* dU^5}{R^2} A_s(St_{\ell}) D_s(\theta, \phi) C(M, \zeta) \right) \]  

(6)

However, a major difference between the BPM models of trailing edge noise and of stall noise is the directivity function - stall noise has the same dipole pattern as inflow turbulence noise as plotted in figure 4a):

\[ D_s(\theta, \phi) = \sin^2(\theta) \sin^2(\phi) \]  

(7)

During stall, the boundary layer thickness \( \delta^* \) increases considerably, so that the length scale of the turbulence is increased, and the Strouhal number at which the non-dimensional spectrum \( A_s(St_{\ell}) \) peaks is also reduced. These effects combine to give the shift to low frequencies that is observed when a aerofoil moves from attached flow to detached flow. Equation 6 shows that the increased value of \( \delta^* \) also leads directly to an increase in far-field noise level, and the level of the BPM source spectrum \( A_s(St_{\ell}) \) also changes compared with the trailing edge source spectrum \( A_s(St_{\ell}) \).

More details on this shift of frequency and increase in far-field sound pressure level are given in Section 4.1.1 with reference to how the changes in blade element source levels were implemented by Oerlemans in WPA1 [13]. It should be noted however that stall behaviour is a complex phenomenon, and that it appears to have been the subject of less study than other sources of noise on aerofoils, perhaps because it generally corresponds to a departure from design conditions.

3.2.4 Doppler shift

Another important factor that needs to be considered is the effect of Doppler shift which alters the perceived frequency of the noise when the source is moving relative to the observer. If noise is generated on the blades at frequency \( f \), and \( \zeta \) is the angle between relative to the direction of motion, then the observer hears the frequency:

\[ f' = \frac{f}{(1 - M \cos(\zeta))} \]  

(8)
For example with a Mach number $M = 0.21$ (71 m/s approx., or 15 RPM for a 90 m rotor diameter turbine), the Doppler shift corresponds to one 1/3 octave band. Thus noise generated at 500 Hz on a section of blade travelling at this Mach number will be perceived at the same frequency downwind where there is no Doppler shift, but may be heard at up to 630 Hz in the nearfield when the blade is moving towards the observer (i.e. when trailing edge noise is near its peak because of the directivity effects).

The Doppler effect is an inherent part of the characteristic ‘swish’ of a wind turbine in the nearfield, and might possibly be manifesting itself in the spectrogram of figure 1 through the slight “slope” of the high frequency peaks. It may also be significant that the slope at low frequencies is different, i.e. there is a progressive shift to lower frequencies during the event, a feature that is discussed in Section 4.1.

### 3.2.5 Propagation effects

Besides the time variation of the noise sources, the character of wind turbine noise will vary with distance because of a number of propagation effects. The effects considered in this section are atmospheric attenuation and ground interference, which both occur in uniform flow, whereas the additional influence of refraction of sound by a non-uniform flow is considered in Section 4.2.

The paper by Bass et al [11] and ISO Standard 9613-1 [12] discuss absorption of sound by the atmosphere, showing that significant attenuation of high frequency noise occurs over large distances. The rate of attenuation varies with relative humidity, but at 50% humidity it is approximately 0.5 dB/km at 100 Hz and 5 dB/km at 1000 Hz. The rate of attenuation under low humidity conditions tends to be proportionately higher, although the trend reverses from 10% down to 0% humidity. Applying the 50% humidity rate of attenuation to the two near-field spectra presented in figure 1a), it is concluded that beyond 1 km the overall A-weighted sound pressure level of both spectra would be dominated by frequency components below 630 Hz.

The effect of ground interference is illustrated in figure 5, showing how for an observer above a hard ground plane the phase interference between the direct and
indirect sound paths causes dips in the spectrum, with the frequency of the dip varying with source height and observer range. In figure 5a) the receiver location is on the ground, and the SPL at large distances is independent of source height. Figures 5b – 5d) show the SPL for a 1.5m receiver height for frequencies of 125, 250 and 500 Hz respectively. These results show how the ground interference dip varies with both source height and frequency.

This model may be used to try to interpret some subtle features of the Normal AM data presented in figure 1, which were measured close to the turbine with a microphone about 1.2m off the ground. For this location, the dominant contribution will be from the downward sweep of each blade when it is close to the horizontal, so that for the 1/3 octave band data in figure 1a) the prediction for the 80m source height in figure 6a) might apply. The ground interference effect could conceivably be contributing to both the 3dB dip around 300 Hz and the roll off below 160 Hz in the measured data (in addition to the effect of A-weighting). These spectral artefacts are not representative of the source level of the turbine, hence the reason for using microphones placed on a fully reflective surface on the ground when sound power tests of wind turbines are carried out.

Considering next the narrowband spectrogram in figure 1b), compared with the narrowband prediction in figure 6b), it is apparent that the spectral ripples seen in the measured data are quite likely to be due to the ground reflection. Finally, figure 6c) presents a prediction for a range of 500m, showing that at this distance some modulation of the 250 – 800 Hz frequency bands may be expected due to the time-varying geometry of the ground interference as the blades rotate. In practice the effect of ground absorption would tend to reduce these effects as the reflected ray is attenuated, but it should be noted that it is the properties of the ground relatively close to the observer that are important, rather than the ground along the propagation path as a whole.

### 3.2.6 Other aerodynamic and aeroelastic effects

There are many subtle effects that may contribute to the detailed incidence of blade stall in particular. It is not possible to discuss these in detail in this report, partly
because little published work on the subject is available, and so a few of the effects are noted here as a marker for a more detailed investigation:

- Depending on the distribution of lift forces along the blade the local twist angle of the blade may be altered from the design value. This would modify the effect of non-uniform flow on stall noise.

- Likewise, the blades of a wind turbine are curved backwards, but straighten under the lift forces. This may compound the effect of wind yaw and veer (see section 4.1.2).

- The onset of stall may be delayed beyond the expected critical angle of attack. Similarly, once stall has occurred, reattachment at lower angles of incidence may be delayed.

- These delays might also mean that stall moves inboard or outboard more or less rapidly than expected from simple angle of attack models.

3.3 A model of Normal AM

The recent wind turbine noise model developed by Oerlemans [10] to explain the characteristics of Normal AM combines three elements: the steady state BPM model of turbulent boundary layer/ trailing edge interaction noise; the directivity model described by Amiet [5]; and a model of the time varying geometry and flow conditions of the wind turbine rotor. He considers short sections of blade for which the blade parameters (chord, thickness, twist angle, etc.) are effectively constant. Typically, the important outer sections of the blade (which dominate the noise emissions because of the high local flow velocities arising from rotation of the turbine) are broken down into about 20 radial segments, and a complete revolution is broken down into about 30 time steps.

The flow parameters (velocity, angle of attack, boundary layer thickness, etc.) for each section are taken to be constant for the complete revolution of the rotor and ‘the effect of atmospheric turbulence, wind shear and yaw are neglected’, i.e. the flow is uniform and orthogonal to the rotor plane. Inflow turbulence noise is not included in the model. Of the other effects outlined above, the Doppler shift is included in the model, but atmospheric attenuation and ground interference for an observer located off the ground are not included.
Oerlemans’ quasi-steady state model is able to predict with reasonable accuracy the time varying spectrum of the near-field noise for a real wind turbine in nominally uniform flow, where the wind speed only varies a small amount with height and lateral location. It is worth noting though that the model appears to under-predict the measured spectrum below 160Hz, figures 15 and 16 in ref [10], which may be indicative of a contribution from inflow turbulence noise on the turbines used for validation, though the A-weighting reduced the importance of these frequencies.

From his time-domain model of trailing edge noise, Oerlemans is able to predict the main characteristics of Normal AM, showing it to be caused by the directivity of the trailing edge noise source mechanism, which dominates the peak of the A-weighted spectrum, combined with the changing position and orientation of the rotating blades. Normal AM is characterised by a variation of up to 5dB in the level of mid-high frequency noise (400 – 1000Hz). At distances less than one rotor diameter from the tower this is evident in all directions, but at larger distances the swish is mainly evident at cross-wind locations close to the rotor plane.

Whereas the maximum absolute noise level peaks at observer angles away from the rotor disk, and the absolute level in the rotor plane is typically 8 dB below the maximum, the peak level of AM occurs in the rotor plane, see figures 18 and 19 of ref. [10]. This occurs because at downwind locations all three blades contribute equally and the angles to the observer do not change significantly during the rotor revolution, whereas at cross-wind locations the single blade that is moving towards the observer dominates and the angle of that blade to the observer changes a lot. Hence, significant levels of Normal AM will only be observed near the rotor plane and are not expected to occur at large distances either downwind or upwind of the wind turbine.
4. Potential sources of Other AM

Since Oerlemans’ basic model of Normal AM is not able to predict features which have been observed at some sites and described as “Other AM”, it may be deduced that the problem occurs because of some deviation from the ideal conditions that are assumed in that model. This section outlines all of the possibilities that have been identified during the course of this study, separating them into source effects and propagation effects. Section 5 then attempts to identify the key features of each effect so as to assess whether it is a potential cause of the observed characteristics of Other AM and to provide guidance for additional data gathering.

4.1 Source mechanisms

Three key simplifying assumptions in the Oerlemans model of Normal AM are:

a) The dominant source is standard trailing edge noise.
b) The flow into the wind turbine is uniform.
c) The wind vector is orthogonal to the rotor plane.

Consider initially the effect of relaxing only the first assumption, for example to allow for the fact that in a natural wind there must always be some inflow turbulence noise, but retaining the other assumptions that the flow is uniform (i.e. the mean wind velocity and the intensity and scale of turbulence are the same at all points on the rotor disk) and that the flow is normal to the rotor plane. In this case, the high levels of inflow turbulence could explain higher levels of low-frequency noise, and the directivity function is a dipole, oriented orthogonal to the blades, so that peak levels will tend to occur downwind. However, high levels of AM cannot occur because the level of inflow turbulence noise is not changing with time and the directivity of the source relative to a far-field observer is not changing with position of the rotor. Hence, the occurrence of high levels of turbulence is not in itself sufficient to explain Other AM features.

Similar arguments apply to stall noise. Under flow conditions where this occurs simultaneously at all circumferential locations, such as is the case for stall-regulated turbines, high levels of AM cannot occur downwind.
The key assumption that needs to be investigated therefore is the uniform inflow condition, i.e. there is either a non-uniform wind speed or direction, or a non-uniform level of turbulence intensity. The effect of relaxing the third condition to allow for effects such as a uniform level of wind yaw will also be considered.

4.1.1 Effect of wind shear

One example of a non-uniform wind speed condition is wind shear, where there is an increase in wind speed with increasing height. This has been raised in the past by some as a potential cause for varying level of AM from wind turbines. In his recent RenewableUK funded study [13], Oerlemans shows how this could give rise to some of the observed characteristics of Other AM. He considered profiles of incident wind speed $U_w$ of the form:

$$
\frac{U_w(z)}{U_w(z_h)} = \left( \frac{z}{z_h} \right)^m
$$

where $z_h$ is the height of the hub above ground. The wind profile with a wind shear exponent factor of $m=0.6$ is presented in figure 7a). It is then apparent from the flow vector plot in figure 3 that, if the wind component $U_w$ is varying with height above the ground, then the angle of attack $\alpha$ must also vary with height.

Figure 7b) plots the flow distribution over the rotor, with $U_w=8$ m/s at the hub and $U_w=10$ m/s at top-dead-centre (TDC). In any specific wind turbine, the angle $\alpha$ will vary depending on the blade geometry for that particular design, current flow conditions, and any pitch adjustment required by the turbine control mechanism (for pitch-regulated models). For the purposes of a simplified assessment, a simple blade twist angle was assumed such that $\alpha=8^\circ$ at all radial positions on the blade when $U_w=8$ m/s. Figure 7c) then shows the resultant angle of attack of the flow onto the blades as a function of position on the rotor disk; the highest angles of incidence, and therefore potential stall, occur on the outer portions of the blades near TDC. It is assumed here that stall will occur beyond an angle of attack of about $\alpha=10^\circ$. Oerlemans considers this in more detail as part of WPA1 [13] using calculated design and flow parameters for a representative turbine blade geometry model, showing that, for certain wind shear conditions, stall could occur locally near TDC. In this case, Oerlemans uses a
modification of the BPM stall model discussed in section 3.2.3, in which source levels are increased (based on Oerlemans’s review of available evidence).

Finally, figure 7d) shows how the BPM source spectrum for a typical blade segment varies as a function of angle of attack, showing how the spectrum shifts to lower frequencies as the blade approaches stall. At angles of incidence beyond stall, however, there is an increase in source level at all frequencies, with the most significant relative increase in A-weighted levels being at frequencies below 400Hz.

With this effect in mind, it is worth considering the temporal characteristic of the noise below 400 Hz in figure 1b). During the second period of the recording there appears to be a progressive reduction in the low frequency peak over the course of about half a second (i.e. opposite to the rising frequency trend at high frequencies). This negative slope of peak low frequency versus time could conceivably be attributed to a region of stall moving progressively towards the root of the blade as suggested by figure 7c), and by figure 8 as described below.

The pre-stall shift in source spectrum for blades near TDC suggested by figure 7d) is reminiscent of the shift in frequency observed in figure 1, initially suggesting that wind shear is a potential candidate for this observed change in spectrum. However, the directivity of the trailing edge source is not altered (up to the point of stall), and on axis all three blades are contributing fairly equal levels of noise, so the Oerlemans model still predicts low levels of AM for distant upwind or downwind observers ($\xi=0^\circ$ or $180^\circ$ in the time history plots of figures 17 and 18 of Ref. [13]). Without stall, the overall A-weighted noise spectrum does not change significantly, even as the wind shear increases the angle of attack of the flow on the blade: figures 23 and 24 of Ref. [13]. This model indicates therefore that the effect of shear (without stall) does not lead in itself to a significant change in the turbine AM. This is consistent with the results of Ref [16].

When the angle of attack increases to the point that stall occurs, the source directivity changes to a dipole oriented orthogonal to the blades, and because the stall is intermittent (only occurring when blades are near TDC), some increase in far-field AM might be expected. The time histories presented in Figures 19 and 20 of
Ref. [13] do now show significant modulation in the downwind/upwind directions, where it wasn’t present previously. The predicted modulation depth however remains below 5 dB in the far-field.

Oerlemans does point out however that there is some uncertainty in the level of stall noise. When the assumed blade element source spectrum was increased by 3 dB (from 10 dB above the trailing edge noise to 13 dB above), the calculated depth of AM also increased by 3 dB, to a maximum of 7 dB in figure 29 of Ref. [13].

Thus the effect of wind shear in causing local stall is a potential explanation of Other AM, but to explain levels of modulation of more than 5 dB with the Oerlemans model, it is either necessary to assume high levels of the stall noise source spectrum or some additional effects need to be considered.

4.1.2 Effect of other steady flow characteristics on localised blade stall

The implications of increased wind shear have been studied in depth by Oerlemans, but, as he notes, this is only one of several potential causes of localised stall. The influence of other types of non-uniform wind distribution should also be considered, including:

- Wind yaw (the wind vector is not orthogonal to the rotor plane in figure 3).
- Wind veer (variation of yaw angle with height).
- Uncertainties in the wind conditions, e.g. due to an error in the estimated mean flow velocity and hence the optimum pitch setting of the blades (this would vary depending on the actual power regulation system of the turbine).
- Lateral variation of the wind, for example a local gust affecting part of the rotor or very large-scale turbulence.
- Perturbation of the flow by some obstruction, e.g. another wind turbine or a building upstream of the rotor, or the flow disturbance upstream of the tower (for example caused by vegetation).

Figure 8a) presents the calculated angle of attack on the rotor disk when a -10° yaw angle error is superimposed on a shear flow with $m=0.6$. Figure 8b) then simulates the effect of assuming some uncertainty in the wind speed at hub height. Note that
this latter effect does not assume that the turbine control system is using a local flow measurement directly since the control algorithm may be more complex and based on some other parameter such as total power output; the aim here is to demonstrate the effect of a deviation from an idealised inflow condition.

Compared with figure 7, it is apparent that with a negative yaw angle or an underestimate of the hub height wind speed the likelihood of stall is increased, but the blade stall region is shifted towards the root of the blade (note that with positive yaw or an overestimated hub height wind speed the opposite effect would be observed and the likelihood of stall is reduced). These inboard sections of blade move relatively slowly and so the strong speed-dependence of the aerodynamic noise sources (Eqs. (1), (4) and (6)) makes it unlikely that the most in-board sections of blade are responsible for Other AM. However, these calculations do indicate that yaw and other uncertainties in the flow may contribute to a further shift towards low frequencies in the overall noise spectrum because the larger chord and lower velocity of inboard sections of blade inherently produce lower frequency noise. This could be the cause of the progressive shift to low frequencies already noted for figure 1b).

Considering next the possible effect of local gusts of wind, figure 9a) shows a wind profile that combines both lateral and vertical variations in wind speed to give a local speed of 10m/s in the lower left quadrant of the rotor disk, compared with a wind speed of 8m/s at the hub. The result of this assumed inflow profile on the angle of attack is presented in figure 9b), in which stall could occur in the region of locally increased wind speed.

One of the reasons for considering this particular flow distribution is to consider whether there would be a significant change in arrival time depending on where in the rotation the blade is stalling. Figure 10 represents a notional example of an observer 50m downwind of an 80m high turbine tower with a source located at a radius of 40m. Blade 1 is nominally at the location where trailing edge noise will dominate for this observer, and we consider the effect of blade 1 stalling due to a local gust or blade 2 stalling because of wind shear.
Compared with a typical blade passing period of about 1 second for this size of wind turbine, the difference in time-of-flight delay of 0.13 seconds is small. Hence the trailing edge noise from blade 1 and any stall noise from either blade 1 or blade 2 would arrive at the observer at close to the same time, and it would be difficult to resolve any change in source position without the use of a microphone array / acoustic camera.

The final type of variation in steady flow to be considered is the effect of an obstruction in the flow. This would lead to a decrease in local wind speed, leading to reduced angles of attack and a drop in lift. Whilst this is a potential source of very low frequency noise (i.e. like the infrasound that occurred in early downwind turbine designs), it is unlikely to be a significant contributor that could help to explain the observed characteristics of Other AM.

4.1.3 Effect of non-uniform unsteady flow

The previous two sub-sections considered non-uniform but otherwise steady flow, but the conclusions there could also be extended to any slow time variation of the wind. This section covers short term unsteady variations that could be called ‘turbulence’.

It was noted in Section 4.1 that a uniform distribution of inflow turbulence could not directly explain Other AM, but other possibilities need to be considered:

- There is a uniform velocity distribution, but the turbulence intensity varies with height, either increasing near the ground because of some upstream flow disturbance, or increasing with altitude because of a meteorological effect.
- The turbulence intensity in the flow is independent of height, but wind shear increases the rate of convection of the turbulence into the rotor near TDC.

Because the directivity of the inflow turbulence noise is the same as the dipole directivity of the blade stall noise, some of Oerlemans’ conclusions in Ref [13] may be used to consider the AM characteristics here. The crucial factor that controls the level of AM is the difference between one blade reaching a maximum source level compared with two blades at a minimum source level. Comparing a single source at 120m height (high noise condition) with two sources at 100m height (low noise...
condition), to have a level of modulation of 7dB requires a difference in source level of 10 dB. Since the source level in decibels varies as $10\log_{10}(\sigma^2)$, this means that the turbulence intensity would have to be 10 times higher at 120m than at 100m.

It should be noted however that whereas, according to the models of [9] and [13], stall noise gives rise to an increase in both low frequency and high frequency noise (figure 7d), inflow turbulence would only increase low frequencies and the level of high frequency trailing edge noise would be largely unchanged. Combined with the effects of atmospheric attenuation this could explain a significant shift to low frequencies observed at large distances.

Given the apparent uncertainty in the level of inflow turbulence noise noted in Section 3.1, a higher than expected level of non-uniform inflow turbulence noise at a particular location might make that turbine more susceptible to high levels of AM at low frequencies.

4.2 Propagation in non-uniform flow

The effect of wind speed gradients in creating an upwind shadow zone and causing channelling of noise down wind is well known. Figure 11a) provides an illustration, and Hubbard and Shepherd [7] and others have detailed empirical methods for predicting both effects.

The curvature of the sound rays is caused by refraction due to the variation of convected speed of sound with height; in the upwind direction this reduces with height; in the downwind direction it increases with height.

Refraction is independent of frequency, but energy is scattered into the upwind shadow zone by diffraction, which makes the depth of the upstream shadow zone frequency dependent. This is similar to the frequency dependence of roadside noise barriers due to diffraction over the top of the barrier.
The magnitude of downstream channelling may also be frequency dependent [7], although this effect is less well established. Sound may also be scattered into the shadow zone by inhomogeneities such as atmospheric turbulence.

It is also worth noting that temperature gradient profiles can produce a similar effect. If temperature decreases with height then a shadow zone is created near the ground in all directions, though the magnitude of this will be small for most realistic temperature variations, compared to the effects of wind shear in conditions in which wind turbines operate.

As noted in the work of Hubbard and Shepherd [7], the source height affects the position of the edge of the upwind shadow zone, and it is conceivable that a receiver could move in and out of this zone as the turbine blade rotates. The Parabolic Equation method is now used for numerical predictions of sound propagation over large distances in non-uniform flow [14]. An in-house PE model developed by A. Peplow at Hoare Lea Acoustics was used to produce Figure 11b), which shows the predicted shadow zone with a wind shear factor m=0.6, a frequency of 125 Hz and a source height of 80m. This shows the upwind shadow zone starting at about 300m.

Using this model to predict the transmission loss as a function of source height for a frequency of 250 Hz, figure 11c), it is apparent that for an observer at 500m there is a 25 dB difference in transmission loss for a source at 120m compared with a source at 80m. Thus, as each blade passes through the ‘window’ of high sound transmission near TDC, it will be more audible to an observer at this distance. The other blades are in regions of high transmission loss and so their masking effect can be discounted.

The consequences of this effect are:
- There are upwind regions where the turbine noise would be expected to have a low level because of the shadow zone, but the noise increases significantly in level for a short period as each blade passed TDC.
- The distance at which this effect occurs is reduced when there is high wind shear.
- The likelihood of it occurring increases with the maximum tip height of the wind turbine rotor.
- The ‘windowing’ effect means that high levels of AM would be expected at certain frequencies and certain distances. Comparing one source at 120m (high noise condition with the source in the window at TDC) with two sources at 100m that occurs 1/6 of a rotation later (low noise condition, for which blade 3 does not contribute significantly), results in a calculated variation of more than 10dB at 250Hz at a distance of 500 m in upwind conditions.
- The level of diffraction into the shadow zone is less at high frequencies and so this effect would periodically increase the relative importance of low frequency noise.

For upwind observers this propagation effect thus has several characteristics that are seen in Other AM, even in the absence of any variation in source level such as those associated with stall or inflow turbulence noise. It should also be borne in mind however that turbine noise levels tend to be reduced upwind and are therefore more readily masked by other sources.

Downwind, Hubbard suggest that the channelling effect of wind shear can reduce the normal 6 dB / doubling of distance due to spherical spreading, and that at very low frequencies and with propagation over water the rate can be closer to 3 dB / doubling of distance which occurs with cylindrical spreading. It is suggested that the change from spherical to cylindrical spreading will occur at larger distances at higher frequencies. It is possible therefore that propagation effects in wind shear could be responsible for increasing the relative importance of low frequencies at large distances downwind of an off-shore wind turbine, though the magnitude of this effect is uncertain. This would only increase the perceived level of Amplitude Modulation if low frequency noise were modulated more than high frequency noise, as occurs for example in the case of time-varying inflow turbulence noise.
5. **Assessment of factors contributing to Other AM**

The findings of the previous sections are summarised in tables 1 – 3, which outline the various factors that could be contributing to the change from Normal AM to Other AM and provide some suggestions for how the relevance of these factors could be tested.

As argued above, propagation effects alone cannot explain high levels of AM downwind of the rotor plane, and so changes at the source must play a key part. The two source mechanisms that have been identified as potentially playing an important role because they can lead to increased low frequency noise are local blade stall and high levels of inflow turbulence. The way in which these propagation and source factors could combine to provide a full explanation of Other AM are now explored.

5.1 **Local blade stall due to non-uniform inflow**

The focus here is on wind shear, but other flow uncertainties such as local wind gusts and variability of wind direction are expected to have a similar or additive effect.

- Local stall induced by high wind shear causes an increase in low frequency noise for blades near TDC. Prior to stall there is a simultaneous drop in high frequency noise, though this may be less apparent when all three blades are contributing. When blade stall occurs the high frequency noise returns (figure 7d).

- The increased depth of modulation is caused by the intermittent nature of the low frequency source, rather than being due to directivity effects as is the case for Normal AM.

- At stall there is a change in directivity, so that peak levels occur orthogonal to the rotor disk. Although the directivity plots in figure 4 suggest that the change may not be very marked, the result in the far-field is significant according to Ref. [13]. This would lead to increased modulation levels at large distances downwind and upwind, whilst the increase in the near-field might be limited to certain cross-wind conditions (e.g. 270 degrees in Figure 22 of [13]). This difference is likely due to these inherent directivity effects.
- Downwind: at large distances the effect of atmospheric attenuation increases the relative importance of low frequencies, and it would strongly attenuate the frequencies above 500 Hz that tend to dominate Normal AM.
- Upwind: the edge of the noise shadow zone moves closer to the wind turbine; diffraction into the shadow zone further increases the importance of low frequencies; the ‘window’ effect may greatly influence or enhance the level of AM; however, overall noise levels will tend to be lower because of these refraction effects.

With reference to the near-field measurement in figure 1b), some features of this recording may be explained by ground reflection effects (described in Section 3.2.5), but the most significant characteristic of this recording is the change in the frequency content in the second half, particularly the additional noise in the 100-400 Hz region.

The onset of local blade stall might be used to explain the time sequence of the spectrogram as follows:
- The first six blade passages (0 – 7s) are Normal AM: i.e dominated by medium frequencies in the 400-1000 Hz range.
- Non-uniform inflow starts to increase, leading to four blade passages (7-12s) with the pre-stall condition of a thickened trailing edge boundary layer. Hence there is an increase in low frequency noise and a decrease in high frequency noise. This is still Normal AM caused by trailing edge noise.
- Non-uniform inflow increases further leading to localised stall, which gives an increased level in both low and high frequencies for five blade passages (13 – 16s). This is probably Other AM.
- Non-uniform inflow decreases after 16s, returning the blades to the pre-stall Normal AM condition with low levels of high frequency noise.

5.2 Non-uniform inflow turbulence

The turbulence entering the rotor disk could be non-uniform for a number of reasons. Low altitude turbulence could be caused by obstructions such as trees; high altitude turbulence can occur naturally in the wind; ‘turbulence’ on the edge of a rotor disk could be due to another turbine upwind.
The characteristics of non-uniform inflow turbulence noise are expected to be as follows:

- Inflow turbulence would cause additional low frequency noise, but the higher frequency trailing edge noise should be largely unaltered.
- The dipole directivity of inflow turbulence noise causes a greater increase in low frequency noise at positions orthogonal to the rotor disk, whereas close to the rotor disk high frequency noise might still dominate. This would lead to increased levels at large distances downwind, whilst the increase in the nearfield might be limited by the relatively important contribution of trailing edge noise.
- Downwind: the effect of atmospheric attenuation increases the importance of low frequencies.
- Upwind: unlike wind shear, there is no change to the position of the shadow zone but the ‘window’ effect could still increase the level of low frequency AM

On this basis, inflow turbulence is less satisfactory in explaining all of the features of the spectrogram in figure 1b):

- The first six blade passages (0 – 7s) are normal AM
- Inflow turbulence increases, leading to high levels of low frequency noise from 10s onwards.
- However, the inflow turbulence model does not readily explain the drop in high frequency noise at 7-12s and beyond 16s.

It is worth noting that Other AM has been reported in conditions of high wind shear due to stable atmospheric conditions, in which inflow turbulence levels would generally be expected to be reduced, as well as for sustained periods of time which is probably not characteristic of the more random character of turbulence. This mechanism alone is thus unlikely to explain all reported incidents of Other AM.
6. Conclusions

The two key mechanisms identified as potentially playing a part in the generation of Other AM in wind turbines are a) detached or stalled flow over the turbine blade, b) high levels of inflow turbulence. However, whilst these mechanisms can explain increased levels of low frequency noise, they are not sufficient to fully explain high levels of AM at large distances downwind as has been observed in some cases.

The key additional condition that is necessary for AM characteristics to change significantly is for the flow into the wind turbine to be non-uniform in some way:

- The wind profile is non-uniform, for example due to: a vertical variation in wind speed (wind shear); a lateral variation in wind speed (perhaps due to local wind gusts or very large-scale turbulence); or a spatial variation of the angle of the wind onto the rotor (yaw or veer). AM is caused by the time varying angle of attack, with high levels of Other AM mainly being produced when local stall occurs. The importance of these effects is likely to be dependent on the control algorithms of each design of turbine.

- The turbulence distribution is non-uniform, for example due to: a layer of turbulent air affecting the top of the rotor disk; turbulence from upwind obstructions such as buildings or trees affecting the bottom of the rotor disk; turbulence from other wind turbines hitting the side of the rotor disk. This will cause time varying levels of inflow turbulence noise as each blade enters the region of high turbulence.

Although trailing edge noise is often assumed to be the dominant source on modern turbines, a residual uncertainty on the relative contribution of inflow turbulence noise has been identified during the course of this study. The most recent wind turbine models [10, 16] have been validated using relatively near-field data (approximately 3 rotor diameters from the turbine), whereas it is possible that inflow turbulence noise is more prominent on-axis at large distances because of the directivity of that source and the lack of Doppler shift.
The role of propagation effects has also been investigated. In the upwind direction the noise shadow created by wind shear could lead to high levels of AM at large distances upwind. The effect of wind shear on modulation is much weaker in the downwind direction and so the main propagation effect in that direction is atmospheric attenuation which causes a shift of the A-weighted spectrum towards lower frequencies. This can complicate the analysis of the relative importance of the different mechanisms at different frequencies as the higher end of the spectrum is “lost” in the background noise in the far-field. If on-axis noise is already inherently lower frequency because it is dominated by inflow turbulence noise, then atmospheric attenuation would enhance this effect.

Ground reflections and reflections from buildings have been shown to add some features to the spectrum, and could increase the level of AM by a small amount, but it is probably not a dominant contributing factor to Other AM.

The way in which these various mechanisms and factors combine together to produce the particular features Other AM at large distances needs to be confirmed by additional data gathering. These additional measurements should have regard to the different characteristics highlighted in Tables 1 - 3.
7. **Acknowledgment**

The content of this report is the responsibility and opinion of the author. He does however wish to acknowledge the considerable contribution of other project partners in putting forward ideas and commenting on all aspects of the work and this report: M. Cand, A. Bulmore, R. Davis, D. Bowdler, J. Bass, G. Grimes, G. Edge, S. Von-Hünerbein, P. White. The contribution of associate researchers is also acknowledged: M. Wright, R. Sandberg and S. Oerlemans.
8. References


### Table 1. Sources of Normal AM in Uniform Steady Flow

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Frequency</th>
<th>Directivity</th>
<th>Level / character of AM</th>
<th>Tests / measurements</th>
<th>Expected occurrence and other comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard trailing-edge noise</td>
<td>Broadband noise, spectrum controlled by boundary layer thickness. Dominated by 1 kHz &quot;swish&quot; in the past, suggestions that this has reduced to ~350-700 Hz (&quot;swoosh&quot;) for larger turbines.</td>
<td>Peaks at about 30°deg to blade angle: i.e. Near the rotor plane, crosswind after blade twist is included.</td>
<td>Modulation depth of 3 – 5 dB expected. Only apparent off-axis, therefore reduces with distance upstream or downstream. Oerlemans [13] indicates similar modulation far-field cross-wind because of directivity.</td>
<td>Decreases with distance, thus measurable in the near-field but not in the far-field.</td>
<td>Part of normal wind farm noise.</td>
</tr>
<tr>
<td>Ground interference for receivers at standard height</td>
<td>Spectrum dip at 200-600 Hz depending on time varying geometry and distance from WT.</td>
<td>Ruled out as significant, could provide 'colouring' of the spectrum.</td>
<td>Simultaneous measurement at height and at ground level.</td>
<td>Would be present at every wind farm.</td>
<td></td>
</tr>
<tr>
<td>Atmospheric attenuation</td>
<td>Spectrum shifts to lower frequencies as high frequencies are attenuated more.</td>
<td>Shift in spectrum increases with distance. Otherwise the same in all directions.</td>
<td>No effect on AM amplitude at one frequency. Possible effect, if any, is due to shift in frequency, potentially affecting the 'thump' character. Would attenuate &quot;swish&quot; or &quot;swoosh&quot; more than &quot;thump&quot;.</td>
<td>Use ground plane measurements at various distances. Record humidity and temperature.</td>
<td>Intrinsic to all wind farms in far-field situations.</td>
</tr>
<tr>
<td>Background noise masking</td>
<td>Would be present at every wind farm to varying extent.</td>
<td></td>
<td>Limits the level of AM due to source characteristics.</td>
<td>Will limit any depth of modulation at large distances; measure at increasing distances in quiet conditions.</td>
<td></td>
</tr>
</tbody>
</table>

### Table 2. Sources of AM in steady flow with wind shear or other wind speed variations

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Frequency</th>
<th>Directivity</th>
<th>level / character of am</th>
<th>Tests / measurements</th>
<th>Expected occurrence/ other comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard TE noise</td>
<td>Shift to lower frequencies in source levels is expected as boundary layer on blade near TDC thickens, though doesn't show up in predicted overall A-weighted spectra.</td>
<td>Source directivity unchanged. Could show up on axis as blades are now different, but effect is small according to Oerlemans [13].</td>
<td>Predicted increase in level and change of spectrum is marginal compared with standard swish, according to Oerlemans [13], unless detached flow occurs.</td>
<td>Detailed measurements at different locations around the turbine.</td>
<td>Shear amount is site-specific and will vary with time of day and atmospheric conditions.</td>
</tr>
<tr>
<td>Partial stall noise</td>
<td>Stronger shift to lower frequencies.</td>
<td>Dipole peaking orthogonal to the blade, i.e. approximately normal to the rotor plane. This neglects drag noise which would peak in the rotor plane but at a lower dB level.</td>
<td>Oerlemans [13] predicts a large increase in average level and also level of AM, though this is a function of the assumed level of stall noise source spectrum.</td>
<td>Ideally, stall flag, torque and RPM measurement, manually change blade pitch to trigger stall. Otherwise: measure changes in directivity.</td>
<td>Stall regulated turbines are designed to go into full stall at high wind speeds. Stall should not normally occur for pitch-regulated turbines in design conditions. Effects of atmospheric absorption would emphasise any shift to lower frequencies.</td>
</tr>
</tbody>
</table>
### Table 2 (continued)

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Frequency</th>
<th>Directivity</th>
<th>Level / character of AM</th>
<th>Tests / measurements</th>
<th>Expected occurrence/other comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propagation effects in shear flow combined with time varying source height</td>
<td>Upwind: additional shift to low frequencies and modulated attenuation of high frequencies because of shadow effect.</td>
<td>Strong AM effect upwind at large distances (+400m) at certain frequencies. Increased average level downwind: Possible “hot-spots” at large distances downwind, changing with azimuthal angle, atmospheric conditions and distance and moving with blade position.</td>
<td>Could explain higher levels of upwind AM when these occur.</td>
<td>Line of ground plane measurement positions upwind; closely spaced measurement positions downwind to show up hotspots.</td>
<td>Wide wind direction range experienced at most sites.</td>
</tr>
<tr>
<td>Temperature gradients</td>
<td>Frequency dependant shadow zone.</td>
<td>All directions.</td>
<td>Not a strong effect for typical thermal variations.</td>
<td></td>
<td>Again wide range but temperature inversions more likely at some sites, although wind gradient are likely to dominate except in very calm conditions.</td>
</tr>
<tr>
<td>Aero-elastic effects: changing angle of attack as blade twists or bends under varying load</td>
<td>Similar to sheared flow above.</td>
<td>As for stall noise.</td>
<td>Not known.</td>
<td>Compare with upwind/downwind microphone studies.</td>
<td>Unknown. It may cause increased angle of attack and off-design conditions.</td>
</tr>
</tbody>
</table>

### Table 3. Sources of AM in unsteady flow, with or without wind shear

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Frequency</th>
<th>Directivity</th>
<th>Level / character of AM</th>
<th>Tests / measurements</th>
<th>Expected occurrence/other comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large-scale structure: tube, packet or layer of low speed air causing sudden decrease in angle of attack – then an increase on the other side generates fluctuating lift noise (as per inflow turbulence noise).</td>
<td>Increased levels of low frequency noise, whilst high frequency TE noise remains the same.</td>
<td>Similar to the Oerlemans assumed dipole directivity for stall noise: peaks orthogonal to blades.</td>
<td>Would explain a particular type of impulsive 'thump' noise, similar to helicopter &quot;blade slap&quot; noise. Would appear as a high level of AM, but is actually harmonics of blade passing frequency noise. Would be highly irregular.</td>
<td>Ground plane measurements at various azimuthal positions to show directivity and spectrum changes. LIDAR measurements. Flow velocity measurements at various heights. Increased vibration on the tower / gearbox. Zoomed frequency analysis of low frequency noise.</td>
<td>Large scale turbulence and high wind shear may be to some extent mutually exclusive (as stable atmospheric conditions may be associated with high wind shear and low turbulence) Occurrence would not be regular or sustained.</td>
</tr>
<tr>
<td>Large scale structure of fast moving air such as a local wind gust.</td>
<td>Same as above, except that it could lead to stall noise.</td>
<td>Same as above.</td>
<td>Would be short duration.</td>
<td>LIDAR measurements, acoustic camera, distribution of microphones.</td>
<td>Same as above.</td>
</tr>
<tr>
<td>Smaller scale turbulence (inflow turbulence noise).</td>
<td>Increase in low frequency noise.</td>
<td>Same as above.</td>
<td>Only leads to AM if the distribution of spatial turbulence is non-uniform.</td>
<td>Measures of turbine inflow turbulence with a high resolution if possible.</td>
<td>Large scale turbulence and high wind shear may be to some extent mutually exclusive (as stable atmospheric conditions may be associated with high wind shear and low turbulence) Occurrence would not be regular or sustained.</td>
</tr>
</tbody>
</table>
Figures

Figure 1 - a) Change in spectrum shape between ‘Normal AM’ and ‘Other AM’ as recorded by Bowdler [1] close to a turbine b) spectrogram of the complete time history.

Figure 2 - Aerofoil self-noise source mechanisms identified by Brooks Pope and Marcolini [8], and illustration of the inflow turbulence mechanism.
Figure 3 - Flow vector geometry showing the components due to the wind speed and rotor motion, the angle of attack, and the blade twist and pitch angles.

Figure 4 - Polar directivity of sources on an aerofoil: a) dipole directivity generally associated with low frequency inflow turbulence noise where the wavelength is large compared with the chord. b) –c) directivity for frequencies typical of trailing edge noise, d) cardioid directivity of trailing edge noise for a semi-infinite plate. From Oerlemans [17]
Figure 5 - predicted 1/3 octave band ground interference effect as a function of varying source height and range at different 1/3 octave band frequencies.
Figure 6 - predicted ground interference effect as a function of varying source height
a) 1/3 octave band averaging at 50m range b) averaging in constant 100Hz bandwidths (plotted every 20Hz) c) 1/3 octave band averaging at 500m range
Figure 7 - effect of wind shear, adapted from Oerlemans [13]: a) incident flow profile as a function of windshear factor $m$; b) wind speed distribution over the rotor disk; c) angle of attack assuming $U_0=8$ m/s and $m=0.6$; d) change in the blade segment source spectrum as a function of angle of attack close to stall.

Figure 8 - a) Effect of combined $m=0.6$ wind shear and -10° yaw on blade angle of attack. b) Additional effect of a 6% error in estimated wind speed at hub height
Figure 9 - Effect of a local gust of wind affecting one area of a turbine  
a) assumed flow distribution;  
b) angle of attack of the blade during the gust

Figure 10 - Geometry for a measurement in the nearfield of a turbine showing time of flight delays. 
Time delay for Blade 3 is the same as for Blade 1, but directivity effects mean that its noise contribution is lower. A rotor diameter of 80m and a hub height of 60 m were assumed.
Figure 11 - effect of wind shear on sound propagation from an elevated source:  a) schematic ‘ray acoustics’ diagram showing the upwind noise shadow and downwind channelling of sound.  b) example prediction of transmission loss at 125 Hz using the Parabolic Equation method, showing the upwind noise shadow zone for a source at 80m  c) calculated transmission loss from the PE model as a function of source height at 250 Hz (applicable to a turbine with an 80m hub height and 80m diameter rotor)
Work Package B1

The measurement and definition of amplitude modulation

University of Southampton, ISVR
The Measurement and Definition of Amplitude Modulations

by

Paul White

January 2012
Contents

Summary

1. Introduction

2. Review of (Amplitude) Modulations in other Fields
   2.1 Amplitude Modulated Communications Signals
   2.2 Passive Sonar
   2.3 Condition monitoring
   2.4 Monitoring of wind turbine noise

3. Formulations of Depth of Modulation
   3.1 Effect of bandwidth

4. Sinusoidally Modulated White Noise Model
   4.1 Variations of the white noise model
      4.1.1 Temporal smoothing of the energy
      4.1.2 Filtering prior to computation of the energy
      4.1.3 Using the analytic form of the signal
      4.1.4 Harmonics of the modulation frequency

5. Modulated Coloured Gaussian Noise
   5.1 Defining modulation depth for coloured noises
   5.2 The multi-band approach to coloured noise

6. Methods based on a periodic correlation n model

7. Results
   7.1 Performance of methods on a single test file
   7.2 Performance across a range of modulation depths
      7.2.1 Measures based on Fourier analysis of short time energy
      7.2.2 Measures based on filter bank analysis
      7.2.3 Measures based Kirsteins’ method
   7.3 Performance on field data
      7.3.1 Performance on a single file
      7.3.2 Performance on the set of files

8. Conclusions

Appendix: Construction of Test Stimuli

References
Summary

There are a very large number of options in terms of how the degree to which a signal is modulated might be measured and rated. These options cover the variety of ideas about what is to be measured, how the frequency dependence of the modulation is taken into account and what methods are used to extract parameters (or metrics) from the data.

Three main forms of methods were identified in this report, for application to the study of modulated noise from wind farms, with reference to similar techniques developed in other fields such as sonar research. These techniques all claim a degree of optimality and have been derived from basic principles, and are therefore considered more robust than methods requiring a degree of subjective evaluation.

Three forms of methods have been considered, and their performance evaluated on a range of representative artificial stimuli and field recordings of wind turbine noise. These three methods types considered and developed are:

1. Short term energy envelope analysis
2. Filter bank method
3. Periodic correlation method

The first method was found to work well, despite the theoretical limitations identified, although signal filtering was required in some cases to minimise the influence of secondary un-modulated noise sources, such as wind noise. The second method is similar to the first one but considers narrower components of the signal in isolation. It produced results which were smoother and somewhat more consistent in time, suggesting greater reliability, although some of the smallest modulation was sometimes not detected. Filtering of the part of the signal in which the modulation is significant was necessary in both cases, which effectively supposes this can be known {	extit{a priori}}. The third method, although designed to work for a broader class of signals, failed in practice to detect modulation except for the strongest signals, and also had a significant computational load and so was not considered in further detail.

In each case, the magnitude of the modulation could be expressed by different values derived from the modulation spectrum produced by the analysis. The consideration of these potential AM magnitude metrics, resulting from the methods identified in this report, is separate to the consideration of their subjective meaning, which is investigated in other elements of the current research project.
1. Introduction

The work presented in this report is part of project funded by RenewableUK and entitled ‘Wind Turbine Amplitude Modulation: Research to Improve Understanding as to its Cause & Effect’. The project comprises a total of six separate work packages. The outcome results of each of the work packages have separately resulted in their own dedicated final reports. A seventh work package, WPF, has produced an overarching final report in which the key findings across the separate work packages have been collated and discussed.

This is the final report of Work Package WPB2: ‘Development of an Objective AM Measurement Methodology’.

Wind turbine aerodynamic noise, by which is meant the noise produced by the rotating wind turbine blades, includes a steady component as well as, in some circumstances, a periodically fluctuating, or amplitude modulated (AM), component. However, AM may take different forms. One form of AM, commonly referred to as ‘blade swish’, is an inherent feature of the operation of all wind turbines. It can be explained by well understood mechanisms, it being the result of the directivity characteristics of the noise created by the air flowing over a turbine blade as it rotates. Because this type of AM is an inherent feature of the operation of wind turbines, whose origin can be explained and modelled, the present project adopts as its definition the term ‘normal amplitude modulation’ (NAM). The key driver for the project, however, is the recognition that some AM exhibits characteristics that fall outside those expected of NAM. Such characteristics include a greater depth of modulation, different directivity patterns or a changed noise character. For this reason the present project adopts as its definition the term ‘other amplitude modulation’, or ‘OAM’, for all observations of AM that lie outside that expected of NAM.

In recent years public concern has grown about the potential annoyance from wind turbine OAM noise. This concern has resulted in an increased interest to establish how AM, and in particular OAM, occurs, how it can be better defined and measured, and how it is generally perceived and responded to. It is the answers to these questions that the present project seeks to address.

This report specifically concentrates on the work considering appropriate metrics with which to measure amplitude modulation.

The observed fluctuations in wind farm noise are quasi-periodic, i.e. over short periods of time they fluctuations repeat themselves with an almost constant period. The study of modulated signals is an area of interest in a range of disciplines, but probably the area which has been the focus of most research activity is the field of communications, wherein modulations are used to code signals prior to transmission [1-5]. There are a variety of modulations which are used in communications systems, one of which is amplitude modulation that is, for example, used in older formats for radio transmission.

A second area, which is less widely studied but more closely related to this work, is passive sonar, i.e. listening to underwater sounds to detect, classify and localise acoustic sources. In particular, under certain circumstances, the propellers on vessels emit modulated sounds [6]. Methods for the detection of such sounds have been a primary tool for passive sonar for a great many years [7].

A similar area in which modulation processing is used is in the field of vibration based machine condition monitoring, in particular monitoring of bearings [8]. For example, imperfections in a bearing give rise to regular impulses as the fault makes contact with a surface. Within condition
monitoring the processing of amplitude modulated signals is referred to as envelop processing [9].
These fault related impulses vary on a cycle-by-cycle basis and are best modelled as a cyclostationary
process, i.e. they can be modelled as amplitude modulated.

This report describes the various approaches to the objective measurement of modulations and then
suggests a variety of metrics which can be assessed to determine which relate most closely with the
results of subjective experiments.
2. Review of (Amplitude) Modulations in other Fields

Before considering the modulations in the context of wind farm noise this section will briefly discuss modulations in the fields of communications, passive sonar and condition monitoring. The open nature of research in the field of communications, allied to its everyday use, means that there more published material in this field. This is in contrast to the classified and rather specialist nature of passive sonar. Like communications, condition monitoring is an established research area in which processing based on amplitude modulation is an established methodology. This section initially reviews work in the area of communications and then describes the role of processing techniques based on amplitude modulation in passive sonar and condition monitoring. Finally it does briefly outline existing methods used in the analysis of wind turbine noise.

2.1 Amplitude Modulated Communications Signals

Historically one on the earliest forms of coding a signal prior to transmission through a medium is to use Amplitude Modulation (AM). In such applications the signal to be transmitted takes the form:

\[ x(t) = A(1 + \mu m(t))\cos(2\pi f_c t + \phi_c) \]  

where \( m(t) \) is the message signal to be transmitted, \( f_c \) is the carrier frequency, which for a communications system is usually very much higher than any frequencies in the message signal, for example medium wave commercial radio stations use frequencies in the approximate range 100 kHz – 1 MHz to convey signals in the audio frequency band. The parameter \( A \) controls the overall amplitude of the signal, \( \phi \) is the initial phase of the carrier signal and \( \mu \) is often called the modulation index [2, 3, 5]. Typically the message signal has a large bandwidth relative to its centre frequency, i.e. it is a broadband signal such as music or speech. This is in contrast to the model we shall use for wind farm noise in which the modulation is quasi-periodic, i.e. relatively narrow-band, but the “carrier” signal is a broadband process.

![Figure 1: Sinusoidal modulation of a sine wave carrier signal. Blue line shows the modulated signal (centre frequency 410 Hz), solid grey line indicates the modulation function (frequency 20 Hz). \( A_{\text{min}} \) is the minimum amplitude, \( A_{\text{max}} \) the maximum and \( A \) the amplitude as defined in (1).](image-url)
It is common practice in communications to consider the simple case where the message signal is itself sinusoidal, such that

\[ m(t) = \cos(2\pi f_m t + \phi_m) \quad (2) \]

In such instances one can define the modulation index in terms of readily measureable quantities and it is tempting to consider these as the basis for metrics for wind-farm noise.

The minimum and maximum amplitudes are related to the modulation index \( \mu \) as follows:

\[ A_{\text{max}} = A(1+\mu) \quad A_{\text{min}} = A(1-\mu) \quad (3) \]

There are several methods by which the modulation index can be measured. These include the modulation factor \([4]\) defined as

\[ M_{\text{fact}} = \frac{A_{\text{max}} - A_{\text{min}}}{A_{\text{max}} + A_{\text{min}}} \quad (4) \]

and the percentage modulation \([1]\)

\[ M_{\text{per}} = \frac{A_{\text{max}} - A_{\text{min}}}{2A} \quad (5) \]

The percentage modulation is normally multiplied by 100 to yield a percentage from which its name derives. The factor of 100 has been omitted here for consistency with the other metrics.

For the simplified case of a sinusoidal message, as in (2), substituting the relationships in (3) into (4) and (5) one can see that both \( M_{\text{fact}} \) and \( M_{\text{per}} \) are equal to the modulation index \( \mu \). But when the message is not sinusoidal then the metrics (4) and (5) generally yield different values. Indeed for non-sinusoidal messages the concept of the modulation index itself becomes poorly defined.

The issues around defining the modulation index arise because there is no unique definition for the amplitude of an arbitrary message \( m(t) \). To illustrate, consider a simple extension of (2) such that a single additional harmonic term is added to the message to give the following simplified formulation. This formulation does not include phase terms to avoid unnecessary algebraic cluttering.

\[ x(t) = A\left(1 + \mu\left(\alpha \cos(2\pi f_1 t) + \beta \cos(4\pi f_1 t)\right)\right) \cos(2\pi f_m t + \phi_m) \quad (6) \]

The message term in (6) has two degrees of freedom, but 3 free parameters (\( \alpha, \beta \) and \( \mu \)). Hence one can choose several equivalent parameterisations. Three example parameterisations are given below:

\[ \begin{align*}
\mu \left( \alpha \cos(2\pi f_1 t) + \beta \cos(4\pi f_1 t) \right) \\
= \mu_1 \left( \cos(2\pi f_1 t) + \beta \cos(4\pi f_1 t) \right), \quad \mu_1 = \frac{\mu}{\alpha}, \quad \beta_1 = \frac{\beta}{\alpha}
\end{align*} \quad (7) \]
In (7) the first parameterisation ensures that the fundamental component has an amplitude of one, whereas the second parameterisation ensures the harmonic’s amplitude is one, whilst the third parameterisation arises from when the overall root mean square (rms) level of the signal is constrained to be one.

Each of the new formulations in (7) depends on two parameters, with the message term being normalised according to different criteria. The modulation indices ($\mu_1, \mu_2$ and $\mu_3$) are all different with no single parameterisation having any theoretical advantages over the others. This ambiguity over what defines the modulation index for non-trivial message signals means that in order to use the modulation index one must specify precisely how the message term is normalised.

2.2 Passive Sonar

The noise from wind farms shares a closer relationship to the underwater noise from the propellers than to communication signals. This is not only because both are acoustic signals, but more importantly both are examples of broad-band processes modulated by narrow-band signals, as opposed to communications signals which are narrow-band signals modulated by broad-band signals.

For passive sonar the model (1) is a little misleading; it is more appropriate to adopt a model of the (simplified) form:

$$x(t) = \left(1 + \alpha \cos(2\pi f_m t)\right)n(t).$$ (8)

In this case $n(t)$ is a broad-band noise process and $\alpha$ plays a role which is the equivalent of the modulation index.

In passive sonar the usual objectives are to detect the presence of a modulated signal and commonly to estimate the modulation frequency $f_m$. The most commonly used technique to detect and measure the modulation frequency is the so-called DEMON (DEModulation Of Noise) processing [7, 10]. It is not common practice in passive to measure the depth of modulation.

2.3 Condition monitoring

The use of envelope analysis, which is essentially the same as DEMON processing in passive sonar, is widespread in the field of condition monitoring. As in the case sonar case the primary objective for most condition monitoring systems is to determine whether there is an amplitude modulation, i.e. to detect a fault, and to determine the frequency of that modulation. In the case of bearings the modulation frequency can yield important information regarding the location of the fault.

2.4 Monitoring of wind turbine noise modulation

This Section concludes with an overview of some of the methods that have been proposed for the use of assessing wind turbine noise. These include methods described in [11-17], many of these techniques can be regarded as adaptations of the principles which are developed herein, such methods are referred to in the text in the appropriate location. These proposed techniques seek to exploit the inherently periodic nature of the AM from turbines. Many such methods exploit $L_{Aeq}$ measurements, since these are readily obtainable from standard sound level meters. One method which differs from these techniques, and the other methods in this report, is outlined in [17] and is referred to as the “Den Brook” method. This is based on applying tests to short (2 s) blocks of $L_{Aeq,125 ms}$ data and looking for periods in which peak-to-trough levels differ by 3 dB(A). These periods are then counted over a
This method fails to exploit the most striking feature of AM which is its periodic structure.
3. Formulations of Depth of Modulation

The acoustic signals we seek to characterise possess periodic fluctuations and the goal is to obtain a measure of the strength of such modulations. A primary objective of this work is to develop a measure of the strength of such modulations which can then be correlated with the results of subjective tests. The quantity in question we refer to as the *depth of modulation*, which is intended as a generic term.

Based on the discussions in Section 2.1 one might consider using a method based on the modulation index in order to assess the depth of modulation, but such metrics are not the only options available. For example one can consider using the ratio

\[
\frac{A_{\text{max}}}{A_{\text{min}}} = \frac{1 + \mu}{1 - \mu}
\]

(9)

This ratio is related to the modulation index via a monotonic function (in the region \(0 < \mu < 1\)). Whilst this ratio is an appropriate measure of modulation depth, it is not equal to the modulation index. This ratio has been proposed for use in measuring modulation in wind farms [13].

For an acoustic signal there are several domains in which the signals can be represented. The depth of modulation can be measured in any of these domains and an ideal metric would be insensitive to the choice of domain. The specific domains one can consider for an acoustic signal include: the linear pressure and the Sound Pressure Level (SPL). In terms of wind-farm noise several authors have considered using the Leq (or its A-weighted equivalent) which is a time-averaged for of the SPL [11, 14], where that temporal averaging is conducted in accordance with a standardised method.

In order to illustrate the issues around defining the depth of modulation consider a simple example of a signal formed using (1), illustrated in Figure 2. The message signal, \(m(t)\), is assumed to be a sinusoid, as in (2), in this example the value of \(\mu\) is 0.5. The data are referred to as pressure, for this numerical example there is no precise physical meaning intended. In each instance the maximum amplitude, \(A_{\text{max}}\), minimum amplitude, \(A_{\text{min}}\) and the time averaged amplitude, \(A\), are shown. Note that in Figure 2 c) the value of \(A\) shown is the time average of the dB value, which is not what constitutes perceived good practice in acoustics, the “correct” approach is to time average the squared values and then convert that to a dB scale. In the following discussion these two averages will both be discussed and will be denoted \(A_{\text{dB}}\) when the averaging is performed on the dB values and \(A_{\text{lin}}\) when the averaging is performed on the squared pressure.

The following considers three measures for the depth of modulation, each of which has been proposed for measuring wind farm noise. The first is the ratio of the maximum and minimum amplitudes, as in (9), which will be denoted \(R_{\text{mm}}\), which is expressed on a dB scale in the different domains as follows:

- **Pressure**: \(20\log_{10} \left( \frac{A_{\text{max}}}{A_{\text{min}}} \right)\),
- **Squared pressure**: \(10\log_{10} \left( \frac{A_{\text{max}}}{A_{\text{min}}} \right)\),
- **dB domain**: \(A_{\text{max}} - A_{\text{min}}\)

The second is the ratio of the maximum value to the time value, denoted \(R_{\text{ma}}\), which is expressed as:

- **Pressure**: \(20\log_{10} \left( \frac{A_{\text{max}}}{A} \right)\),
- **Squared pressure**: \(10\log_{10} \left( \frac{A_{\text{max}}}{A} \right)\),
- **dB domain**: \(A_{\text{max}} - A\)

There are two forms for \(R_{\text{ma}}\) in the dB domain depending upon which form of averaging is employed, i.e. whether \(A_{\text{dB}}\) or \(A_{\text{lin}}\) is used. These two options will be denoted (inelegantly) as \(R_{\text{ma},\text{lin}}\) and \(R_{\text{ma},\text{dB}}\).
Finally a measure which is the ratio of half the difference between the maximum and minimum value and the time averaged value, denoted here as $R_{\text{mma}}$ and expressed as

\[
\text{Pressure: } 20\log_{10}\left(\frac{A_{\text{max}} - A_{\text{min}}}{2A}\right), \quad \text{Squared pressure: } 10\log_{10}\left(\frac{A_{\text{max}}^2 - A_{\text{min}}^2}{2A^2}\right),
\]

There is no simple direct equivalent for $R_{\text{mma}}$ in the decibel domain, since it is based on subtraction in a linear domain.

![Figure 2: Modulations in various domains. a) Pressure wave form, b) Squared pressure waveform and c) Pressure on a (unreferenced) decibel scale](image)

The results of applying the various metrics to the data shown in Figure 2 are shown in Table 1.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Pressure (dB)</th>
<th>Squared Pressure (dB)</th>
<th>dB Domain (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{\text{mm}}$</td>
<td>9.5</td>
<td>9.5</td>
<td>9.5</td>
</tr>
<tr>
<td>$R_{\text{ma}}$</td>
<td>3.5</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>$R_{\text{mma,lin}}$</td>
<td></td>
<td></td>
<td>$R_{\text{mma,lin}}$: 1.0</td>
</tr>
<tr>
<td>$R_{\text{mma,dB}}$</td>
<td></td>
<td></td>
<td>$R_{\text{mma,dB}}$: 4.1</td>
</tr>
<tr>
<td>$R_{\text{mma}}$</td>
<td>-6</td>
<td>-0.5</td>
<td>N/A</td>
</tr>
</tbody>
</table>

**Table 1**: Table of metrics for depth of modulation for different
From Table 1 it is clear that the different metrics generally yield different values when computed in different domains. The metrics, $R_{ma}$, $R_{mm}$ and $R_{mma}$ aim to compute subtle different quantities so one might reasonably expect that they generate different values. One also needs to appreciate that different values are (generally) obtained when the metrics are computed in the different domains. The exception is $R_{mm}$ which is consistent between all domains; a property that can be regarded as a significant benefit. However, measuring the minima and maxima in a time series, as is proposed in the “Den Brook” method [17], is prone to greater uncertainty than measuring a time averaged quantity.

These are not the only similar reasonable metrics which can be considered. There are few physical principles which allow one to justify the use of one metric in preference to another. For this project this judgement may be based on how well the metrics correlate with subjective preference, and how they can be applied to realistic signals, rather than any physical arguments.

3.1 Effect of bandwidth

A final consideration when assessing the depth of modulation is the analysis bandwidth. Measures of depth of modulation are always ratios. Loosely they relate the magnitude of the fluctuations to the steady background level. Commonly for wind farm noise the majority of the modulated sound occurs in a low frequency band, for the sake of this discussion assume the band is 100 Hz - 1 kHz. The measured depth of modulation will depend on the bandwidth of the recording processed. For example, if in the above case the acoustic pressure is measured only over the band from 100 Hz to 1 kHz then all of the energy in the modulated signal is captured. Whereas if the measurement is made over a wider band, say 1 Hz to 44 kHz, then this signal includes noise from the frequency band which is distinct from the modulated band. This additional noise serves to mask the modulation and so results in a lower depth of modulation. To further illustrate this point consider the signal divided into a set of frequency bands, the depth of modulation in each band is different and depends on the signal to noise ratio of the modulation in that particular band. In practice modulated energy is spread across a range of frequencies and the signal to noise ratio in each will be different. Determining which bands should and should not be included in a measure of depth of modulation is not a trivial problem. However to ensure that a consistent metric is achieved this selection should be performed according to objective criteria.
4. Sinusoidally Modulated White Noise Model

The initial approach adopted here is to consider models for modulations and fit those models to measured data sets. In doing so one explicitly obtains estimates for the parameters of the model from which an estimate of the depth of modulation can be extracted. This requires one to consider the form of the model to be fitted. Selecting the form of the model usually entails a compromise. As the complexity (and the realism) of the models is increased, the problem of fitting that model to the data becomes more challenging and the associated algorithms used typically require a commensurate increase in computational resources.

This section considers the simplest (non-trivial) model of a modulated random process, based on (8): white Gaussian noise modulated by a sine wave. This model is not expected to be a particularly accurate representation of noise from wind farms: in particular the fact that the signals are white, so have a flat spectrum, is not realistic. However, the resulting algorithm developed for this signal forms the basis of a more general approach described later.

A discrete time model for the signal, \( x(n) \), can be written as

\[
x(n) = w(n)(1 + \mu \cos(2\pi f_0 n + \phi)) = w(n)(1 + \alpha \sin(2\pi f_0 n) + \beta \cos(2\pi f_0 n))
\]  
(10)

where \( w(n) \) is a Gaussian white noise process with variance \( \sigma^2 \). In terms of acoustic signals this serves as a potential model for the acoustic pressure, since the model anticipates that the amplitude of signal will be symmetrically distributed about zero.

Assuming that \( \alpha^2 + \beta^2 = \mu^2 < 1 \), ensures that the amplitude of oscillation is such that the signal’s variance is never zero, i.e. there is always some stationary (unmodulated) noise present.

The formulation (10) differs from the early representation (8) in three ways: it incorporates an initial phase term, \( \phi \), in the modulation, the model is expressed in terms of discrete time (\( n \) instead of \( t \)) and, consequently, the modulation frequency is denoted as \( f_0 \), as opposed to \( f_m \), to indicate that it now represents a normalised discrete time frequency.

The instantaneous variance of \( x(n) \) is given by

\[
\sigma^2_i (n) = \sigma^2 \left( 1 + \alpha^2 \sin^2 (2\pi f_0 n) + \beta^2 \cos^2 (2\pi f_0 n) + (\alpha + 1)\beta \sin(2\pi f_0 n) + (\alpha + 1)\beta \cos(2\pi f_0 n) \right)
\]

\[
\sigma^2_i (n) = \sigma^2 \left( 1 + \frac{\alpha^2 + \beta^2}{2} + (\alpha + 1)\beta \sin(2\pi f_0 n) + (\alpha + 1)\beta \cos(2\pi f_0 n) + \frac{\beta^2 - \alpha^2}{2} \cos(4\pi f_0 n) \right)
\]  
(11).

According to (10) and (11) it is evident that a process which is sinusoidally modulated in terms of linear quantities will be not sinusoidally modulated in terms of its variance. Emphasising that the choice of domain in which the modulation is measured generally affects the values obtained for the depth of modulation.

It transpires that adopting a sinusoidal model for the modulation of the variance, as opposed to a sinusoidal modulation for the signal itself, (10), leads to a mathematically more tractable solution. Accordingly an alternative model for modulated white noise is to assume that the variance which is sinusoidally modulated, i.e.
Note that the variance parameter \( \sigma^2 \) in (12) is not equivalent to that in (11), although these parameters play essentially the same role, which is why they are represented by the same symbol here.

In order to estimate the depth of modulation from a set of measured data one needs to fit the model (12) (or (11)) to a data set, this allows one to estimate the parameters \( a \) and \( b \) which will form the basis of a measure of depth of modulation.

This fitting can be performed in a variety of ways but a common approach which is asymptotically efficient is to use the principle of maximum likelihood \([18, 19]\). Maximum likelihood is a general principle used to fit models to data and has a long history dating back to R.A. Fisher in 1912 \([20]\). It requires one to find the model which maximises \( p(\theta|x) \) (the probability density function of the data given the model parameters, which is termed the likelihood). Loosely speaking the method of maximum likelihood aims to identify the parameters which are most likely to have given rise to the data. One can argue that it is more logical to seek to identify the most likely set of parameters given the data, i.e. to maximise \( p(\theta|x) \). This can indeed be achieved by invoking the principles of Bayesian statistics \([21]\) and modifying the maximum likelihood estimator accordingly. However in this work we shall consider the maximum likelihood approach.

The application of the maximum likelihood principle to the estimation of the parameters of modulated white noise was first detailed by \([10]\) and the following description mirrors that development.

For a Gaussian process the likelihood, \( l(x(n)) \), for a single sample \( x(n) \) is given by

\[
l(x(n)) = \frac{1}{\sigma(n)\sqrt{2\pi}} e^{\frac{x(n)^2}{2\sigma(n)^2}}
\]

The likelihood for a set of \( N \) samples uncorrelated samples, arranged in a column vector \( x = [x(0), x(1), \ldots, x(N-1)] \) can be written as

\[
p(x|a, b, f_0) = l(x) = \frac{1}{(2\pi)^{N/2} \prod_{n=0}^{N-1} \sigma(n)^{N/2}} e^{-\sum_{n=0}^{N-1} \frac{x(n)^2}{2\sigma(n)^2}}
\]

Forming the logarithm of the likelihood, i.e. the log likelihood, \( L(x) \), one obtains

\[
L(x) = \log(l(x)) = -\frac{N}{2} \log(2\pi) - \sum_{n=0}^{N-1} \log(\sigma(n)) - \frac{1}{2} \sum_{n=0}^{N-1} \frac{x(n)^2}{\sigma(n)^2}
\]

The optimal (maximum likelihood) estimates for the modulation parameters \( a, b \) and \( f_0 \) are obtained by maximising (15) with respect to these parameters. The first term on the right-hand side of (15) is constant with respect to the modulation parameters, so does not need to be considered in the maximisation process.

\[
\sigma^2(n) = \sigma^2(1 + a \sin(2\pi f_0 n) + b \cos(2\pi f_0 n))
\]

\( ^1 \) Where \( x \) represents the set of measurements and \( \theta \) represents the model parameters.
The second term \( \sum_{n=0}^{N-1} \log(\sigma(n)) \) is the sum of an oscillating expression. Assuming \( N \) is sufficiently large, so that the summation extends over many cycles of the oscillations, it is approximately constant with respect to \( a, b \) and \( f_0 \) [10].

Hence to approximately maximise (15) one can consider maximising

\[
L(x) = -\frac{1}{2\sigma^2} \sum_{n=0}^{N-1} x(n)^2 \left(1 + a \sin(2\pi f_0 n) + b \cos(2\pi f_0 n)\right)^2
\]

where the model for a sinusoidal modulation of the variance, (12), has been included. Following the approach taken by Lourens and du Preez [10] and assuming that the modulation is small so that both \( a \) and \( b \) are small, i.e. \( |a|, |b| \ll 1 \), one can use the approximation

\[
L(x) \approx -\frac{1}{2\sigma^2} \sum_{n=0}^{N-1} x(n)^2 \left(1 - a \sin(2\pi f_0 n) - b \cos(2\pi f_0 n)\right)
\]

\[
= \frac{1}{2\sigma^2} \left[ -\sum_{n=0}^{N-1} x(n)^2 + a \sum_{n=0}^{N-1} x(n)^2 \sin(2\pi f_0 n) + b \sum_{n=0}^{N-1} x(n)^2 \cos(2\pi f_0 n) \right]
\]

The optimisation of (17) presents an impasse as there is no analytical solution for any of the unknown parameters, \( a, b \) or \( f_0 \). Lourens and du Preez [10] suggest the adoption of the following estimates for the amplitude parameters \( a \) and \( b \). They show that these estimators are unbiased but fail to show that they are optimal in any sense. This is a short-coming of their method and one can reasonably argue that it undermines their claim to have developed a maximum likelihood estimator.

The estimates of \( a \) and \( b \) use by Lourens and du Preez are denoted \( \hat{a} \) and \( \hat{b} \) respectively and are given by:

\[
\hat{a} = \frac{2}{N\sigma} \sum_{n=0}^{N-1} x(n)^2 \sin(2\pi f_0 n)
\]

\[
\hat{b} = \frac{2}{N\sigma} \sum_{n=0}^{N-1} x(n)^2 \cos(2\pi f_0 n)
\]

Using these approximate amplitudes, and neglecting terms which are independent of \( f_0 \), one can see that the maximum likelihood estimate of \( f_0 \) is obtained by maximising

\[
\Psi(f_0) = \left[ \sum_{n=0}^{N-1} x(n)^2 \sin(2\pi f_0 n) \right]^2 + \left[ \sum_{n=0}^{N-1} x(n)^2 \cos(2\pi f_0 n) \right]^2 = |F(x(n))|^2
\]

where \( F\{ \} \) denotes the operation of taking the Fourier transform.

Consequently the (approximate) maximum likelihood estimator of frequency is obtained by seeking the largest peak in the Fourier transform of the square of the signal. The amplitude of the modulation is obtained using the modulation amplitudes \( \hat{a} \) and \( \hat{b} \), with the overall amplitude being computed using \( \sqrt{\hat{a}^2 + \hat{b}^2} \). Note that these estimated amplitudes are obtained from the real and imaginary parts of the Fourier transform \( F\{x(n)^2\} \).
An alternative derivation of (18) has been developed as part of this work so that the optimality of the solution is clear and does not rely upon the incomplete development found in [10]. This new derivation is based on a higher order approximation of (16). The algebraic representations in this development is simplified if the following vector notation is adopted

\[
\mathbf{a} = [a \ b]^T, \quad \Theta(n) = \begin{bmatrix} \sin(2\pi n) & \cos(2\pi n) \end{bmatrix}
\]

The paper [10] used an approximation for \((1 + a'\Theta(t))^{-1}\) based on its series expansion, specifically to develop (17) from (16) the following linear approximation is used

\[
(1 + a'\Theta(t))^{-1} \approx 1 - a'\Theta(t) + (a'\Theta(t))^2 + \ldots.
\]

The following development uses one more term in the expansion, specifically

\[
(1 + a'\Theta(t))^{-1} \approx 1 - a'\Theta(t) + (a'\Theta(t))^2 + (a'\Theta(t))^3
\]

Which, when substituted into (16), this leads to

\[
L(x) = -\frac{1}{2\sigma^2} \sum_{n=0}^{N-1} x(n)^2 \left(1 - a'\Theta(n) + a'\Theta(n)\Theta(n)\right)^2 a
\]

\[
= -\frac{1}{2\sigma^2} \sum_{n=0}^{N-1} x(n)^2 + \frac{a'}{2\sigma^2} \left(\sum_{n=0}^{N-1} x(n)\Theta(n)\right) - \frac{a'}{2\sigma^2} \left(\sum_{n=0}^{N-1} x(n)^2\Theta(n)\right)\right] a
\]

Accordingly the optimal amplitudes are obtained using

\[
\frac{\partial L(x)}{\partial a} = \frac{1}{2\sigma^2} \left\{ \sum_{n=0}^{N-1} x(n)^2\Theta(n) \right\} - \frac{1}{\sigma^2} \left\{ \sum_{n=0}^{N-1} x(n)^2\Theta(n)\Theta(n) \right\} a = 0
\]

\[
\Rightarrow a = 2 \left\{ \sum_{n=0}^{N-1} x(n)^2\Theta(n)\Theta(n) \right\}^{-1} \left\{ \sum_{n=0}^{N-1} x(n)^2\Theta(n) \right\} = R^{-1}p
\]

The matrix \(R\) can be simplified by examining its individual elements. Specifically

\[
R = \left\{ \sum_{n=0}^{N-1} x(n)^2\Theta(n)\Theta(n) \right\}, \quad R_{11} = \sum_{n=0}^{N-1} x(n)^2 \sin^2(2\pi fn)
\]

\[
R_{12} = R_{21} = \sum_{n=0}^{N-1} x(n)^2 \sin(2\pi fn) \cos(2\pi fn), \quad R_{22} = \sum_{n=0}^{N-1} x(n)^2 \cos^2(2\pi fn)
\]

These elements of \(R\) can be approximated as

\[
R_{11} = R_{22} \approx \frac{N\sigma^2}{2}, \quad R_{12} = R_{21} \approx 0
\]

\[
R \approx \frac{N\sigma^2}{2} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \Rightarrow R^{-1} \approx \frac{2}{N\sigma^2} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}
\]
Hence

\[
\mathbf{a} = \begin{bmatrix} a \\ b \end{bmatrix} = \frac{2}{N\sigma^2} \begin{bmatrix} \sum_{n=0}^{N-1} x(n)^2 \sin(2\pi fn) \\ \sum_{n=0}^{N-1} x(n)^2 \cos(2\pi fn) \end{bmatrix}
\] (27)

This agrees with the result (18) proposed (without a demonstration of optimality) by Lourens and du Preez [10]. Thus the above development confirms that the original solution did indeed represent an approximate maximum likelihood solution, but the development presented here provides a more sound theoretical basis for that result.

The resulting likelihood value is given by

\[
L(x) = -\frac{1}{2\sigma^2} \left( \sum_{n=0}^{N-1} x^2(n) - \frac{\Psi(f_0)}{N\sigma^2} \right). \tag{28}
\]

In order to estimate the depth of modulation the values of \(\sigma^2\) and \(f\) need to be estimated and applied in (27) to obtain values of \(a\). As represented by (19) the modulation frequency, \(f_0\), is estimated by locating the maximum of the Fourier transform of the square of the signal. This general approach has been applied in the field of wind farm noise by several authors [11, 12, 14]. The value of \(\sigma^2\) is obtained by noting from the model (12) that \(\sigma^2\) represents the time averaged energy, i.e. the overall rms value of the signal, and as such can be estimated in a standard manner.

4.1 Variations of the white noise model

The above model can be regarded as the basis of many approaches. There are some simple variations that might be considered. These are very briefly discussed in the following subsections.

4.1.1 Temporal smoothing of the energy

For instance one might consider using temporal averaging of \(x(n)^2\) over some time window prior to taking its Fourier transform. This form of averaging is that employed when computing \(L_{eq}\). Such averaging removes high frequency components in \(x(n)^2\). This is identical to attenuating high frequency values of the cost function \(\Psi(f_0)\), see (19). For such an algorithm smoothing offers little benefit for the applications of interest here, since the modulation rates for wind farm noise are low-frequency and so are unaffected by such smoothing, unless that smoothing is extreme and acts over periods which are significant relative to a period, i.e. of several hundreds of ms. There is a practical advantage that can accrue from such smoothing, namely that after smoothing the data can be down-sampled to a lower sampling rate and hence the computational burden of the method can be reduced [15]. However, in its basic form this is a very efficient algorithm and computational loading is not normally a significant factor when considering this routine.

4.1.2 Filtering prior to computation of the energy

In many recordings the modulation only affects energy over a limited bandwidth. It is an obvious extension to the method described in Section 4 to apply some form of filtering to \(x(n)\) prior to
computation of $x(n)^2$. Such filtering, if performed appropriately, will serve to concentrate the processing on the particular band of interest so can enhance system performance by rejecting out-of-band noise.

This filtered version of the algorithm forms the basis of DEMON processing in passive sonar and envelope processing in condition monitoring, see Sections 2.2 and 2.3 respectively.

One can opt to use a filter which is designed for the purposes of imposing a perceptual weighting, for example an A-weighting filter. This introduces a weighting which reflects the perceived importance of the modulated spectrum, it does not account for the perceptual effects of the modulation itself.

If an A-weighting is performed then this method is essentially a technique which is based on the Fourier transform of $\text{LA}_{eq}$, an approach which has been proposed [11, 14].

4.1.3 Using the analytic form of the signal

Some authors have suggested employing the squared magnitude of the analytic form of the signal [12, 22] (sometimes called the pre-envelope [23]) rather than simply squaring the signal. The analytic signal, $\mathbf{x}(t)$, which is complex valued, is created from the original (real-valued) signal using the Hilbert transform. Specifically

$$\mathbf{x}(t) = x(t) + \mathbf{H}\{x(t)\}$$

where $i = \sqrt{-1}$ and $\mathbf{H}$ represents the Hilbert operator such that

$$\mathbf{H}\{x(t)\} = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{x(\tau)}{t-\tau} d\tau$$

The analytic form of a signal is commonly used in a variety of signal processing applications based around narrow-band signals, e.g. [24, 25]. Indeed in condition monitoring it is common practice to process the pre-envelope, which is why such process in that field is referred to envelope processing, see Section 2.3.

There are distinct advantages to processing pre-envelope, $|\mathbf{x}(t)|^2$, rather than $x(t)^2$ in applications where the signals are narrow-band, but for wind farm noise the pre-envelope and the squared signal produce very similar results. To illustrate this Figure 3 compares the Fourier transform of the square of the signal and the Fourier transform of the pre-envelope for Gaussian white noise. One can see that in the low frequency region the two spectra are very similar. Typical wind farm modulation frequencies are very low-frequency, i.e. in the region where the two results are almost identical, suggesting there is no benefit to be gained by employing the analytic signal.
4.1.4 Harmonics of the modulation frequency

In practice modulations are never exactly sinusoidal. The consequence is that the Fourier transform of the energy generates a set of peaks at harmonic frequencies. This can be regarded as energy which has leaked away from the fundamental frequency and so reduced its amplitude making it less detectable.

The problem of analysing harmonic periodic signals has been studied [26] and the optimal solution in that instance is to form the harmonogram which is created using the Fourier transform of the data. Specifically for each hypothesised frequency the sum of the Fourier transform at that frequency and the energy at the assumed set of harmonics is formed. In practice this method does introduce some practical difficulties since it requires one to define the number of harmonics believed to be present in the signal and the summing process tends to introduce a set of spurious peaks which can lead to incorrect estimation of the fundamental frequency.

Accepting the limitations of the harmonogram, which are (arguably) fundamental issues that are a consequence of assuming a model with a set of harmonics, then this approach can be extended to modulations. For detecting the presence of modulations the algorithm described in this section can be simply extended by including a summation over the assumed set of harmonics, specifically the new cost function, $\Lambda(f_0)$, based on that found in (19) is obtained as

$$\Lambda(f_0) = \sum_{k=1}^{K} \Psi(kf_0)$$  \hspace{1cm} (31)
where $K$ is the assumed number of harmonics. Typically because of the need for the $K^{th}$ harmonic not to exceed the Nyquist frequency means that the cost function $\Lambda(f_0)$ would be evaluated for frequencies in the range $0 < f_0 < f_s/(2K)$.

The function defined by (31) is an optimal estimator of the modulation frequency and is a candidate metric for defining the depth of modulation for non-sinusoidal modulations (modulations with harmonics) it is not the only measure. The problem of determining what metric should be used for non-sinusoidal modulations is non-trivial. There are several potential approaches. One might consider using the amplitude (or power) of the largest single component, normally the fundamental frequency. Such a method effectively neglects the presence of harmonics and treats all modulations as if they were sinusoidal. Alternatively one might employ the total power in the modulation function, which leads to a method based on (31). Finally one might seek to use a metric based on the amplitude of the modulation waveform, for example forming the ratio of the modulation peak to its trough. Such a metric could be computed by reconstructing the modulation waveform the measured harmonics, but requires estimation of the modulation phase as well as amplitude at the harmonic frequencies.

5. Modulated Coloured Gaussian Noise

Measured wind farm noise usually consists of (at least) two parts: a stationary noise source and a modulated noise, neither of which is normally white. Consider the following model of the spectrum of such a noise.

$$S_{\text{m}}(t,f) = S_{\text{n}}(f) + S_{\text{m}}(f)(1 + \sin(2\pi f_0 t + \phi))$$ (32)

where $f_0$ is the modulation frequency and $\phi$ is the initial phase of the modulation, $S_{\text{n}}(f)$ and $S_{\text{m}}(f)$ are the spectra of the measured signal and the stationary noise respectively. The quantity $S_{\text{m}}(f)$ is the time averaged spectrum of the modulated process (the averaging occurring over many cycles of the process).

5.1 Defining modulation depth for coloured noises

In addition to the discussions in Section 3 regarding how to define the depth of modulation, the model (32) introduces an additional confounding factor into such definitions. The ratio $R(f) = S_{\text{m}}(f)/S_{\text{n}}(f)$ is a function of frequency which controls the degree to which modulation appears at a particular frequency. To extract a single value representing modulation depth across all frequencies one needs to consider how to combine the values to yield a single metric.

Assuming the ratio $R(f)$ can be computed (we shall shortly consider how this ratio might be achieved) then one approach is to compute a value by forming a weighted average across frequency in the form

$$M_d = \frac{1}{\delta} \int_{-\delta}^{\delta} W(f) R(f) df$$ (33)
where \( B \) is the bandwidth of the measured signal (for a digital signal this would be half the sample rate) and \( W(f) \) is some weighting function. Choosing different forms for the weighting function generates a range of “reasonable” methods. For instance an A-weighting function might be considered to partly account for the frequency dependent characteristics of the human auditory system. Alternatively one might consider a flat (or uniform) weighting function. Such an un-weighted measure of depth of modulation might be applying to studies which are more based on understanding the physical properties of the acoustics field, as opposed to the human perception of that field (where an A-weighted value might be deemed more appropriate).

To compute the ratio \( R(f) \) the spectra \( S_{in}(f) \) and \( S_{mm}(f) \) need to be estimated separately. This can be achieved in a number of ways, one of which is to first compute the time averaged value of, \( S_{xx}(t,f) \), which we denote, \( \hat{S}_{xx}(f) \), so that, from (32), one can write

\[
\hat{S}_{xx}(f) = \frac{1}{T} \int_0^T S_{xx}(t,f) dt = S_{in}(f) + S_{mm}(f)
\]

(34)

In some circumstances the stationary source may be measured in isolation (for instance the modulation strength might be time varying and there could be periods when the modulated signal is absent from recordings) allowing direct estimation of \( S_{in}(f) \). In cases when only measurements containing both sources are available then one can employ order statistics to estimate \( S_{in}(f) \) [27]. A similar approach, using minimum statistics, has been proposed for estimating the background noise spectrum in speech processing [28], however, employing a more general order statistics based method allows the estimation of \( S_{in}(f) \) with greater accuracy [27]. Once \( \hat{S}_{xx}(f) \) and \( S_{in}(f) \) have been determined then using (34) one can compute \( S_{mm}(f) \), or the ratio \( R(f) \) directly using

\[
R(f) = \frac{\hat{S}_{xx}(f)}{S_{in}(f)} - 1
\]

(35)

In practice the ratio may be negative at some frequencies because of estimation errors and one should set any such values to zero. Combining this with (33) leads to

\[
M_f = \int_0^\infty W(f) \frac{\hat{S}_{xx}(f)}{S_{in}(f)} df - 1
\]

(36)

in which it has been assumed that \( \int W(f) df = 1 \) which would normally be the case for a suitable weighting function.

5.2 The multi-band approach to coloured noise

One solution to the problem of analysing modulations in which the noise and the modulated process are both coloured, i.e. to fit model (32) to data, is to adapt the method described in Section 4 [29]. This is based on the observation that if a signal is filtered around a sufficiently narrow frequency band then that signal can be approximated as white over the bandwidth of the filter. This approach requires one to apply a bank of filters to divide the signal into a set of narrow-band components. Each of these narrow-band signals can then be analysed under the assumption that they are modulated white noise.
processes immersed in white noise, as in Section 4. The results from each band can then be combined in order to create an overall output.

Formerly, if the filter bank consists of $K$ filters then applying it to the signal $x(t)$ creates a set of signals $x_1(t), x_2(t), \ldots, x_K(t)$, representing the outputs of each of the filter banks. If one assumes that each of the filter outputs is independent then the combined likelihood can be written as

$$L(x) = \sum_{k=1}^{K} L(x_k)$$

(37)

where the vectors $x$ and $x_k$ represent the set of samples from the signals $x(t)$ and $x_k(t)$ respectively. The assumption of independence is generally not valid for modulated processes since the modulation tends occur across multiple frequency bands, so that the levels in the bands are inter-dependent, hence the signals in those bands also have inter-dependences. Measuring and correcting for the dependence between bands requires considerable effort and adaptations to account for this have not been developed. Methods for detecting amplitude modulation by exploiting the fact that band will be co-modulated, i.e. there will be correlation between different bands [16]. This requires one to determine which bands to compute the correlation between and requires that more than one band be modulated, which, in the low SNR limit, will, in general, not be true. For the development here the assumption of independence underlying (37) is invoked, it is done so on a pragmatic basis rather than a theoretical one.

Based on (28) and employing (37) one can write

$$L(x) = \frac{1}{2} \sum_{k=1}^{K} \frac{1}{\sigma_k^4} \left( \sum_{n=0}^{N-1} x_k(n)^2 - \frac{\Psi_k(f_k)}{N\sigma_k^2} \right)$$

(38)

where the subscript $k$ is used to denote quantities computed within the $k$th sub-band. Eliminating the terms in (38) which do not depend on the model parameters means that the problem of estimating the modulation frequency reduces to

$$\arg \max_{f_k} \sum_{k=1}^{K} \frac{\Psi_k(f_k)}{\sigma_k^4} = \arg \max_{f_k} \sum_{k=1}^{K} \frac{\left| F \left[ x_k(n)^2 \right] \right|^2}{\sigma_k^4}$$

(39)

Note that if the signal is pre-whitened, such that $\sigma_k^2$ is the same for all frequency bands then (39) can be simplified further to

$$\arg \max_{f_k} \sum_{k=1}^{K} \left| F \left[ x_k(n)^2 \right] \right|^2$$

(40)

Using (39) or (40) the modulation frequency can be estimated. Having determined the modulation frequency the amplitude of the modulation $a_k$ can be computed for each sub-band, using a band equivalent form of (27). Finally an overall measure of depth of modulation can be obtained by combining the results from each of the individual bands. The ideas in Section 5.1 also applying in this case and the combination can be extend to include some weighting function, the most obvious choice for which is the A-weighting function.
This approach is not specific to any form of filter bank, the output of each filter is incorporated into (39) or (40). There are obvious candidate forms of filter bank which might be considered including constant bandwidth, octave, 1/3rd octave and perceptual filter banks.

However some forms of filter bank can be more efficiently implemented than others. For example if a constant bandwidth filter bank is used then the implementation can be achieved via a spectrogram. Since spectrograms can be implemented via the fast Fourier transform (FFT) they are computationally efficient. Similar an octave filter bank can be efficiently implemented using the wavelet transform [30] and this would provide a route to a suitable practical implementation of such a solution. Indeed this approach has been adopted by Lee et al. [15] for the analysis of wind farm noise, albeit that they did not combine data across frequency bins to yield a single metric.
6. Methods based on a periodic correlation model

Amplitude modulated signals fall within a broader class of signals, namely those which have periodic correlation functions [31]. Specifically if we consider the definition of a correlation function

$$r(t, \tau) = E[x(t)x(t + \tau)]$$  \hspace{1cm} (41)

where \(E[\cdot]\) denotes the expectation operator and \(r(t, \tau)\) is the time-dependent correlation function [24, 32]. This definition of a correlation function is the general one that does not rely upon an assumption of stationarity (modulated processes are non-stationary). A periodically correlated process is one for which

$$r(t + T, \tau) = r(t, \tau) \quad \forall t, \tau$$  \hspace{1cm} (42)

where \(T\) is the period of the process. Using this model Kirsteins et al. [31] developed a maximum likelihood estimator for the modulation frequency (or more generally the frequency associated with the periodicity in the correlation function). To obtain the solution requires considerable effort, but it leads to an estimator which is computed by evaluating

$$\arg \max_{f_0} \Gamma(f_0), \quad \Gamma(f_0) = \sum_{\tau=0}^{N-1} \left[ \sum_{m=0}^{N-1} x(m)x(m + \tau)e^{-2\pi i m \Delta} \right]^2$$  \hspace{1cm} (43)

where \(\Delta\) is the sampling interval and is equal to \(1/f_s\) in which \(f_s\) represents the sampling frequency. It is worth noting that in [31] a more general model containing harmonics is considered and the resulting algorithm is a combination of (31) and (43).

The quantity \(\Gamma(f_0)\) is not particularly amenable to ready interpretation. To provide some understanding consider inner-most summation, which can be expressed as:

$$e^{\pi i \Delta} \sum_{m=0}^{N-1} x(m)e^{-\pi i m \Delta} x(m + \tau)e^{-\pi i (m+\tau) \Delta}$$  \hspace{1cm} (44)

Comparing this to the cross-correlation function for discrete complex signals, \(r_{uv}(\tau)\), which is defined as

$$r_{uv}(\tau) = \frac{1}{N} \sum_{n=0}^{N-1} u(n)^* v(n + \tau)$$  \hspace{1cm} (45)

where \(^*\) denotes complex conjugation. Then by defining

$$u(n) = x(n)e^{\pi i n \Delta} \text{ and } v(n) = x(n)e^{-\pi i n \Delta}$$  \hspace{1cm} (46)

one can write (43) in the form

$$\Gamma(f_0) = \sum_{\tau=0}^{N-1} \left| r_{uv}(\tau) \right|^2$$  \hspace{1cm} (47)
The signals $u(n)$ and $v(n)$ which have been introduced in this development, themselves have a straightforward interpretation. Specifically $u(n)$ represents the original signal up-shifted in frequency by $f_0/2$, whereas $v(n)$ represents the signal down-shifted by the same amount. The quantity $\Gamma(f_0)$ then represents the sum of the square of this cross-correlation function across all lags.

Equation (47) provides a computationally efficient method for evaluating $\Gamma(f_0)$. This because the correlation function can be evaluated using FFTs and the fact that $u(n)$ and $v(n)$ are conjugates of each other (see (46)) means that only one FFT needs to be evaluated.
7. Results

These methods are initially demonstrated on one of the test signals used in the listening tests conducted by the University of Salford Acoustics Research Centre as part of Work Package B2 of this project. These test signals are constructed using the method outlined in the appendix to this report. In Section 7.1 the performance on a single file is considered with the performance over a broader range of signals being considered in Section 7.3. The following section presents results obtained from a set of field recordings of amplitude modulated sounds made in the vicinity of wind turbines.

7.1 Performance of methods on a single test file

The results here have been obtained by applying the methods to the complete stimulus data sets which are of 20.25 s duration. In practice one would expect to apply these methods in a short-time framework wherein the data is divided into small windows (or blocks). Each block is then processed individually. The block length needs to be selected according to the stationarity of the modulation process. Generally longer windows will yield more accurate parameter estimates, assuming the modulation is consistent (stationary) throughout the block. Excessively long block sizes may lead to parameter estimates which are unrepresentative, since the characteristics of the modulation may evolve within the block.

The file chosen for the initial assessment is a recording of stimulus 21 used in the final listening tests (target modulation 6 dB(A))[33]. This data contains modulations that are clearly discernible and are relatively strong for this particular data set. By using data with clearly discernible modulations one can understand the features that such modulations produce. Figure 4 shows time series data for the chosen data.

![Figure 4: Time series data for stimulus 21](image)

From Figure 4 the oscillations in amplitude can be clearly seen. Counting the number of cycles within the 20 s section of data suggests there are approximately 16 cycles of the modulation process within that period. This suggests a modulation frequency of approximately 0.8 Hz.
Figure 5 shows the result of computing the short time energy for two instances, in the first where there is no temporal smoothing and in the second case the data is smoothed using a Hanning windowing function of 100 ms duration. The quantities in Figure 5 are essentially $L_{eq}$ measurements.

Visual examination of these energy time-series suggests that the smoothed curve (the lower frame) the modulation function is more apparent than in the unsmoothed data (the upper frame). This might lead one to suspect that there is an advantage to processing the smoothed data as opposed to the unsmoothed sequence; in fact there is comparatively little advantage since the noise affecting the unsmoothed data primarily lies in a frequency band which is very different to the modulation rate, as discussed in Section 4.1.1. This is illustrated in Figure 6.

![Figure 5: Short time energy. Upper frame: no smoothing, lower frame: smoothing with a Hanning window of 100 ms duration.](image)

Since we are interested in detecting periodic oscillations in plots like those shown in Figure 5 then it is natural to consider taking Fourier transforms of those traces: which is precisely what the theory outlined in Section 4 suggests is optimal if the signals are white noise processes. Taking Fourier transforms of the data in Figure 5 yields the results shown in Figure 6 (note these transforms are shown on a reduced frequency scale 0-30 Hz to focus the reader’s attention on the region where modulation rates and their harmonics are likely to appear for wind turbine data).
Figure 6: Fourier transforms of the short time energies shown in Figure 5. Upper frame: no smoothing, lower frame: smoothing with a Hanning window of 100 ms duration.

Comparing the two frames in Figure 6, one can see that the effect of smoothing is to attenuate the data in the high modulation rate region. In this case above a frequency of about 10 Hz; which corresponds to the reciprocal of the smoothing period (100 ms). In the band 0-10 Hz where the majority of components for the wind farm modulations are likely to appear the smoothing has no effect.

Consequently if one is processing these short time energy traces in the frequency domain (as is optimal, by virtue of the arguments in Section 4) then applying smoothing to the short time energies is of little benefit.

In order to examine the peaks in Figure 6 (upper frame) greater detail Figure 7 shows the same data on an expanded frequency axis, in the range 0-10 Hz. There is a large value at 0 Hz. This is a consequence of the fact that the average value in the short time energy (Figure 5) is not zero, this peak is a measure of the average energy in the time-series.

Figure 7: Fourier transform of short time energy for data shown in Figure 4, on an expanded frequency axis.
The peak at a frequency of a little below 1 Hz is measured to be at a modulation frequency 0.79 Hz which corresponds closely with the value estimated from the raw time series. This peak represents a fundamental frequency for which the harmonics are also evident (at least four are readily observable in this data set). This harmonic set indicates that the modulation is not sinusoidal: this is apparent in the short time energy traces (Figure 5 in particular the lower frame) where the shape of the energy waveform is more peaked than one expects from a sinusoidal signal. The value of the largest peak represents the power of the modulation only at the fundamental frequency. Alternatively summing three or four harmonic peaks which can be observed in the plot, would yield an estimate of the total modulation power, which could be used as single metric. As stated previously such a metric would not equate to a trough-to-peak measure of AM.

Figure 8: Output of the filter bank method for data shown in Figure 4

The filter bank method discussed in Section 4.3 is applied to this same data and the result is shown in Figure 8. In this instance a constant bandwidth filter bank has been applied, using a short-time Fourier transform (spectrogram) and a uniform weighting function used. This result is noticeably less variable (noisy) that the corresponding data for the Fourier transform of the short time energy, as seen in Figure 7. In Figure 8 one can again see a series of peaks, the fundamental frequency is measured to be 0.79 Hz (in agreement with other measures) and a series of harmonics can once again be observed. Despite the reduced variability in the data seen in Figure 8 it is not clear that more harmonics can be seen here than in Figure 7. This suggests that whilst the filter bank method produces a plot that is more visually appealing it is not clear that it in fact contains more useful information.

The reason for the reduced variability in the filter bank approach would seem to derive from the fact that it is the result of averaging data across many frequency bands.

Finally the method of Kirsteins, as summarised by (43), is applied to the time series in Figure 4. This routine is particularly slow on long data sets. This signal is stored at a sample rate of 48 kHz, whereas the majority of the energy is at a much lower frequency. Further this method is particularly sensitive to noise, even if that noise is in a frequency band which is distinct from that where the modulation lies. Hence before applying this method, the data is down-sampled to a sample rate of 4 kHz. The result is shown in Figure 9.
Figure 9: Result of applying Kirsteins’ algorithm to the time series data in Figure 4, after it has been down-sampled to 4 kHz.

From Figure 9 one can see that there is a definite peak at approximately the correct frequency. In this case the peak is actually measured to be at 0.77 Hz, somewhat different to that obtained from the other methods. The resolution of this approach is not clear, the spectrum shown is evaluated with a frequency spacing of 0.01 Hz, so the observed difference in estimated modulation rate corresponds to only a few sample points.

In this plot only one harmonic component in the data can be observed at about 1.5 Hz. Away from the main peak there appears to be considerable noise with significant oscillations.

7.2 Performance across a range of modulation depths

The subset of the Salford stimuli data set considered consists of times series with different levels of modulation. The recordings are named with numbers (13-24) and the higher numbered files are those with greater levels of modulation (target modulation depth (MD) of 1 to 12 dB(A)). The following sub-sections consider the analysis of four such files, in particular those numbered 13, 17, 20 and 24 (respectively target MD of 1, 3.5, 5 and 12 dB(A)) and document the results on the whole set.

In these tests in order to facilitate a fair comparison between the methods all the sample sets are down-sampled by a factor of 12 to make them compatible with the results for Kirsteins’ method.

7.2.1 Measures based on Fourier analysis of short time energy

Figure 10 shows the results of Fourier transforming the short time energy for each of the four signals. In each case a peak close to 0.79 Hz can be identified: for the lowest level of modulation (File 13) the peak value in the spectrum is at 0.74 Hz and in all the other cases it is at 0.79 Hz. This method creates a set of frequency bins of width, \( \Delta f = 1/T \), where \( T \) is the signal’s duration, in this instance this means that \( \Delta f = 1/20.25 = 0.049 \) Hz, so the difference between the result for File 13 and the others corresponds to a single frequency bin.
As the modulation level increases then the height of the peak also increases. The height of this peak relates to the amplitude of the fundamental frequency in the modulation. So one might consider using the following as a metric of depth of modulation, which is denoted $D_M$.

$$ D_M = 10 \log_{10} \left( \max \{ \Omega(f_0) \} \right), \quad \Omega(f_0) = \left\| F \{ x(t)^2 \} \right\|^2 $$ (47)

The maximum is taken over a limited frequency range to encompass realistic modulation rates, in these simulations the range used is 0.15 Hz$^2$ to 20 Hz.

Further, as discussed in Section 4.1.2 then one can apply a filter to $x(t)$ prior to squaring it, so that the processing focuses on the frequency band where the modulation is strongest. In this instance a low-pass filter with a cut-off at 800 Hz is applied. This filter captures energy in the modulated band. The results for the four example signals are shown in Figure 11.

Comparing the unfiltered and filtered results (Figure 10 and Figure 11 respectively) there are only very small differences in the plots. This is largely because the signals actually contain comparatively little energy above 800 Hz, so the filter’s effect is quite small. Had the recordings contained more high frequency noise one might anticipate that the effect of the filter would have been more noticeable.

---

2 The value 0.15 Hz corresponds to 3 cycles in the measurement period (20.25 s).
The metric (47) is a reasonable measure when comparing similar data sets, but it is not scale invariant, i.e. if the signal's amplitude is altered, then this measure of depth of modulation will change. It seems intuitive that depth of modulation is scale invariant, i.e. it is a relative measure. In order to accommodate this data is pre-scaled prior to processing. This is achieved by computing the mean value of the smallest 25% of values of $x(t)^2$. The idea being that the smaller values of $x(t)^2$ occur at times when the modulation is small, so that this measure is a measure of the stationary noise component. The choice of 25% involves a compromise: using a larger percentage would mean that data is included which contains significant contributions from the modulated energy is present, using a lower percentage increases the variability of the estimated energy.

Table 2 summarises the results of applying this metric to the full range of stimuli considered. The measure of modulation depth ($D_M$) shows an increasing trend for higher stimulus numbers, which is consistent with the manner in which the stimulus is constructed. The results obtained on the filtered data are somewhat greater than those obtained without the filter: they tend to be consistently 2 dB greater. One might speculate that this might convert into an ability to detect modulations in noise at lower Signal-to-Noise Ratios (SNR), but there is no direct evidence of this.
<table>
<thead>
<tr>
<th>Stimulus Number</th>
<th>$D_M$ (dB) Unfiltered</th>
<th>$D_M$ (dB) Low Pass Filtered (800 Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>0.8</td>
<td>2.3</td>
</tr>
<tr>
<td>14</td>
<td>4.3</td>
<td>6.7</td>
</tr>
<tr>
<td>15</td>
<td>8.8</td>
<td>10.6</td>
</tr>
<tr>
<td>16</td>
<td>12.6</td>
<td>14.6</td>
</tr>
<tr>
<td>17</td>
<td>13.8</td>
<td>15.5</td>
</tr>
<tr>
<td>18</td>
<td>16.3</td>
<td>18.0</td>
</tr>
<tr>
<td>19</td>
<td>17.0</td>
<td>19.0</td>
</tr>
<tr>
<td>20</td>
<td>18.7</td>
<td>20.5</td>
</tr>
<tr>
<td>21</td>
<td>20.9</td>
<td>22.6</td>
</tr>
<tr>
<td>22</td>
<td>23.4</td>
<td>25.0</td>
</tr>
<tr>
<td>23</td>
<td>27.3</td>
<td>28.9</td>
</tr>
<tr>
<td>24</td>
<td>32.7</td>
<td>34.0</td>
</tr>
</tbody>
</table>

Table 2: Results of the metrics based on Fourier analysis of the short time energy to the Salford stimulus set

7.2.2 Measures based on filter bank analysis

As in Section 6.2.1 the range of stimuli considered is analysed using the filter bank method. Figure 12 shows the results of applying the filter bank method to the four examples from the Salford data.

Figure 12: Output of the filter bank method for four test files a) File 13, b) File 17, c) File 20, d) File 24
From Figure 10 one can clearly see a peak close to 0.79 Hz in each instance, with the exception of the first example (frame a)). In that case in fact the maximum value occurs at 0.98 Hz, it is very close to the noise floor and does not produce a discernible peak: there is also a smaller visually imperceptible peak at 0.79 Hz. Consequently we conclude that this method has failed to detect the modulation in the first example (File 13). Further analysis of these stimuli reveals that there is a detection made in File 14, i.e. the largest peak occurs at 0.79 Hz when that file is analysed.

Since the peak height increases with modulation depth then we consider using this as the measure of depth of modulation, as outlined in Section 7.2.1. The data is normalised by the energy estimated from the lowest quartile of the data. Applying this method to the full data set one obtains the results shown in Table 3. Once again the general trend is for increasing measures of modulation depths with increasing stimulus number.

<table>
<thead>
<tr>
<th>Stimulus Number</th>
<th>$D_M$ (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>6.2</td>
</tr>
<tr>
<td>14</td>
<td>8.6</td>
</tr>
<tr>
<td>15</td>
<td>12.3</td>
</tr>
<tr>
<td>16</td>
<td>17.0</td>
</tr>
<tr>
<td>17</td>
<td>18.9</td>
</tr>
<tr>
<td>18</td>
<td>21.3</td>
</tr>
<tr>
<td>19</td>
<td>22.4</td>
</tr>
<tr>
<td>20</td>
<td>24.9</td>
</tr>
<tr>
<td>21</td>
<td>29.2</td>
</tr>
<tr>
<td>22</td>
<td>32.8</td>
</tr>
<tr>
<td>23</td>
<td>34.9</td>
</tr>
<tr>
<td>24</td>
<td>38.8</td>
</tr>
</tbody>
</table>

Table 3: Results of the metrics based on the filter bank method applied to the Salford stimulus set, the value in bold italics represents the point at which the detection failed.

### Measures based on Kirsteins’ method

The procedure described in the previous two sections is repeated using Kirstein's method, i.e. the method described by (43). Firstly the method is applied to the four example data sets and the results are shown in Figure 13.

It is evident from Figure 13 that this method fails to detect the modulation for the first two examples: Files 13 and 17, since no clear peaks are generated. In the two examples where there is a clear peak (Files 20 and 24), it appears at a modulation frequency of 0.77 Hz.

This method is also used to compute estimates of the modulation depth for all of the files, in manner mirroring that of the previous sections. The results of this analysis are shown in Table 4. Note that the values in italics in that table indicate peaks at frequencies which are different to the modulation rate for this data, i.e. the algorithm is not detecting the modulation. This algorithm only detects the modulation in 5 of the recordings, compared to the other methods which only fail to detect the modulation on a single occasion.
Table 4: Results of the metrics based on Kirsteins’ method applied to the Salford stimulus set, the values in bold italics represent the points at which the detection failed.

<table>
<thead>
<tr>
<th>Stimulus Number</th>
<th>$D_M$ (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>17.0</td>
</tr>
<tr>
<td>14</td>
<td>15.8</td>
</tr>
<tr>
<td>15</td>
<td>15.6</td>
</tr>
<tr>
<td>16</td>
<td>14.8</td>
</tr>
<tr>
<td>17</td>
<td>13.9</td>
</tr>
<tr>
<td>18</td>
<td>13.6</td>
</tr>
<tr>
<td>19</td>
<td>13.4</td>
</tr>
<tr>
<td>20</td>
<td>15.4</td>
</tr>
<tr>
<td>21</td>
<td>17.9</td>
</tr>
<tr>
<td>22</td>
<td>20.8</td>
</tr>
<tr>
<td>23</td>
<td>23.2</td>
</tr>
<tr>
<td>24</td>
<td>27.0</td>
</tr>
</tbody>
</table>

7.3 Performance on field data

This section discusses performance of the various algorithms on recordings from wind farms as opposed to the synthetic stimulus data. These recordings were provided as an output from Work Package C of the current project [34]. Some of these recordings are considerably longer than the stimulus data, see Table 5. This requires modification to the way in which the algorithms are applied to data sets. Such modifications are also necessary if the algorithms are applied to an incoming data stream, i.e. they are to be applied in an on-line mode. The approach adopted is a standard segmentation approach. The data are divided into blocks of a fixed length (10 s is typically used here) and the algorithm is applied to each block individually. The blocks are overlapped by a fixed
percentage (75% being used here). This overlapping increases the number of time points, so reducing the interval between output points, creating plot which has a smoother appearance. However, increasing the overlap increases the computational load without enhancing the inherent temporal resolution: it is a form of interpolation. The output from each such block is either the spectrum (as in Figure 7, Figure 8 and Figure 9) for each block or the estimated modulation depths. In the former instance one obtains data as a function of both time and modulation frequency, in a manner akin to a spectrogram, whereas in the latter case one obtains a time-series showing modulation depth as a function of time.

<table>
<thead>
<tr>
<th>File number</th>
<th>Filename</th>
<th>Duration (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>DTI LFN study – Site 1</td>
<td>570.0</td>
</tr>
<tr>
<td>2</td>
<td>File 1 - extract, last 20s</td>
<td>19.9</td>
</tr>
<tr>
<td>3</td>
<td>DTI LFN study - Site 2 - external</td>
<td>82.6</td>
</tr>
<tr>
<td>4</td>
<td>DTI LFN study - Site 2 - internal</td>
<td>81.2</td>
</tr>
<tr>
<td>5</td>
<td>Van Den Berg sample (JSV article)</td>
<td>172.6</td>
</tr>
<tr>
<td>6</td>
<td>Web-sourced audio (extract)</td>
<td>23.1</td>
</tr>
<tr>
<td>7</td>
<td>&quot;Other AM&quot; example 1</td>
<td>60.0</td>
</tr>
<tr>
<td>8</td>
<td>&quot;Other AM&quot; example 2</td>
<td>60.0</td>
</tr>
<tr>
<td>9</td>
<td>&quot;Other AM&quot; example 3</td>
<td>60.0</td>
</tr>
<tr>
<td>10</td>
<td>&quot;Other AM&quot; example 4</td>
<td>60.0</td>
</tr>
<tr>
<td>11</td>
<td>&quot;Other AM&quot; example 5</td>
<td>60.0</td>
</tr>
</tbody>
</table>

Table 5: Durations and names of files used in the assessment of algorithm performance

For the purposes of this discussion all the data is resampled to a sample rate of 3 kHz prior to processing.

7.3.1 Performance on a single file

Initially consider the data from the recording of File 1, which contains 570 s of data at an original sample rate of 6.4 kHz. Spectrograms of this data, after down-sampling to a sampling rate of 3 kHz, are shown in Figure 14. The spectrograms are plotted on a dB scale but with an unspecified reference level.
Figure 14: Spectrograms from File 1 a) Spectrogram of the full time-series b) Expanded view of spectrogram about region in which audible “squeaks” appear c) Expanded view of spectrogram about region where low-frequency frequency modulated signal occurs.

Figure 14 a) shows the spectrogram of all 570 s of data. On such a time-scale the general features of the time series are visible, specifically the rather consistent nature of signal is evident. It is clear that the frequency band up to 100 Hz contains a high level of noise. There are two clear events that happen in the data, for which the spectrogram is plotted in a smaller region around the events. Between 15 and 45 seconds there are series of audible “squeaks”, the source of which is not clear, they produce short duration bursts of energy visible in the spectrograms close to 1 kHz; at least four such events are evident in Figure 14 b). The second event occurs roughly between 240 and 250 seconds, it takes the form of a narrow-band frequency modulated sound centred on 100 Hz. This is less readily audible, due to its low-frequency content.

This file is processed using three algorithms: the Fourier transform of the squared signal, the Fourier transform of the signal after band-pass filtering between 200 Hz and 1 kHz and the filter bank algorithm. The results are shown in Figure 15 in the form of images, each vertical line in the image represents the spectrum formed using the various algorithms for a data segment centred on the corresponding time. The values in the image are displayed on a decibel scale (unreferenced).
Figure 15: Results of applying three different modulation algorithms to File 1. The plots show the modulation spectra computed for 10 s segments, overlapped by 75%. a) The Fourier transform of the unfiltered energy, b) The Fourier transform of the energy after band-pass filtering between 200 Hz and 1 kHz, c) The results for the filter bank algorithm.

It is clear from Figure 15 a) that without filtering the Fourier transform of the square of the signal fails to detect a modulated component. This is in contrast to the results with filtering (in the band 200 Hz – 1 kHz), shown in Figure 15 b), where a band of increased values at a modulation frequency of slightly more than 1 Hz can be seen. Harmonics of this modulation can also be (faintly) seen in this plot. At approximately 20 s there is a vertical band of high values, this corresponds to the time at which squeaks occur (see Figure 14 b)). In Figure 15 c) the modulation is also clearly apparent at a frequency slightly in excess of 1 Hz. Also the effects of the squeaks between 10 and 50 s are clearly seen. Comparing Figure 15 b) and c) the modulation frequency is probably most obvious in Figure 15 c) suggesting some level of performance enhancement when using the filter bank method for this data set.

The same results are presented in an alternative form in Figure 16. These plots show the peak value of the spectrum computed for each 10 s data segment. Comparing Figure 16 a) and b) then it is clear that the values in Figure 16 b) are generally larger than those in Figure 16 a), suggesting that the modulation is more detectable in the filtered data than the unfiltered data. When considering these results with those in Figure 16 c) one has to takes some care since the absolute levels are not comparable.

There are peaks in Figure 16 c), for example the peak at approximately 520 s, which would appear to correspond to period of increased levels of modulation when the spectrogram is examined.
Figure 16: Results of applying three different modulation algorithms to File 1. The plots show the modulation spectra computed for 10 s segments, overlapped by 75%. a) The Fourier transform of the unfiltered energy, b) The Fourier transform of the energy after band-pass filtering between 200 Hz and 1 kHz, c) The results for the filter bank algorithm.

Figure 17 shows another aspect of these results. In particular it depicts the estimated modulation rate for each 10 s block. The upper frame, Figure 17 a), shows the results obtained using the FT of the unfiltered energy. The estimated modulation rates fluctuate considerably. This is a consequence of the fact that the maximum values in the corresponding spectra, as shown in Figure 15 a), do not occur at consistent modulation frequencies. This is in contrast to the data in Figure 17 b), where many of the points are close to 1 Hz (a realistic blade pass frequency for the turbine). The peaks away from this frequency correspond to points in time when the data in the corresponding 10 s window generates a peak due to noise which is greater than the peak due to the modulation rate. Finally, Figure 17 c) shows a greater level of consistency, most of the points are close to 1 Hz. This suggests that the filter bank method has achieved a more consistent metric of modulation in this data set.
Figure 17: Estimated modulation frequencies for File 1. The plots show the modulation spectra computed for 10 s segments, overlapped by 75%. a) The Fourier transform of the unfiltered energy, b) The Fourier transform of the energy after band-pass filtering between 200 Hz and 1 kHz, c) The results for the filter bank algorithm.

7.3.2 Performance on the set of files

In order to examine the performance of the algorithms on the remaining 10 files, listed in Table 5, a full analysis, similar to that conducted in the previous subsection is not practical. In this section only the results from the filtered energy algorithm and the filter bank method are considered. The analysis depicting the estimated modulation depths and modulation rates as a function of time, as in Figure 16 and Figure 17 are shown.

The results from these analyses are depicted in the following in a sequence of figures. These figures are drawn in a consistent format, each showing the analysis of five files, so that two figures represent the analysis on the full dataset. The modulation depths and estimated modulation rates are shown side-by-side to allow for visual identification of regions where the detection is reliable (i.e. when the modulation rate is in the region of 1 Hz). The fact that some files are very short in duration means that the segment based approach is not very suitable for them as only a small number of segments are produced. However this form of analysis is still applied in order to maintain consistency.
Figure 18: Results using the filtered energy algorithm (filter pass band 200 Hz – 1 kHz). Left hand column shows the depth of modulation, right hand column the estimated modulation frequency. File 2: a) and b), File 3: c) and d), File 4: e) and f), File 5: g) and h), File 6: i) and j).

The results for Files 2 and 6 shown in Figure 18 suggest good performance, in both case the modulation depth is high and the corresponding estimated modulation frequency is consistent and realistic, i.e. the modulation frequency is in the region of 1 Hz. Although both these recording are short, approximately 20 s. The results for Files 3-5 illustrate a rather less impressive level of performance, other methods also fail to strongly detect modulations in these files, see Figure 19, suggesting that this data is weakly modulated. The algorithm estimates realistic modulations frequencies for periods of time, but is prone to generating rather wild values when the depth of modulation is low. For example the results for File 5 (Figure 18 g) and h)), at around 50 s and 120 s there are significant drops in depth of modulation resulting in erratic values for the modulation frequency, excluding these unrealistic modulation rates would result in more consistent values.
Figure 19: Results using the filtered energy algorithm (filter pass band 200 Hz – 1 kHz). Left hand column shows the depth of modulation, right hand column the estimated modulation frequency. File 7: a) and b), File 8: c) and d), File 9: e) and f), File 10: g) and h), File 11: i) and j).

The results in Figure 19 show results for recordings which were supplied as examples of “Other AM”, of varying levels, measured in the far-field of a wind farm. In general the estimated depth of modulation for File 7 is low and consequently the estimated modulation rates are largely unrepresentative. In Files 8-11 there is all show a similar pattern of behaviour; at the start of the recording modulation depth is large and the estimated modulation frequency close to one, with the depth of modulation generally decreasing with time and the modulation frequency becoming less reliable. Files 10 and 11 have clear modulations that can be easily detected in the filtered waveform and in the spectrogram.
Figure 20: Results using the filter bank method. Left hand column shows the depth of modulation, right hand column the estimated modulation frequency. File 2: a) and b), File 3: c) and d), File 4: e) and f), File 5: g) and h), File 6: i) and j).

The results in Figure 20 should be compared to those in Figure 18 for the filtered energy algorithm. In general the estimated modulation depths show the same trends, albeit the that the two algorithms are not expected to yield values for the depth of modulation that are the same, i.e. comparisons of actual numerical values should not be considered. The performance on File 2 and 6 qualitatively matches that shown in Figure 18 a), b) and i), j). For Files 3-5 this algorithm seems to yield a more consistent estimate of modulation frequency, suggesting a more appropriate measure of depth of modulation. For example comparing the performance on File 4 (frames e) and f)) one sees that the filtered energy algorithm fails to detect a modulation prior to 40 s (with the possible exception of the
first segment), whereas the filter bank method tracks this modulation successfully throughout that time.

**Figure 21:** Results using filter bank method. Left hand column shows the depth of modulation, right hand column the estimated modulation frequency. File 7: a) and b), File 8: c) and d), File 9: e) and f), File 10: g) and h), File 11: i) and j).

Figure 21 should be compared to those in Figure 19. These results are interesting in that they would appear to suggest that the filter bank method, for these data, is performing somewhat less well than the filtered energy method. In general the modulation frequencies are rather larger than 1 Hz (not always unrealistically so) but the trends suggested involve turbine dynamics which probably are unrealistic (halving or doubling of turbine rotation rates in tens of seconds). Examination of the data in File 9 reveals that the start of the recording is contaminated by bird noise (carrion crows and pheasant calls).
These calls have energy which resides primarily above 1 kHz, so the filtered algorithm removes them, whereas the filter bank method is affected by their presence. More problematic are the pheasant calls at the start of File 8. Audibly these are completely different to the swish of a turbine blade, but they do appear as a sequence of (almost) periodic bursts of energy. Figure 22 shows a spectrogram of this section of data, at the original sample rate of 6 kHz. The periodic clucking is seen as vertical lines between 1 and 2.5 kHz. There are 16 clucks, approximately regularly spaced, within a 5 second interval, corresponding to a clucking rate of approximately 3 Hz. Inspection of Figure 21 d) reveals that the estimated modulation rate is also approximately 3 Hz, indicating that it is indeed these sounds which have been detected. From the spectrogram one can also see that there is some energy in these signals in the 1 – 1.5 kHz band, which is included in filter bank method, but is removed from the filtered energy approach, this explains why the latter is unaffected by these sounds.

There is a similar burst of pheasant clucking which occurs at 30 s in File 9. This event is quieter and harder to analyse, but it is at a noticeably high rate that that shown in Figure 22 and consequently is the likely cause of the peak in the estimated modulation frequency seen in Figure 21 f).

In this instance the problem can be readily removed from this algorithm by only using frequency bands up to 1 kHz.

**Figure 22:** Spectrogram of data segment in File 8. Data contains the clucking of a common pheasant (*Phasianus colchicus*).
8. Conclusions

There are a very large number of options in terms of how the degree to which a signal is modulated might be measured. These options cover the variety of ideas about what is to be measured, how the frequency dependence of the modulation is taken into account and what methods are used to extract parameters from the data. All of this variety exists without considering the additional problems associated with making these measures subjectively meaningful.

The majority of this report considers the algorithms which can be used to estimate the parameters of the modulation. There are three forms of method that have been considered, all of which claim a degree of optimality and have been derived from basic principles.

The methods based on short term energy (akin to \( L_{eq} \) based methods) are optimal if the noise and modulation process are both Gaussian white processes and the modulation is sinusoidal. These methods are simple to implement and can be adapted using various ways. Their performance is surprisingly good over the stimulus data set.

These short term energy methods can be adapted to deal with non-white processes by applying a filter bank and treating the output of each filter bank as a separate white noise signal. This can be efficiently realised using spectrograms. The performance of these methods on the stimulus set used for research on subjective response is similar to the short-term energy methods. The spectra produced by this method do look smoother, but the very smallest modulations may fail to be detected.

The results from the field recordings suggest that in general the method based on the FT of energy without filtering does not perform particularly well. In these examples the large amount of unmodulated low-frequency noise tended to disrupt the algorithm’s performance. Applying appropriate filtering prior to computation of the energy can focus the processing on the frequency band where the modulation is significant. This does require one to identify the suitable band \( \text{a priori} \).

The filter bank method seems to offer a small advantage over the FT of filtered energy. It tends to produce results which are somewhat more consistent in time, suggesting greater reliability. In these tests it is affected more by the presence of external sounds, in this case bird calls, which happen to fall within the frequency band that it employs, but is rejected from the filtered energy approach.

Finally the method of Kirsteins et al. [31] has been considered. This approach is optimal for a broader class of processes, not just amplitude modulated but for periodically correlated processes. This approach seems to require a high SNR in order to function adequately and in the stimulus data set considered it was unable to detect the modulation in most instances. Further the computational load for this method is significantly greater than that needed for the other methods.
Appendix: Construction of Test Stimuli

To facilitate the subjective listening tests a set of synthetic stimuli were desirable. The content of such stimuli are completely known, with a fully variable set of input parameters, and one can be confident that the subjects are not responding to unknown factors in the data. However, such stimuli need to be sufficiently close to real stimuli as to elicit the same response.

To this end a model of modulated wind farm noise was developed. This model was constructed by modulating Gaussian noise with a defined spectral shape. The parameters of the model were then fitted to recordings of wind turbine AM in the far-field, in an attempt to mimic that dataset.

The basic model uses shaped Gaussian noise. This noise is filtered using filters whose frequency response functions have the form:

$$H(f) = \begin{cases} e^{-\left(f - f_c\right)^2} & f < f_c \\ e^{-\left(f - f_c\right)^2} & f > f_c \end{cases}$$  \hspace{1cm} (48)$$

where $f_c$ is the centre frequency of the modulated signal. The spectrum is asymmetric about this centre frequency, having a bandwidth of $B_l$ below the centre frequency and a bandwidth of $B_u$ above.

This filtered noise is then modulated with a time waveform which has the form:

$$m(t) = \sum_{n=0}^{N_p} p(t - nT_p)$$  \hspace{1cm} (49)$$

where $T_p$ is the interval between modulation pulses, $N_p$ is the number of pulses in the waveform and the $p(t)$ shape of each pulse. The pulse waveform $p(t)$ is selected to be an asymmetric Gaussian shape, similar to that used in (48), specifically

$$p(t) = \begin{cases} e^{t^2/\alpha^2} & t < 0 \\ e^{-t^2/\alpha^2} & t > 0 \end{cases}$$  \hspace{1cm} (50)$$

where $D_l$ and $D_u$ define the pulse durations before and after the peak respectively. The model can be summarised as:

$$x(t) = \alpha m(t) \times \left(n(t) * h(t)\right) + b(t)$$  \hspace{1cm} (51)$$

in which $\alpha$ is a measure of the depth of modulation, $h(t)$ is the impulse response of the filter whose frequency response is defined by (48), $*$ denotes convolution, $n(t)$ is a Gaussian white noise process and $b(t)$ represents the ambient (or masking) noise, which can be synthetic or a sample of real world data.

This model is parameterised via seven parameters: the centre frequency ($f_c$) and the two bandwidths ($B_l$ and $B_u$), the inter-pulse interval $T_p$, the durations $D_l$ and $D_u$ and a parameter to control the depth of modulation $\alpha$ (this parameter represents the ratio, expressed in dB, of un-weighted peak root-mean-square (r.m.s.) level of the modulation and the r.m.s. level of the masking noise).
References


Work Package B2
Development of an AM dose – response relationship

University of Salford,
Acoustics Research Centre
Wind Turbine Amplitude Modulation:
Research to Improve Understanding as to its Cause & Effect

Work Package B(2): Development of an AM Dose-Response Relationship

Prepared for RenewableUK by:
Sabine von Hünerbein, Andrew King, Benjamin Piper, Matthew Cand
## Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contents</td>
<td>2</td>
</tr>
<tr>
<td>Table of Figures</td>
<td>4</td>
</tr>
<tr>
<td>1. Preface</td>
<td>8</td>
</tr>
<tr>
<td>2. Executive Summary</td>
<td>9</td>
</tr>
<tr>
<td>3. Definitions</td>
<td>11</td>
</tr>
<tr>
<td>4. Context and Aims</td>
<td>12</td>
</tr>
<tr>
<td>5. Overview of annoyance related literature</td>
<td>13</td>
</tr>
<tr>
<td>5.1 General methods used for sound related human response studies</td>
<td>13</td>
</tr>
<tr>
<td>5.1.1 Survey studies</td>
<td>14</td>
</tr>
<tr>
<td>5.1.2 Laboratory experiments</td>
<td>14</td>
</tr>
<tr>
<td>5.2 Previous work on the response to modulated sounds</td>
<td>15</td>
</tr>
<tr>
<td>5.3 Previous work on the annoyance of modulated wind turbine sounds</td>
<td>17</td>
</tr>
<tr>
<td>6. Listening test design</td>
<td>18</td>
</tr>
<tr>
<td>6.1 Modulation Model &amp; Parameters</td>
<td>18</td>
</tr>
<tr>
<td>6.2 Scenarios</td>
<td>21</td>
</tr>
<tr>
<td>6.3 Stimulus Design</td>
<td>22</td>
</tr>
<tr>
<td>6.3.1 Step 1 – un-modulated masking noise</td>
<td>23</td>
</tr>
<tr>
<td>6.3.2 Step 2 – modulated noise</td>
<td>24</td>
</tr>
<tr>
<td>6.3.3 Step 3 – playback adjustments</td>
<td>24</td>
</tr>
<tr>
<td>6.4 Parameter specifications for different parts of the listening tests</td>
<td>26</td>
</tr>
<tr>
<td>6.4.1 AM parameters in Sensitivity Test I</td>
<td>27</td>
</tr>
<tr>
<td>6.4.2 AM parameters in Sensitivity test II</td>
<td>28</td>
</tr>
<tr>
<td>6.4.3 AM parameters for Final Test (incl. Validation Tests I and II)</td>
<td>30</td>
</tr>
<tr>
<td>6.5 Participant recruitment and screening</td>
<td>32</td>
</tr>
<tr>
<td>6.5.1 Sensitivity tests</td>
<td>32</td>
</tr>
<tr>
<td>6.5.2 Final tests</td>
<td>33</td>
</tr>
<tr>
<td>6.5.3 Participant protection</td>
<td>35</td>
</tr>
<tr>
<td>6.6 Participant briefing</td>
<td>35</td>
</tr>
<tr>
<td>6.6.1 Sensitivity Tests</td>
<td>35</td>
</tr>
<tr>
<td>6.6.2 Final Test</td>
<td>37</td>
</tr>
<tr>
<td>7. Results of Sensitivity Test I</td>
<td>38</td>
</tr>
<tr>
<td>7.1 Conclusions</td>
<td>41</td>
</tr>
<tr>
<td>8. Results of Sensitivity Test II</td>
<td>42</td>
</tr>
<tr>
<td>8.1.1 Stimuli set I: Fixed masking noise level</td>
<td>43</td>
</tr>
<tr>
<td>8.1.2 Stimuli set II: fixed modulation depth</td>
<td>45</td>
</tr>
<tr>
<td>8.1.3 Stimuli set III: Fixed peak level</td>
<td>47</td>
</tr>
</tbody>
</table>
17.1 Stimuli Components Step I ................................................................. 96
17.2 Step 2: Modulation for Sensitivity Tests I and II .................................. 97
17.3 Step 2: Modulation for Final Tests I and II ........................................... 99
17.4 Approach to Combining Stimuli Components to Achieve Target L_Aeq and
Modulation Depth .................................................................................. 101
17.5 Detailed list of stimuli parameters ....................................................... 103
  17.5.1 Sensitivity Test I ................................................................. 103
  17.5.2 Sensitivity Test II ................................................................. 105
  17.5.3 Final Test, participant subgroup 1 .............................................. 107
  17.5.4 Final Test, participant subgroup 2 .............................................. 108
18. Appendix VI: Participant instruction documents .................................. 109
  18.1 Sensitivity Test I ................................................................. 109
  18.2 Sensitivity Test II ................................................................. 110
  18.3 Final Test I and II ........................................................................ 111
19. Appendix VII: Participant and observer comments ................................ 112
  19.1 Participant observations ............................................................... 112
  19.2 Observer comments ...................................................................... 112
20. Appendix VIII: Results of validation test 1 ......................................... 113
  20.1 Rating distributions ........................................................................ 113
  20.2 Absolute Ratings ........................................................................... 114
  20.3 ABBS results .................................................................................. 115
21. Appendix IX: Results of Validation Test II ........................................ 117
  21.1 Rating distributions ........................................................................ 117
  21.2 ABBS results .................................................................................. 117
22. Appendix X: Annoyance ratings as a function of L_90 ......................... 119
23. Appendix XI: Data tables ...................................................................... 122
  23.1 Final Test composite figures ........................................................... 122

Table of Figures

Figure 6.1 Simplified schematic defining terminology of amplitude modulated signals. .... 18
Figure 6.2 Visualisation of parameter changes a) ML constant, MPL and MD change
simultaneously; b) MD constant, ML and MPL change simultaneously, c) MPL constant, ML
and MD change simultaneously .......................................................... 28
Figure 6.3 Zimmer and Ellermeier noise sensitivity score distribution for participants (final
tests). ............................................................................................................ 34
Figure 6.4: Age distribution of participant a) main test, b) subgroup 1, c) subgroup 2 ...... 35
Figure 6.5: Graphical user interface for final test. Participants were first asked to rate the
annoyance of the AM test sound on the sliding scale in the top of the window and to then
adjust the level of the ABBS (Reference Sound in the GUI) to match the annoyance of the
AM test sound. ................................................................................................................................. 38
Figure 7.1: Annoyance rating for changes in modulation depth (MD). ................................ 39
Figure 7.2: Annoyance ratings as a function of signal shape.................................................. 40
Figure 7.3: The effect of pulse width on annoyance. .................................................................. 41
Figure 8.1 Mean A-weighted stimuli levels after participant adjustment............................... 43
Figure 8.2: Annoyance rating for fixed background noise level and increase in MD (and peak
level) (as indicated by inset) for RFAM and MFAM compared.................................................. 45
Figure 8.3: Annoyance rating for fixed MD of 8 dB(A) for MFAM and 2 dB(A) for RFAM and
increasing background noise and peak level (as indicated by inset) resulting in a systematic
change of overall L_{Aeq} in steps of 3 dB(A). ..................................................................................... 47
Figure 8.4: Annoyance rating for fixed peak modulation amplitude and increasing MD by
means of decreasing background noise (as indicated by inset) for RFAM and MFAM
compared. ........................................................................................................................................ 49
Figure 8.5 Average annoyance ratings for all stimuli vs a) the average stimuli L_{Aeq} and b) the
Modulation Depth.............................................................................................................................. 51
Figure 8.6: Annoyance rating as a function of pulse bandwidth and frequency skew for
RFAM and MFAM compared........................................................................................................... 52
Figure 8.7: Annoyance rating as a function of MD for two modulation frequencies and for
RFAM and MFAM compared......................................................................................................... 53
Figure 9.1 Distribution of ratings a) for absolute annoyance scale, b) for the difference in L_{Aeq}
between the unmodulated ABBS and AM stimuli. ....................................................................... 56
Figure 9.2 Mean annoyance rating of AM test stimuli as a function of modulation depth. Solid
lines are results from final test, dotted lines from the validation tests with reduced participant
numbers. The legend specifies MD. See data in Table 22.1......................................................... 57
Figure 9.3 Absolute annoyance ratings of AM stimuli as a function of modulation depth. Solid
lines are results from final test, dotted lines from the validation tests with reduced participant
numbers. The legend specifies the L_{Aeq} of the test stimuli in dB(A). See data in Table 22.1.58
Figure 9.4 ABBS level adjustments in comparison to AM stimuli as a function of modulation
depth – Solid lines are results from final test, dotted lines from the validation tests with
reduced participant numbers. The legend specifies the L_{Aeq} of the test stimuli in dB(A).............. 59
Figure 9.5 Normalised relative annoyance ratings of AM stimuli as a function of modulation
depth. Solid lines are results from final test, dotted lines from the validation tests with
reduced participant numbers........................................................................................................... 60
Figure 9.6 Comparison of MD ($L_{eq}$) and main WPF routine metrics on absolute annoyance. ................................................................. 65
Figure 9.7 Comparison of WPB1 metric (noise-referenced) on absolute annoyance. ........ 66
Figure 9.9 Comparison of psychoacoustic metrics on absolute annoyance. ................... 66
Figure 14.1 Zimmer-Ellermeier Questionnaire for the assessment of noise sensitivity .... 82
Figure 15.1 Loudspeaker and seating arrangement in listening room ......................... 86
Figure 16.1 Filters used to correct for headphone (dotted green) and HATS (dotted red) measurement system response. The blue line is the intended response, the red the smoothed achieved response. ................................................................. 87
Figure 16.2 Left Loudspeaker Response and Correction .............................................. 88
Figure 16.3 Front Left Loudspeaker Response and Correction ................................... 89
Figure 16.4 Front Right Loudspeaker Response and Correction ................................ 89
Figure 16.5 Right Loudspeaker Response and Correction .......................................... 90
Figure 16.6 Back Right Loudspeaker Response and Correction ................................. 90
Figure 16.7 Back Left Loudspeaker Response and Correction ................................... 91
Figure 16.8 CABS Loudspeaker Response and Correction ......................................... 91
Figure 16.9 Left Loudspeaker Response and Correction ........................................... 92
Figure 16.10 Front Left Loudspeaker Response and Correction ................................ 92
Figure 16.11 Front Right Loudspeaker Response and Correction .............................. 93
Figure 16.12 Right Loudspeaker Response and Correction ......................................... 93
Figure 16.13 Back Right Loudspeaker Response and Correction .............................. 94
Figure 16.14 Back Left Loudspeaker Response and Correction ................................. 94
Figure 16.15 CABS Loudspeaker Response and Correction ....................................... 95
Figure 17.1 Measured third-octave data for wind turbine and garden masking noises. .... 96
Figure 17.2: MFAM stimulus properties a) frequency envelope with centre frequency of 600 Hz and bandwidth of 350 Hz. b) time envelope with a rise and drop time of 70% ................ 97
Figure 17.3: RFAM stimulus properties a) frequency envelope with peak at 350 Hz, and bandwidth of 400 Hz. b) time envelope with a rise time of 70% and a drop time of 30%. .... 98
Figure 17.4 Spectrogram of MFAM stimulus with Code Identifier AC. For details on parameter specification see Section 17.5.2 ............................................................... 98
Figure 17.5 Spectrogram of RFAM stimulus with Code Identifier MI. For details on parameter specification see Section 17.5.2 ............................................................... 99
Figure 17.6 Time and frequency content of RFAM signal used to create test stimuli (modulation pulses shown without masking noise) .............................................. 100
Figure 17.7 Time and frequency content of MFAM signal used to create test stimuli (modulation pulses shown without masking noise) .............................................. 100
Figure 9.6 Comparison of MD ($L_{Aeq}$) and main WPF routine metrics on absolute annoyance. ................................................................................................................................. 65
Figure 9.7 Comparison of WPB1 metric (noise-referenced) on absolute annoyance. ........ 66
Figure 9.9 Comparison of psychoacoustic metrics on absolute annoyance. ...................... 66
Figure 14.1 Zimmer-Ellermeier Questionnaire for the assessment of noise sensitivity .... 82
Figure 15.1 Loudspeaker and seating arrangement in listening room ............................... 86
Figure 16.1 Filters used to correct for headphone (dotted green) and HATS (dotted red) measurement system response. The blue line is the intended response, the red the smoothed achieved response. ................................................................................. 87
Figure 16.2 Left Loudspeaker Response and Correction .................................................. 88
Figure 16.3 Front Left Loudspeaker Response and Correction ......................................... 89
Figure 16.4 Front Right Loudspeaker Response and Correction ................................. 89
Figure 16.5 Right Loudspeaker Response and Correction .............................................. 90
Figure 16.6 Back Right Loudspeaker Response and Correction ................................. 90
Figure 16.7 Back Left Loudspeaker Response and Correction ....................................... 91
Figure 16.8 CABS Loudspeaker Response and Correction ........................................... 91
Figure 16.9 Left Loudspeaker Response and Correction ................................................ 92
Figure 16.10 Front Left Loudspeaker Response and Correction ..................................... 92
Figure 16.11 Front Right Loudspeaker Response and Correction .................................... 93
Figure 16.12 Right Loudspeaker Response and Correction ............................................ 93
Figure 16.13 Back Right Loudspeaker Response and Correction .................................... 94
Figure 16.14 Back Left Loudspeaker Response and Correction ...................................... 94
Figure 16.15 CABS Loudspeaker Response and Correction ......................................... 95
Figure 17.1 Measured third-octave data for wind turbine and garden masking noises ...... 96
Figure 17.2: MFAM stimulus properties a) frequency envelope with centre frequency of 600 Hz and bandwidth of 350 Hz. b) time envelope with a rise and drop time of 70% ........ 97
Figure 17.3: RFAM stimulus properties a) frequency envelope with peak at 350 Hz, and bandwidth of 400 Hz. b) time envelope with a rise time of 70% and a drop time of 30%. .... 98
Figure 17.4 Spectrogram of MFAM stimulus with Code Identifier AC. For details on parameter specification see Section 17.5.2 ................................................................. 98
Figure 17.5 Spectrogram of RFAM stimulus with Code Identifier MI. For details on parameter specification see Section 17.5.2 ................................................................. 99
Figure 17.6 Time and frequency content of RFAM signal used to create test stimuli (modulation pulses shown without masking noise). .................................................. 100
Figure 17.7 Time and frequency content of MFAM signal used to create test stimuli (modulation pulses shown without masking noise). ............................................ 100
Figure 17.8 Measured time series for stimulus (24) containing a 12±0.25 dB(A) modulation depth and with an L_{Aeq} of 40±0.15 dB(A).

Figure 17.9 Measured time series for stimulus (21) containing a 6±0.25 dB(A) modulation depth and with an L_{Aeq} of 40±0.15 dB(A).

Figure 17.10 Measured time series for stimulus (16) containing a 3±0.25 dB(A) modulation depth and with an L_{Aeq} of 40±0.15 dB(A).

Figure 17.11 Cubic fit to Measured AM and un-modulated WTN values to create stimuli with an L_{Aeq} of 40 dB(A).

Figure 18.1 Test sheet for Sensitivity Test I

Figure 18.2 Test sheet Sensitivity Test II

Figure 18.3 Instruction sheet for Final Test and Validation

Figure 20.1 Distribution of ratings a) for absolute annoyance scale, b) for the level difference between the ABBS and the AM stimuli with and without garden noise, mean = 2.2 dB(A), minimum rating = -11 dB(A).

Figure 20.2 Absolute annoyance ratings as a function of modulation depth for four different scenarios. The legend specifies the L_{Aeq} of the test stimuli in dB(A).

Figure 20.3 Absolute ABBS L_{Aeq} as a function of modulation depth for two types of modulation and in the presence and absence of masking garden noise.

Figure 20.4 ABBS-AM L_{Aeq} as a function of modulation depth for two types of modulation (RFAM left, MFAM right) and in the presence (bottom) and absence (top) of masking garden noise. The legend specifies the L_{Aeq} of the AM stimuli in dB(A).

Figure 21.1 Distribution of ratings for the level difference between the ABBS and the AM stimuli with and without garden noise, mean = 2.6 dB(A), minimum rating = -15 dB(A).

Figure 21.2 Comparison of equal annoyance ratings between stimuli with constant overall L_{Aeq} (top) and constant masking noise with increasing L_{Aeq} as a function of MD (bottom). Note that the legend has therefore a different meaning for top and bottom graphs. Left panel: absolute ABBS L_{Aeq}, right panel: ABBS-AM L_{Aeq}.

Figure 22.1 Annoyance ratings as a function of L_{90} b) in comparison to ratings as a function of L_{Aeq} a) (identical to Figure 9.2)

Figure 22.2 ABBS ratings normalised by a) L_{Aeq} (identical to Figure 9.5), b) L_{90}. 
1. Preface

The work presented in this report is part of project funded by RenewableUK and entitled 'Wind Turbine Amplitude Modulation: Research to Improve Understanding as to its Cause & Effect'. The project comprises a total of six separate work packages. The outcome results of each of the work packages have separately resulted in their own dedicated final reports. A seventh work package, WPF, has produced an overarching final report in which the key findings across the separate work packages have been collated and discussed.

This is the final report of Work Package WPB2: ‘Development of an AM Dose-Response Relationship’.

Wind turbine aerodynamic noise, by which is meant the noise produced by the rotating wind turbine blades, includes a steady component as well as, in some circumstances, a periodically fluctuating, or amplitude modulated (AM), component. However, AM may take different forms. One form of AM, commonly referred to as ‘blade swish’, is an inherent feature of the operation of all wind turbines. It can be explained by well understood mechanisms, it being the result of the directivity characteristics of the noise created by the air flowing over a turbine blade as it rotates. Because this type of AM is an inherent feature of the operation of wind turbines, whose origin can be explained and modelled, the present project adopts as its definition the term ‘normal amplitude modulation’ (NAM). The key driver for the project, however, is the recognition that some AM exhibits characteristics that fall outside those expected of NAM. Such characteristics include a greater depth of modulation, different directivity patterns or a changed noise character. For this reason the present project adopts as its definition the term ‘other amplitude modulation’, or ‘OAM’, for all observations of AM that lie outside that expected of NAM.

In recent years public concern has grown about the potential annoyance from wind turbine OAM noise. This concern has resulted in an increased interest to establish how AM, and in particular OAM, occurs, how it can be better defined and measured, and how it is generally perceived and responded to. It is the answers to these questions that the present project seeks to address.
2. Executive Summary

Amplitude modulated (AM) sound from wind turbines is difficult to characterise and there is insufficient knowledge about listener response to the characteristic physical properties (metric) of AM sound.

The first objective of the present Work Package was to test whether the AM metrics developed in Work Package B1 (WPB1) would provide a meaningful measure of AM ‘value’ that correlates with subjective annoyance ratings. The second objective was to quantitatively investigate the relationship between the AM value and a measure of average annoyance in the form of a dose-response relation.

Key to obtaining representative results was the design of stimuli which were representative of the spectrum and character of actual noise experienced by wind farm neighbours exposed to AM. Extensive work was done to obtain this, based on input from Work Package C, test signals were synthesised for a characteristic range of wind turbine sounds, with a wide range of input parameters. This model is described in an annex to WPB1. It was considered by the project team that the artificial stimuli obtained were representative of AM experienced in the field.

In a first phase, sensitivity tests were undertaken to find the AM parameters that listener response was most sensitive to. 80 test sounds of at least 20 second duration were presented via calibrated headphones in a quiet room and 11 volunteers were asked to score the annoyance on a numeric 11 point scale. The outdoor sounds included test wind turbine noise at typical levels, with varying AM characteristics and some natural background noise.

Then, a final set of tests was undertaken in a quiet listening room with a sound reproduction that mimicked the outdoor directivity of one wind turbine in the distance. 32 test sounds were generated for and presented to 20 participants. Two validation tests containing another 158 and 32 test sounds respectively were conducted to clarify results from the sensitivity tests in the better-controlled listening room. Participants rated annoyance directly as before, and also adjusted an un-modulated test sound in level to be equally annoying to the modulated test sound.

The sensitivity tests showed in accordance with previous literature that annoyance crucially depended on the A-weighted level of the test sound, as measured in $L_{Aeq}$, and to a lesser extent on modulation depth which is a measure of the modulation strength. Modulation depth was shown to be also best expressed in terms of A-weighting to give consistent results. The use of $L_{A90}$ as an alternative to $L_{Aeq}$ produced similar results at the low and medium modulation depths most often observed from wind turbines.
In the final test there were therefore three sets of test sounds with the constant $L_{Aeq}$ of 30, 35, and 40 dB(A) for which the estimated modulation depth was systematically varied from 0 to 12 dB(A) in increasing steps. After taking into account the effect of $L_{Aeq}$, which always dominated the annoyance rating, the modulation depth seemed to increase the annoyance rating slightly but consistently. However, the effect was not statistically significant because there was a large spread of ratings. This suggests that given a large enough group of participants it can possibly be shown that annoyance increases consistently (monotonically) with modulation depth. In contrast, the $L_{Aeq}$ level of the adjusted un-modulated wind turbine noise remained broadly constant as the modulation depth increased above about 3 dB(A). This answered the question of how much louder would an equivalent un-modulated sound have to be to be equally annoying to a modulated sound. The adjustments were on average 1.7 dB(A) for a 40 dB(A) test sound and 3.5 dB(A) at 30 dB(A). Validation tests at two additional levels of 45 dB(A) and 25 dB(A) confirmed this trend. When levels were measured as $L_{A90}$, results suggest that annoyance ratings were similar for modulation depths of up to 6 dB(A) and generally increased with both modulation depth and $L_{Aeq}$. Because results for sets of stimuli with constant $L_{Aeq}$ and changing modulation depth are not available simple average adjustments cannot be identified and further work would be necessary. A clear onset of annoyance at a particular modulation depth could not be found for either of the two rating methods.

In a validation test with a subgroup of 11 participants, the spectral characteristics of the test sound were changed to represent Mid-Frequency AM, often described as swish, as opposed to Reduced Frequency AM which is sometimes described as a “swoosh” or “whoomp”. Also garden noise was added at a low level to change the character of the sound for both types of AM sounds. For all four groups the results for both absolute annoyance ratings and un-modulated level adjustments appeared very similar. This suggests that the relative effect on annoyance is small as long as the garden noise does not reduce the audibility of the modulated sound.

In a last step the annoyance ratings were compared for 6 different metrics, four of them based on different physical definitions of modulation depth, using input from WPB1, and 2 using the perceptive measure of fluctuation strength. The comparison showed that the main effect of the physical metric is to change the range of modulation depths. The same stimuli would have a range of 0 – 12 dB(A) modulation depth in one metric but 4 – 32 dB in another metric. Fluctuation strength results showed a further step towards a metric that correlates with listener response but not even a perception based metric can ever account for contextual and attitudinal aspects of annoyance rating.
3. Definitions

Different types of noise are present where wind turbine noise is audible and the sound at the receiver location can be thought of as a combination of some or all of these types of noise.

**Wind Turbine Noise** (WTN) includes a steady component as well as, in some circumstances, a periodically fluctuating or **Amplitude Modulated (AM)** component or character. The report for Work Package C (WPC) has highlighted the difference between different instances of this modulation. Firstly, **Normal Amplitude Modulation** (NAM) can be explained by well-understood mechanisms, as noted in the Preface. The second type named **Other Amplitude Modulation** (OAM) appears to have other characteristics, such as increased modulation level and/or frequency content, and does not seem consistent with the available theories, although different potential mechanisms have been described in Work Package A2 (WPA2). When the abbreviation AM is used in this report, this covers both NAM and OAM.

The differing frequency characteristics sometimes identified for AM signals has also led to the definition within the current report of **Medium-Frequency Amplitude Modulation** (MFAM) and **Reduced-Frequency Amplitude Modulation** (RFAM): see Section 6.1.

In general wind turbine noise can also contain tones, which might sometimes be audible above the steady WTN, but this study will not focus or include any tones, as subjective response to tones has already been studied extensively.

The audibility of wind turbine noise at the listener position can be reduced or completely masked by environmental or ambient **Background Noise** (BN). Residents near wind turbines experience BN as any noise that is not originating from the wind turbines. A specific type of BN is **Vegetation noise** (VN). It is also commonly called **Garden Noise** (GN) which in the context of this study is the sum of vegetation and other outdoors background noise. But the term **Masking Noise** (MN) is used in the present study as noise that will mask the AM component of stimuli experienced, and therefore MN will represent either steady WTN on its own, or the combination of steady WTN and all or some of vegetation noise and background noise.
4. Context and Aims

In recent years the debate about the annoyance from wind turbine noise in general, and RFAM noise in particular, has increased as this has been reported by some wind farm neighbours to be annoying [WPC, 1]. It is plausible that AM noise may be more disturbing than steady noise, and there is an ongoing discussion on whether current guidelines for the assessment of WTN such as ETSU-R-97 [2] are sufficiently taking AM and in particular RFAM in noise into account. Therefore wind farm developers, planners and policy makers are interested to find out how and why AM in general and in particular RFAM occur as well as how this type of noise is generally perceived and how listeners respond to it. Unfortunately not much is known about the occurrence of RFAM. The other parts of the current Renewable UK were aimed at improving the understanding, measurement and prediction of AM. Details can be found in the project reports, [WPA2, WPB1, and WPC]. They informed this report which focuses on the response of listeners to AM.

The work aimed to develop a scientifically based procedure for the rating of AM effects. Previous work suggests that the following general behaviour might be observed:

- **threshold of onset of annoyance** – when the fluctuation becomes strong enough sound becomes more annoying than steady sound of the same $L_{Aeq}$
- **relation between AM characteristic parameters and mean annoyance score at AM values above the threshold.** Previous research suggests that annoyance might be observed to systematically increase with the increase of certain characteristic parameters

If one or both of these hypotheses can be validated then they can aid the development of guidance for any AM based planning condition. For example a relation between mean annoyance scores and fluctuation strength could potentially be used to define a ‘penalty’ procedure for AM, by matching the mean annoyance scores of AM noise with continuous noise. This would provide the basis for rating the AM characteristic of wind turbine noise if this is considered to be necessary.
5. Overview of annoyance related literature

As a background to the listening test design this chapter aims to give an overview over common investigation techniques for sound related human response studies. In the second part of the literature study a short overview over the current knowledge of the annoyance from AM sounds is given.

5.1 General methods used for sound related human response studies

In sound related studies it is useful to recognise the systematic differences between physical, perceptual and affective measurements as laid out in the Filter model [3]. It describes how perceptual measurements are different from physical measurements because they are "filtered" by the senses like the ear and the capability of the brain to process sounds. Affective measurements are different from perceptual measurements because they are influenced by non-acoustic factors such as mood, context, emotion, background and expectation of the listener. Typical physical properties of AM sounds are equivalent A-weighted sound pressure level $L_{Aeq}$, spectral content, modulation depth and modulation frequency. Perceptual measures in this context are loudness and pulsation whereas the affective measure that this report focuses on is annoyance.

Recent literature reviews [4, 5] have discussed the methods for assessing noise annoyance in the general context of environmental noise and for wind turbine noise in particular. The following paragraphs contain excerpts from [5].

Common methods to study the perception of sound are scaling magnitude estimations and paired-comparisons. In the first a participant assigns a numerical value to a test sound or "stimulus". This value quantifies the property (loudness, annoyance, etc). A stimulus can be a naturally occurring sound or a sound that is synthesised in a laboratory. Another method is paired comparison, whereby two stimuli containing examples of the property are presented and a two-way rating scale is adjusted to indicate the relative rating of the two stimuli. Alternatively, one of the two stimuli can be actively adjusted by the participant until the two are equally representative for the property being studied. While the method of magnitude estimations can be used in survey studies and laboratory experiments the paired comparison method is naturally restricted to laboratory environments where stimuli can be presented in a controlled way. Paired comparisons are more difficult to do with stimuli of long duration. However, a number of studies such as [6] and [7] have concluded that stimuli
length of as short as 30 sec give comparable results to long stimuli. Also the listening
duration for adjustment procedures is harder to control as the listeners need to be given the
choice to re-listen to both stimuli.

5.1.1 Survey studies
At present, the majority of work focuses on measuring the environmental noise levels, either
at the source and using propagation algorithms or at nearby residences, and acquiring
annoyance ratings via surveys. These two measures are combined to create dose-response
relations for noise levels (or any other characteristic) and community annoyance classified
by source. [8] provides a good synthesis of 11 such examples for various forms of transport
noise.

Survey studies have the advantage that they measure in the listener’s natural environment.
Therefore context and attitude can be taken into account. The disadvantages are that these
studies are retrospective studies on an emission that already exists. Apart from the well-
known problems with this method it is not applicable in a situation where there the
occurrence of AM sound is doubtful or infrequent. This limits the available data base where a
large number of participants would be necessary because of the source variability and other
factors.

5.1.2 Laboratory experiments
Another way of studying environmental noise annoyance is to present either recordings of
noise or similar, synthesised sounds to participants in the controlled environment of a
laboratory such as an anechoic chamber or listening room/booth. Many of the physical
properties of sound and environment and some personal variables can be controlled,
thereby allowing accurate estimates of how acoustical parameters affect noise annoyance.
To an extent, researchers can choose to study noise annoyance with respect to its non-
acoustical factors, although never quite as realistically as in field studies, by including non-
acoustic sensory stimuli typically associated with the noise source.

Additionally, an experimental design can either allow or restrict the influence of context by,
for example, asking participants to imagine a particular scenario during exposure. For
attitude, the participant can be explicitly informed of the source thereby allowing their
expectations and previous experiences of the source to influence their ratings of annoyance.
Alternatively, researchers can study noise annoyance purely from an acoustical perspective
by limiting other sensory stimuli or keeping them constant, removing contextual cues and keeping participants naïve to the source.

However well designed, a laboratory experiment will never give the same absolute ratings as a survey study because the laboratory environment is incompatible with the natural environment where the noise occurs and the listeners are out of their usual context. Therefore relative annoyance measures will give a better impression when comparative results are useful.

Because this current project studied the affective response to AM sound as compared to steady sound, the laboratory environment was suitable for controlled comparisons. Firstly, because the stimuli can be well controlled in a way which has not been studied before. This is important because WPC has highlighted the difficulties in measuring this type of WTN even in situations where its occurrence was relatively prominent, and the significant variability encountered. Secondly, it was chosen to expose all listeners to the same noise in the same environment thereby making the experiment reproducible and thirdly to control the context as described above.

5.2 Previous work on the response to modulated sounds

The known characteristics of the perception of modulated sounds can be described in terms of a basic psychoacoustics model proposed by Fastl and Zwicker [9]. In its simplest form the model can be applied to the amplitude modulation of pure tones. This is not representative of wind turbine noise as that is broadband in nature. A more complex form of the model which is extended to broadband AM sounds in the presence of masking noise, is used because it may be applicable when considering typical wind turbine noise modulation. The corresponding model uses the perception parameter loudness as well as the measureable physical parameters modulation depth, modulation frequency and frequency deviation as predictors for a perception parameter called fluctuation strength. This model was developed based on a series of observations and experiments. It is conceivable that this subjective parameter could relate to annoyance although [9] does not provide a direct relation.

Fluctuation strength is reported to experience a maximum for modulation frequencies around 4 Hz. A basic unit called a vacil is therefore defined by the authors relative to the subjective perception of a 60 dB, 1 kHz tone which is 100% amplitude modulated at 4 Hz. The model of broadband sinusoidally modulated sound is given by the following equation:
\[ F_{BBN} = \frac{5.8(1.25m - 0.25)[0.05(L_{BBN} \, / \, dB) - 1]}{(f_{mod} / 5)^2 + (4 / f_{mod}) + 1.5} \text{ vacil} \]

where \( L_{BBN} \) is the level of the broad band noise, \( m \) is the modulation factor\(^1\) and \( f_{mod} \) is the modulation frequency. \( m \) is here used in a way that is defined in [10]. In general modulation factor/depth is a parameter that has been defined in various different ways in the past and is known to be subject to substantial uncertainty as shown in WPB1 among others.

The following comments can be made on the results of this work:

- the fluctuation strength at a modulation frequency of 1 Hz\(^2\) is approximately 50% the fluctuation strength at a modulation frequency of 4 Hz;
- fluctuation strength increases with increasing overall level (maintaining 100% amplitude modulation as the overall level increases) with a 40 dB increase in overall level corresponding to an increase by a factor of approximately 2.5 in the fluctuation strength;
- fluctuation strength increases with modulation depth (maintaining the same overall level as the modulation depth increases) – for the example of a 60 dB overall level, the fluctuation strength is zero until a modulation depth of approximately 3 dB (modulation factor ~17%) after which it increases approximately linearly with the logarithm of the modulation depth until it flattens out at around 30 dB (modulation factor ~94%);
- the fluctuation strength (based on experiments with 70 dB level pure tones amplitude modulated by 40 dB at 4 Hz) shows an insignificant correlation with tone frequency.

Lenchine [11] uses the model above to estimate how typical wind turbine noise would vary in fluctuation strength with modulation frequency and modulation factor: both parameters affect fluctuation strength within the same order of magnitude. Legarth [12] conducted listening tests using the model. Participants were asked to rate the fluctuation strength and modulation frequency of artificial stimuli. The author reports satisfactory correlation for the ability of the participants to identify fluctuation strength (“swishing sound”). They were not

\(^1\) In analogy to AM as used in electronic communication the **modulation factor** is a value between 0 and 1 and defined as the ratio of low frequency modulation signal amplitude to un-modulated broadband signal amplitude.

\(^2\) Note that modulation frequency is not the signal frequency. Therefore 1 Hz does not refer to infrasound.
good at rating the modulation frequency. Jiggins [13] reported a study of loudness perception of simulated broad-band sounds of increasing modulation depth. He found that modulated signals tended to be rated louder than their numerical values suggested.

It is important to note that while fluctuation strength seems to describe the perception of fluctuating sound well, the affective response to wind turbine sounds has to be measured by the degree of annoyance in response to the sound and there is no simple or direct link between the two.

5.3 Previous work on the annoyance of modulated wind turbine sounds

Little is known about the effects of AM WTN sound on annoyance. A survey study on wind turbine noise annoyance [14] reports complaints about different types of AM. The authors state that most of the complaints were associated with reports of “swishing” or “lashing”, and with these there were roughly equal number of people annoyed as not-annoyed. There were many fewer reports of “thumping” or “throbbing”, but where this description was used four times as many people were annoyed as not annoyed.

Lee et al. [15] conducted listening tests on stimuli in which both the $L_{Aeq}$ and modulation factor parameters varied. The stimuli were generated from two different wind turbines which were recorded in the near field. They were then adapted by changing the masking noise to achieve the desired modulation factor. Annoyance is shown to vary with both parameters. In these results annoyance scales more clearly with $L_{Aeq}$ than with modulation factor. The findings are in agreement with low frequency noise studies such as [16] which is not related to wind turbines. However, for both studies it is difficult to judge how large the spread in the data was and therefore how reliable the results are because error bars are not shown. Also some detailed information on the exact nature of the stimuli was missing in both studies (such as how the $L_{Aeq}$ were achieved). In the absence of more detailed studies such results have been interpreted as preliminary dose-response relations.

Moorhouse et al. [17] studied the response of subjects to amplitude modulated low frequency tones using an $L_{A90}-L_{A10}$ criterion for tones and found that night time acceptability thresholds changed from a high level at low modulation depth / $L_{A90}-L_{A10}$ to a low level at higher values of that parameter. This study is designed to find whether a similar threshold behaviour can be found for AM sounds.
Members of the project research and the management team have observed that WTN AM display high temporal variability of parameters such as modulation depth and $L_{Aeq}$, and can also have varying spectral characteristics.

Based on this review of existing research on the subject, it was decided to design listening tests to derive a dose-response relation for the annoyance from WTN AM sounds using both scaling magnitude estimation and paired comparison methods. These tests would also evaluate the effect of different spectral and temporal characteristics of these signals. Initially, many modulation parameters were piloted in participant Sensitivity Tests to define a final set of stimuli.

6. Listening test design

6.1 Modulation Model & Parameters

On the basis an analysis of AM data samples collected as part of other parts of this project WPC, the stimuli were designed using model described in the WPB1 Appendix. For better understanding of all variable properties of WTN AM sound a strongly simplified but representative model of a modulated sound signal is shown in Figure 6.1.

![Figure 6.1 Simplified schematic defining terminology of amplitude modulated signals.](image)

The signal printed in blue is the AM sound: the modulated wind turbine noise is modelled as pulses of a certain height (variable in the general case), profile shape, width and spectral content. The separation period between the pulses defines the modulation frequency. This varying signal is overlaid over the masking noise (in black), which can have different spectral characteristics (and can be different to the AM pulses in the general case, as represented by different colours in Figure 6.1). The effective depth of modulation is determined by the
emergence of the pulses above the masking noise. In the WPB1 model, both the amplitude of the pulses and their spectra were defined by potentially asymmetric Gaussian profiles (see WPB1 Appendix).

Figure 6.1 illustrates the importance of comparing the absolute amplitudes of a modulated signal with the amplitudes of the masking noise levels because if the two are comparable or the masking noise amplitudes are even higher, then the modulated sound is inaudible. The parameter that describes this ratio is the modulation depth which can be defined in different ways (WPB1). Different definitions can be considered, and the determination of a metric was considered from the outset to be dependent on the outcome of the subjective tests themselves. During the stimuli design, a preliminary measure of modulation depth proved useful to design a representative range of stimuli signals:

**Modulation depth (MD)** derived from 100 ms averages of $L_{Aeq}$. The modulation depth is defined as the difference between the mean peak level and the mean trough level in the A-weighted RMS time series for any consecutive group of all pulses over the length of the test stimuli (Figure 17.8 and Figure 17.9, Appendix V). A-weighting is a common filter that takes the sensitivity of the human ear to different frequencies into account and is therefore perception related, and the $L_{Aeq}$ acts as a signal envelope. This is comparable to measures such as those proposed by [18].

Other measures of modulation depth were evaluated in WPB1 of the project to consider different metrics of "modulation depth" and how to best relate them to listener reaction.

Whilst the time envelope in Figure 6.1 is symmetrical about the maximum this is not the case for every naturally occurring signal. If the envelope is skewed to one side then the modulation may sound more impulsive. A strongly skewed envelope looks like a sawtooth with a certain slope and a vertical side. The slope can be characterised in terms of rise/fall time or the skew in terms of percentage. At present little is known about the occurrence of impulsive modulation and its impact on perception has not been quantified.

Other properties of the envelope are its width, and its repetition rate which is also called modulation frequency. The modulation frequency of wind turbine noise occurs at the blade passing frequency. For most modern large-scale wind turbines, this modulation frequency is generally between 0.5 and 2 Hz, which is the frequency range that the study has focused on.
Other key characteristics of AM signals, that cannot be easily represented in Figure 6.1, are measures of the frequencies that are contained in the different elements of the sound signal. This is called the spectral content. In WPC the spectral content of AM noise has been shown to vary from sample to sample. Because of the limited database of AM sound samples, generalisations on spectral content are difficult and the stimuli were therefore based on the available knowledge of those AM spectra. The observed far-field data fell broadly into two types of categories with differing spectral content:

A. Dominated by the 500-1000Hz region (mid-frequencies)
B. Dominated by the 200-600Hz region, with a slight-low frequency bias (peaking around 300Hz) (reduced frequencies)

Because of this difference, the first type is more likely to be described as “swish” whereas the second may be described as “swoosh” or “whoomp” because of the increased prominence of lower frequencies. To differentiate between these two spectral types, type A may be labelled Medium-Frequency Amplitude Modulation (MFAM) and type B Reduced-Frequency Amplitude Modulation (RFAM). These labels will refer in the remainder of this report to the different spectral types.

Corresponding examples of representative frequency spectra are shown in Figure 17.6 (Appendix V) and Figure 16.7 (Appendix IV). Note that the frequency spectra envelope are defined in this study using a "filter function" with its respective properties called centre frequency, bandwidth (BW) and symmetry/skewness.

AM sound from wind turbines can be intermittent and the duration of its occurrence can vary strongly in reality. The effect of intermittency (i.e. cumulative effect of variable occurrence of AM on annoyance over long periods) is difficult to test in a laboratory environment and has therefore not been included in this study. The study of subjective response over long periods (minutes or hours) would require extensive testing periods, even if restricting the range of variables in the stimuli, after which the tests would become increasingly impractical and unrepresentative of realistic situations. The need to consider a sufficiently extensive and representative range of different scenarios of length and repetitions would equally increase testing requirements beyond what was reasonably feasible as part of this project. This was particularly relevant for the paired comparisons discussed in Section 5.1.2.

Apart from AM of broadband noise another type of AM which is the amplitude modulation of tones within a wind turbine sound has also been observed in practice. However tonal
modulation is outside the scope of this study. Precise and robust methods already exist to rate non-stationary tones, both in general [19] and for wind turbine noise [2].

6.2 Scenarios

Many of the reported complaints about AM were about sound heard indoors, which is not surprising as residents tend to be inside their dwellings at night when background levels are quieter and WTN (including AM if present) will tend to be more audible. It may therefore seem intuitively natural to try to reproduce indoors conditions for listening tests, especially as listening tests for this study were conducted in a listening room; although it should be noted that the characteristics of a listening room will be different to a typical dwelling room (in terms of reverberation and background noise levels). One advantage would be that naturally sounding LAeq that meet the expectation of the participant can be produced.

There are several problems with indoor stimuli:

- Because every dwelling is different it is unclear how realistic or representative wall sound insulation loss or room acoustics models are. This would introduce further variables including room furnishings, open/closed windows, etc. This would therefore increase test length and uncertainty to an unreasonable degree. And these stimuli would not be representative for all indoors environments.
- Previous attempts at using indoor stimuli with the general research question of whether participant ratings are context dependent [5] did not yield conclusive results.
- The associated significantly lower noise levels associated (as both WTN and MN are reduced to the internal) would be increasingly challenging to test and reproduce even in a controlled and dedicated testing environment,
- The noise environment inside dwellings is often affected by internal sources (fridge, heating systems etc), as well as human activity, including sleeping noises at night.
- Because of these difficulties a limited number of suitable internally measured recordings were available
- Further complications arise through room acoustics in listening rooms: unrealistic stimuli can easily result, particularly for monaural signals.

Wind turbine noise is generally assessed outdoors at a free-field location for similar reasons. Therefore developing a metric based on outdoor measured noise was the preferred option within the research team. For the results of the study this means that the absolute annoyance ratings cannot be directly compared to studies such as [14] that are based on questionnaires about the perception of wind turbine noise in the listeners home environment. This is for two reasons, firstly the context of the home environment can never be fully
reproduced in a laboratory. Secondly, outdoor sounds that are played back in an indoor environment at typical outdoor $L_{Aeq}$ sound often too loud to the listener (e.g. [5]). The relative ratings within the study will nonetheless give meaningful results.

Adding local vegetation noise to a WTN or MN stimulus seemed natural, because this type of noise occurs naturally and a stimulus without vegetation noise might sound unrealistic of an outdoor amenity area. Vegetation noise may naturally decrease the audibility of wind turbine noise, and it is the most likely source of masking in rural areas, therefore providing potentially more realistic annoyance ratings.

However, there are a number of counter arguments including that adding another type of noise complicated the tests and was not directly related to the task of establishing a dose-response relationship between amplitude modulation and annoyance. The representativeness of vegetation noise can be questioned because it varies with location and time. For example, in high wind shear conditions wind speeds close to the ground are low while the noise level produced at turbine height is high. Therefore, masking vegetation noise can be limited, so the presence of significant masking would be representative of some conditions, but not all. For the present study a large part of the tests therefore included both stimuli without and with vegetation noise to explore the potential effect of local vegetation noise on annoyance.

6.3 Stimulus Design

Following extensive discussions and preliminary assessments within the project team, the synthesised stimuli were designed in three steps:

1. Firstly, synthesised representative un-modulated masking noise which consisted in some cases of WTN and in some cases of WTN plus garden noise in a certain fixed proportion. The garden noise was kept at a low level (1 GN : 5 WTN) so that it would not dominate the stimuli.

2. Secondly, the modulated part of the signal was added, with varying parameters, according to the model described in WPB1 and above.

3. And finally the stimuli were converted to the optimum format to be played back either over headphones or in the listening room.
The modulation model is based on an analysis of wind turbine noise recording made in the far field rather than near field recordings adjusted with propagation model. Whilst this approach provided reproducible stimuli which could be compared with recordings and enabled a systematic study of the response to certain AM parameters, the stimuli were simplified and could not represent all possible scenarios. However, the use of naturally occurring recorded sounds would encounter the same difficulties but would not assist the systematic control of modulation parameters. They would have the added complications contamination by background noise or other features of the turbine noise such as tonal noise. Recordings vary in distance to turbine; they are typically highly variable in time and artefacts can be introduced by the recording techniques. The use of carefully controlled synthesised stimuli in comparison to recordings was therefore considered to be the only realistic way to derive thresholds of annoyance onset and a systematic study of relations between AM characteristic parameters and mean annoyance score at AM values above the threshold. The resulting stimuli were judged by the project team to sound realistic compared to real WT sound at similar distances.

6.3.1 Step 1 – un-modulated masking noise

The previous stimuli design procedure that has been described in [5] was used. It can be summarised as follows:

- Recordings (in accordance with [20]) of 47 wind turbines have been analysed and an average spectrum compiled.
- The spectrum was "propagated" to an immission site that experienced a fixed sound level using the NORD2000 propagation model [21].
- A random white noise of constant amplitude was filtered using the spectrum and the phase randomised to produce the unmodulated WTN sound.

The un-modulated WTN spectrum can be found in Figure 17.1 and was considered representative of typical un-modulated WTN in the far-field by the research team. The advantage of this procedure is that the use of average spectra and sound propagation model delivered a set of standardised stimuli. Importantly this did not contain any significant modulation or audible tonal content. Different distances from the turbine in flat terrain can within a limited range be simulated realistically by changing the \( L_{\text{A eq}} \) of the stimuli although a propagation model needs to be used where more accuracy is required. Propagation parameters such as ground impedance were well defined and therefore reproducible. The stimuli were based on recordings in the downwind direction and are therefore not representative for other directions.
The local garden noise was chosen to match a noise spectrum of 8 m/s wind through deciduous foliage (see Figure 17.1). This was generated in a similar way as for the WTN above, using a random process adapted to the derived spectrum shape. There again, whilst real recordings may sound more realistic, this would introduce similar concerns of reproducibility and bias with repetition of looped recordings. Both the un-modulated WTN and GN were combined to give the masking noise (MN).

6.3.2 Step 2 – modulated noise

AM stimuli were created by overlaying the resulting constant masking noise (MN) with AM pulses according to WPB1. The different modulation parameters which were varied are investigated throughout the different tests below and detailed in Sections 6.4 and 17.5.

6.3.3 Step 3 – playback adjustments

This step differed between the sensitivity tests which were conducted using headphones and the final tests which took place in the listening room. The two different reproduction systems were chosen to optimise the test procedure for the different tasks. Using headphones for the sensitivity tests allowed simultaneous testing of up to 10 participants giving flexibility to stimuli design and fast results. A disadvantage of that method was that monaural stimuli sound less realistic than ambisonic reproduction. In contrast, the listening room allows very accurate, realistic directional sound reproduction at sound levels down to just below 20 dB(A)\(^3\), but thereby restricting the number of simultaneous tests to one participant. This latter test environment was judged by the research team to be most suitable to attempt to derive a dose-response relation between a more limited number of modulation parameters and annoyance, as determined from the preliminary sensitivity tests undertaken using the headphone arrangement.

**Multi-participant headphone tests**

To assess the sensitivity of participants to modulation parameters that can vary in wind turbine noise, two preliminary sensitivity studies were conducted (see below). A relatively fast test procedure was employed using the annoyance scale method and calibrated headphones, which allowed several participants to be tested in parallel.

---

\(^3\) Noise floor measurements in the listening room which conforms to ITU-R BS 1116-1 are described in detail in [5].
To achieve a good approximation of a free-field signal at the ear a ‘transfer function’ taking the effect of the headphones and sound card into account was derived and applied to the monaural stimuli. This was done via a 1/3 octave-band filter function implemented in Adobe Audition, firstly with a correction for the headphone/sound card combination, and secondly with a correction that compensated for the differences between omnidirectional microphone mono recordings and HATS binaural measurement system as shown in Figure 16.1. This correction meant that close to free field response could be achieved. Using these readily available but not highly specified headphones also resulted in a slightly less accurate reproduction and a higher noise level than necessary for the quietest occurring wind turbine sounds compared to reproduction in a more controlled environment.

It should be noted though that the stimuli in the preliminary stages of the test were not designed to sound totally realistic through the headphones because they were based on monaural signals. They were however designed so that relative changes in modulation parameters would be clearly audible and therefore allow changes in annoyance ratings to be interpreted in terms of listener sensitivity. Absolute annoyance ratings are therefore meaningless for such a design and the results need to be compared to each other to allow meaningful conclusions.

The stimuli file names were randomised to ensure that participants could not guess the nature of the stimulus but the garden noise stimulus which served as a reference sound for these tests was clearly labelled for easy participant access.

**Listening room**

The stimuli for use in the listening room were auralised using a planar ambisonic reproduction technique consisting of a ring of 6 loudspeakers to introduce different directional reproduction for the wind turbine and the surrounding garden noise. Subwoofers were used in a CABS configuration [22]. This is a set of 8 woofers four on the front wall and four on the back wall of the room which achieves a local cancellation of low frequency room

---


5 Beyerdynamic DT100, specification available at http://www.beyerdynamiconline.com/Datasheets/DT100_DB_E_a3.pdf [18/1/2012]

6 Head And Torso Simulator (HATS), Brüel & Kjær, Type 4128, specifications available at http://www.bksv.com/products/telecomaudiosolutions/headtorso/headandtorsosimulatorhatstype4128c.aspx [18/1/2012]

---
modes. This reduces the effect of room acoustics and makes the reproduction as similar to outdoor sound as possible. The system was calibrated using a custom measurement system and modification of the stimuli signals sent to each loudspeaker. The overall approach, equipment and room used is similar to that used in a previous study of the response of subjects to tonal noise stimuli, described in [5].

Wind turbine sound at a listener position would be usually perceived as coming from a specific direction. This was achieved in the test design by playing the stimuli over one loudspeaker right in front of the listener. In contrast garden noise - where present - was played by all loudspeakers in the ambisonic ring to achieve an immersive effect.

The response of the system was evaluated using a sound level meter\(^7\) and a low noise microphone\(^8\). The superior spatial performance of this reproduction technique was judged by the research team to be more important than the disadvantage of restricted calibration accuracy at frequencies above 600 Hz due to the interference of the ambisonic ring. When listening to the stimuli the characteristics of the broadband sounds were not audibly changed compared to other reproduction systems. For full details of the sound reproduction setup and calibration see Appendix IV: Sound Production System and [5].

### 6.4 Parameter specifications for different parts of the listening tests

The first important question to answer was which modulation model parameters (see Section 6.1) would most determine the affective response of a listener. This was following a process in which different stimuli models and a variety of comments made in the available literature and in subjective reports were reviewed within the project team. Two sensitivity tests were conducted to systematically study and potentially exclude some parameters from the test. Sensitivity Test I was conducted with a very limited number of varied modulation parameters and served mainly to test the stimuli design procedure and to compare rating sensitivity to these parameters using a simplified reproduction technique. Sensitivity Test II was then a more comprehensive and systematic rating exercise to find the modulation

---


parameters to which participants would react most sensitively. That second test enabled the choice of parameters that would be used for the Final Test. However, a few additional parameters were included in parts of the Final Test to validate and extend the results. The rationale for the choice of parameters will be discussed further in Sections 7 to 9 as each set of parameters has been based on the results of the previous tests.

6.4.1 AM parameters in Sensitivity Test I

While variation in all modulation parameters can possibly change the affective response of listeners the aim of the first test was to use a very simple modulation based on the present knowledge about AM WTN signals. An obvious choice was to systematically vary the modulation depth to find out whether there is evidence that the affective response might change in a continuous way with increasing modulation depth and whether a sudden onset of annoyance will be observed. The shape and width of the time envelope of amplitude modulated wind turbine noise (Figure 6.1) were parameters that were easily changed in the WPB1 model by at the time and were therefore included in the first test.

Increasing the peak amplitude of the AM pulses, through the increase of the input MD, achieved a progressive increase in modulation depth. It was thought to be important to keep the level and therefore the annoyance from the background noise constant. However, this meant that the stimuli get louder with increasing modulation depth, both of which parameters could contribute to changes in the affective response (see Section 5.2).

Two other parameters that might conceivably change the character of the stimulus and therefore the listener response were shape and width of the time envelope depicted in Figure 6.1 [23]. The chosen waveform was a saw-tooth-type shape with varying rise times. From analysis of wind turbine noise recordings data (particularly for OAM), this was judged by the research team to be a feature of some of the available recordings. This was modelled by an asymmetry percentage factor (% rise time).

A fixed but representative modulation frequency of 0.8 Hz was used. The duration of the modulation pulses was raised as another factor which may potentially influence subjective response, as it may be related to descriptions of “impulsiveness” of the signals. The pulse length was varied from very short pulses of 0.1 s duration to long pulses of 0.45 s. Table 6.1 gives an overview over the chosen modulation parameters. A garden noise was added for comparison. A detailed list of stimuli including all signal parameters is available in Table 17.3.
Table 6.1 Stimuli design parameters for Sensitivity Test I. Main modulation parameters under investigation were the modulation depth, shape and width of the modulation pulse envelope. Other parameters were kept constant.

### 6.4.2 AM parameters in Sensitivity test II

To further evaluate the number of variable AM parameters to establish meaningful dose-response relations and thresholds, a second preliminary sensitivity study was conducted including a further set of modulation parameters that were thought to be possibly influencing listener reactions. Also, the issue that had been observed in the first test where an increased modulation depth inevitably resulted in louder stimuli was considered by creating three independent sets of stimuli:

To differentiate between the annoyance from masking level (ML), peak level of the modulated part of the signal (highest value in blue curves) (MPL) and modulation depth MD were varied as shown in Figure 6.2 a) – c):

![Figure 6.2 Visualisation of parameter changes](image)

The aim of this design was originally to separate the response to the parameters. All scenarios necessarily resulted in a variation in overall energy content of stimuli. Although this variation in level is known to affect annoyance, the effect might be compensated by the fact that participants could initially adjust the level of the masking garden noise to suit their preconception of how garden noise would sound.

Spectral shapes were varied by using
- masking noise which in addition to the WTN sound included two different types of garden noise (artificial and real recording) to explore the influence of garden noise on annoyance. The amplitude ratio between WTN and GN was 5:1.
- differing values for bandwidth, peak frequency and frequency skew to create a range of spectra representative of AM recordings

Two modulation spectra labelled as 'MFAM' and 'RFAM' were used similarly to those defined in Section 17.2. However in this test, a preliminary spectral shape was used: 'MFAM' had a peak frequency at 600 Hz and a bandwidth of 350 Hz and 'RFAM' had a peak frequency of 300 Hz and a bandwidth of 400 Hz. The sets of stimuli generated by these conditions were tested with two types of garden noise to assess the effect on annoyance. The modulation spectra were also found to be asymmetric, based on analysis of measured spectra in WPC: this was also modelled using a percentage factor. Different skew factors and therefore spectral shapes were investigated as specified below. Finally, different modulation frequencies were tested (0.65 and 1.3 Hz), again based on observations from WPC.
In detail the following parameters were used:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>MD, dB(A)</td>
<td>4 different values</td>
</tr>
<tr>
<td>Period (s)</td>
<td>fast and slow turbines = 2 values</td>
</tr>
<tr>
<td>Bandwidth (Hz), Peak Frequency (Hz), Frequency Skew (%)</td>
<td>2 types used</td>
</tr>
<tr>
<td><strong>Frequency Skew (%)</strong></td>
<td>6 levels to investigate the role of frequency skew systematically</td>
</tr>
<tr>
<td><strong>Background Noise Type</strong></td>
<td>WTN + 2 different GN spectra in an amplitude ratio of 5:1</td>
</tr>
<tr>
<td>Total Level Change</td>
<td>Results from other changes</td>
</tr>
<tr>
<td>RFAM:</td>
<td>1, 2, 4, 6</td>
</tr>
<tr>
<td>MFAM:</td>
<td>5, 8, 12, 15</td>
</tr>
<tr>
<td>RFAM:</td>
<td>350 (peak), 400 (width), 70 %</td>
</tr>
<tr>
<td>MFAM:</td>
<td>600 (peak), 350 (width), 50 %</td>
</tr>
</tbody>
</table>

| Frequency Skew (%)                             | MFAM frequency skew of 67, 70 and 80 % corresponding to BW 300, 400, 500 Hz |
|                                                | RFAM frequency skew of 30, 50 and 61 % corresponding to BW 250, 350 and 450 Hz |

| Background Noise Type                          | WTN + GN based on the filtered synthesised garden noise               |
|                                                | WTN + GN based on a direct recording                                 |

| Total Level Change                             | Results from other changes                                            |

Table 6.2 Stimuli design parameters for Sensitivity Test II

The following parameters were fixed for all stimuli:
- Envelope width = 0.2 s
- Envelope rise time = 70% of pulse length

A detailed list of stimuli filenames with their respective parameters can be found in Table 17.4.

### 6.4.3 AM parameters for Final Test (incl. Validation Tests I and II)

The main purpose of the final test was to investigate from which modulation depth annoyance starts to increase and, when modulation exceeds that threshold, whether there is a continuous increase of annoyance with increasing modulation depth or whether annoyance

---

9 The WTN is the same in both cases but the second type of GN is identical to GN used in [5: Part B].
assumes a constant value from a certain threshold. The stimuli were normalised to keep the overall $L_{\text{Aeq},20s}$ of the stimuli constant at defined and calibrated levels, for the different modulation depths. Three main representative $L_{\text{Aeq}}$ values of 30 to 40 dB(A) were used to compare the well-researched response to increased sound level with the less well-researched response to modulation depth. The stimuli were limited to one type, RFAM, without garden noise. This main test contained 32 stimuli per participant.

For the purpose of designing a representative range of stimuli, the modulation depth was varied by changing the modulation depth (MD), as evaluated by averaged $L_{\text{Aeq},100\text{ms}}$ readings, as presented in Section 17.4. The main test included values of MD between 2 to 12 dB(A). Modulation depth intervals were chosen to be less than 1 dB(A) below 5 dB(A) and larger intervals from 5 dB(A) up to 12 dB(A). The choice of high resolution at low MD was aimed at determining a threshold of the onset of annoyance as it was thought that AM signal characteristics might not be perceptible at low MD [9]. Whereas maximum modulation depths were reported by the research team to be occurring at a maximum of 10 dB(A) in reality, the range of the synthetic stimuli was extended to the higher value of 12 dB(A).

For validation purposes, (validation I), subsets of participants also listened to RFAM and MFAM with and without garden noise, and considering additional $L_{\text{Aeq}}$ levels and intermediate MD values. The number of additional stimuli per participant was up to 160 for this part of the test.

As part of these final tests, in addition to providing an absolute annoyance rating (scaling magnitude estimation), the participants compared the AM stimulus to an unmodulated wind turbine sound with the same spectral shape as the one that the modulated stimuli were based on. The participants adjusted the level of this unmodulated sound until it was equally annoying as the modulated wind turbine sound (paired comparison method). This Adaptive BroadBand Stimulus (ABBS) used the un-modulated broadband WTN noise, and was therefore identical to the un-modulated (0 dB) stimulus (MN without garden noise).

As concerns were raised within the project team that the effect of normalising for set $L_{\text{Aeq}}$ levels in the stimuli might reduce the relative effect of the increased modulation rate, a second validation test (II) therefore compared the results from the main test to a set of stimuli that had a constant masking noise (MN) level, with increasing modulation depth and corresponding increasing $L_{\text{Aeq}}$. By using the adaptive test method and normalising for the $L_{\text{Aeq}}$ of the test stimuli, the influence of the overall level on annoyance was limited. The additional number of stimuli for this part of the test was 32.
Detailed lists of stimuli for the first and the second subgroup of participants can be found in Table 17.6 and Table 17.7. The following parameters were used:

| Key parameters (main test in **bold**) |  
|----------------------------------------|---------------------------------|
| Modulation depth MD, dB(A)             | 8 different values in main test plus 5 intermediate values for validation I |
|                                        | 0, 2, 3, 4, 5, 6, 9, 12          |
|                                        | 1, 2.5, 3.5, 4.5 and 7           |
| Sound level of total stimulus, $L_{Aeq}$ dB(A) | 3 values plus 2 for validation I |
|                                        | 30, 35, 40                       |
|                                        | 25 and 45                        |

| Additional parameters for validation I (main test in **bold**) |  
|---------------------------------------------------------------|--------------------------------|
| Type of AM                                                    | 2 types                        |
| Type of Masking                                               | 2 types                        |
| Additional stimuli for validation II                         | 8 different values in main test |
| Modulation depth MD, dB(A)                                   | 0, 2, 3, 4, 5, 6, 9, 12        |
| Sound level of masking noise, $L_{Aeq}$ dB(A)                 | 3 values plus                  |
|                                                              | 30, 35, 40                     |

Table 6.3 Stimuli design parameters for Final Test

### 6.5 Participant recruitment and screening

#### 6.5.1 Sensitivity tests

For the two sets of sensitivity tests, the participants were directly recruited from the staff and student population of the Acoustics Research Centre at the University of Salford by email and word of mouth. As these tests were designed to identify the physical modulation parameters that can be significantly distinguished, there was felt not to be a need to aim for a representative population sample. Because of the preliminary nature of the sensitivity tests participant details for these were not recorded. The expected higher number of expert listeners in an acoustic department can be an advantage in that situation. For the Sensitivity Test I, 5 students from local secondary schools who were on a work placement and 8 postgraduate students from the Acoustics Research Centre at the University of Salford volunteered as participants. And for Sensitivity Test II, 11 postgraduate students and staff members students from the Acoustics Research Centre at the University of Salford volunteered as participants. The number of participants in the sensitivity tests was large
enough to test stimuli design and rating procedures and to decide which modulation parameters dominate the response. The number was too small to be used for statistical analysis.

6.5.2 Final tests

For the final tests the sampled population was initially contacted via an article placed on the main University of Salford website and the separate websites for the staff and students at the university in September and another article in late November 2011 to increase participant numbers. The articles are detailed in Appendix I. The articles explicitly mention wind turbine noise in an attempt to attract attention. While this has the potential disadvantage of the attitude towards the source affecting judgements this could not be avoided as the stimuli would have been likely to be identified as wind turbines by several participant in any case. The article mentioned that volunteers for participation were requested and that they would be paid. It also mentioned that participation was subject to a screening procedure. This procedure entailed the volunteer providing their names, age, nationality, occupation, sex, and previous listening test experience; then volunteers completed several multiple-choice questions about the type of area they live in (see Appendix II). Participant details were recorded but kept confidential. Non-leading questions were used to prevent responders to the advert from falsely claiming to belong to the population of interest.

In comparison to some of the studies referenced in Section 5, the noise sensitivity of volunteers was assessed in the screening procedure by the Zimmer and Ellermeier short noise sensitivity measure (Appendix II). This is a 9-item self-reported questionnaire that asked the participant to either strongly agree, slightly agree, slightly disagree or strongly disagree with statements about disruptions caused by everyday noises. This was deemed a useful measure as an individual’s sensitivity to noise may influence how annoying they perceive sounds to be [28] and would therefore inform the choice of participants.

![Graph showing Zimmer-Ellermeier Score distribution](image)
Figure 6.3 Zimmer and Ellermeier noise sensitivity score distribution for participants (final tests).

The sensitivity distribution in Figure 6.3 has a similar mean value as for the participants in [5] which was 49.8. The distribution is very different though with six participants being very sensitive to noise as seen by their high scores and 5 participants being very insensitive.

Another criterion for participant selection was that their hearing was not impaired. This aimed to recruit participants with ‘normal’ hearing for their age, rather than a sample of particularly sensitive or impaired hearing participants and was necessary because some stimuli were close to the hearing threshold. If not heard, the results for these stimuli would have been meaningless. Additionally to choosing participants on their assertion that they were of normal hearing, an audiometric test was performed for each participant confirming that all volunteers were of normal hearing and nobody needed to be excluded because of significant hearing loss.

A total of 20 volunteers, 8 female and 12 male, participated in the final tests. The age distribution is centred between 20 and 30 as shown Figure 6.4a) with only 6 participants in their mid-thirties and beyond.

A subgroup of 11 volunteers, 4 female and 7 male, participated in the first validation of the final test. The age distribution is mainly centred between 20 and 30 as shown in Figure 6.4b) with only two participants older than 40 years. Another subgroup of 9 volunteers 4 female and 5 male, took part in the second validation of the final test (Figure 6.4c).
6.5.3 Participant protection

The data set from the screening process contained potentially sensitive personal information. Therefore it was stored in password protected spreadsheets on a secure server that was only accessible by project staff. No other copies were kept. Outside these files participant information was made anonymous by the use of ID numbers; therefore the data could only be traced back to the participant via the protected spreadsheet. Informed consent forms as specified in Appendix I were signed by each participant in accordance with standard University procedures.

6.6 Participant briefing

6.6.1 Sensitivity Tests

Participants were given the test sheets (Figure 18.1 and Figure 18.2), and told to put headphones on. Headphone positions were checked. Stimuli of 10 second length were presented in a looped configuration using the Windows™ Media Player. The listening time for each stimulus was therefore controlled by the participants. Participants were then instructed to listen to the garden noise stimulus and told that the stimulus represents the sound of wind in trees and bushes. There was no aim in these tests to closely represent the
situation of a resident relaxing in his garden, as all were done in a standard university computer music room, and the tests therefore focused on the comparative effect of different stimuli parameters. Using the onscreen volume slider participants were instructed to adjust the level until the sound was reflective of conditions in which they would spend time in their garden relaxing, but still audible. The level adjustment resulted in a range of stimuli $L_{Aeq}$ shown in Figure 8.1. It was useful because it avoided the situation when a participant felt the stimuli to be very unrealistic and therefore more difficult to rate for annoyance which had been found to be the case in [5]. The volume was subsequently not changed so that the $L_{Aeq}$ of all stimuli would be traceable relative to each other. After Sensitivity Test I, it was recognised that the information of $L_{Aeq}$ for every participant was required for data analysis and participants were told make a note of the volume in Sensitivity Test II.

In both tests participants were then asked to rate on a numerical scale between 0 and 10 (Figure 18.1 and Figure 18.2) how annoying the garden noise was if they were sitting in their garden trying to relax after a hard day’s work. The rating scale was similar but not identical to the standard rating scale [24] in that the maximum rating was described as “very annoying” in contrast to the “extremely annoying” suggested in the standard but in agreement with studies like [4]. The context information was given to make the ratings as similar as possible to ratings that would occur in the participant’s home environment. The garden noise served as a reference to compare responses between a noise that is usually experienced as pleasant to responses to noises that are known to attract complaints. The annoyance rating of garden noise was introduced as a measure of how difficult participants found it to imagine a pleasant noise in a laboratory environment. This was in case they were not able to make the sound ‘not at all annoying’.

The stimuli were then presented to participants in random order which is important to avoid fatigue bias$^{10}$. Participants were asked to rate the stimuli on the same scale and in the same context as the garden noise. Therefore the response to garden noise became the reference to which all other responses could be compared.

Due to the random order of stimuli presentation a participant might listen to a number of, for example, very quiet stimuli to start with and then realise that their ratings for the very loud stimuli would not fit within the scale. Therefore participants were given the option to manually select stimuli to re-listen to any sounds and amend prior ratings. The importance of not

$^{10}$ An effect on the statistical data analysis from systematically different ratings between the beginning and the end of a test.
listening to the sounds in alphabetical order by manual selection was pointed out to participants.

### 6.6.2 Final Test

When volunteers first arrived they were instructed to do a standard audiometric test to ensure their hearing was adequate for participation. They were then shown into the listening room where they were handed an instruction sheet (Figure 18.3). When they were ready to start, stimuli were played back using a setup shown in Figure 15.1 and described in more detail in Appendices IV and V and [5] including pictures of the room in its final set up. The room was set up to try and approximate the feel of an outdoor amenity area used for relaxation. The participant was facing the direction from which the wind turbine sound was played from the front loudspeaker as shown in Figure 15.1. When garden noise was added, the sound was produced from all loudspeakers to make the directional impression as authentic as possible by making it immersive.

Participants used a touch screen to rate the annoyance of stimuli and adjust levels of the unmodulated ABBS to equal annoyance level as shown in the graphical user interface (Figure 6.5). The 20 second stimuli were looped and the total listening time for each stimulus was controlled by the participant. To test the different responses for sliding scales and for equally annoying ABBS the participants were asked to:

- first directly rate the annoyance of a sound on the sliding scale (*scaling magnitude estimation*) which resulted in annoyance ratings from 0 to 10 on a numerical scale;
- then for the same stimulus, adjust the ABBS level so that the (un-modulated) sound becomes equally annoying to the AM test sound (*paired comparison method*).

The rating scale in Figure 6.5 is an 11 point scale like the one used in the sensitivity tests but instead of discrete values a continuous slider was implemented for ease of use.

Participants started the test off with practice ratings until they were comfortable with the task and decided to go on to the main test. Stimuli were then presented in random order, which changed for each participant. The listening test procedure is outlined in further detail in Appendix II.
Figure 6.5: Graphical user interface for final test. Participants were first asked to rate the annoyance of the AM test sound on the sliding scale in the top of the window and to then adjust the level of the ABBS (Reference Sound in the GUI) to match the annoyance of the AM test sound.

7. Results of Sensitivity Test I

To assess the sensitivity of participants to a subset of the possible modulation parameters that can vary in the model of WTN AM produced, a fast test procedure using the annoyance scale method and calibrated headphones was designed, and two preliminary sensitivity studies were conducted.

In Sensitivity Test I results of participant annoyance ratings are shown as a function of a very limited number of modulation parameters to demonstrate the viability of the stimuli design and sound reproduction method (Section 6). Some initial conclusions on sensitivity to the modulation parameters are drawn.

The sensitivity tests were designed using the amplitude related model input parameter $\alpha$ defined in Section 6.1. However, a simple modulation depth (MD) metric, based on A-weighted 100 ms $L_{100}$ averages peak-trough levels (see 17.4) seemed more useful (in a first instance) to provide context to participant responses, because this measure is expected to be more directly related to the frequency response of the ear. Although the test stimuli were
not designed for equal distribution of this parameter, for consistency with the following sections, results are displayed as a function of MD.

It was observed that participants in their first task adjusted garden noise sound levels to very different values in their judgement of what sounded natural. The range was from just audible to medium levels. Because the level was not changed subsequently all other judgements were relative to this garden noise level.

In Figure 7.1 the mean annoyance score ranged between 3 and 4 and rose to a value of 7 for a modulation depth of 8 dB(A). Increasing annoyance scores with increasing modulation depth have also been found by other authors ([15] and [16]). This result is also in agreement with theory on psychoacoustic annoyance which increases with fluctuation strength [9].

The error bars in Figure 7.1 and all subsequent figures represent 95 % confidence intervals (CI)\(^{11}\). With a range of about two points on the rating scale they are relatively large in this case. There are three possible reasons for their size. Firstly the number of participants was small. Secondly every participant had chosen their individual reproduction volume. And lastly affective responses are generally influenced not only by the sound characteristics but potentially by many other factors as pointed out in Section 5. The error bars for very small

---

\(^{11}\) A 95 % confidence interval is an interval in which a measurement or trial falls corresponding to a 95 % probability
and large modulation depths do not overlap. This suggests that the rise in annoyance is possibly significant.

Because of the stimuli design, signal energy/loudness increases with modulation depth. But it was noted that the rise in annoyance could be due either to the change in modulation depth or to the increase in signal energy/loudness. The error bars are also too large to conclude whether annoyance ratings start to increase from a particular modulation depth or whether the increase is continuous from the lowest modulation depth. [9] suggest that there should be a "threshold" modulation depth which is at the limit of perception and a continuous increase of annoyance above that threshold. However, a wind turbine related study [14] reports that Fastl and Zwicker's metric was not sufficient to explain annoyance ratings.

Figure 7.2 shows the annoyance ratings as a function of signal shape. The change in rise time proportion ranged from 10 – 90 %, from a sharp saw-tooth signal (<50%), to symmetric pulse (50%), to a saw-tooth in the other direction (>50%). The modulation depth of the stimuli was constant at 1.7±0.2 dB(A). Annoyance was rated at values between 3.8 and 4.5 but a trend is not obvious. This is clear from the 95% confidence intervals. . The average annoyance at 80% rise time was slightly higher than other values but the large error bars suggest that this is probably not reproducible. The rating could well be due to temporal masking effects where a change in modulation can take up to 200 ms to be fully perceived [9] and therefore the difference between a stimulus with a rise time of 10 % can possibly not be distinguished from a stimulus with a rise time of 20 %. The relatively small modulation depth might also have contributed to difficulties in distinguishing between stimuli of different envelope shapes. In spite of the small modulation depth used it seemed nevertheless unlikely that the envelope shape would influence annoyance strongly.

![Figure 7.2: Annoyance ratings as a function of signal shape.](image)
Figure 7.3 shows the statistics of annoyance versus pulse length. Most mean values were close to an annoyance rating of 4. The stimulus with 0.3 s pulse length was omitted because of an error in the signal design stage: that stimulus sounded quite different and could therefore not be compared with the others, and this was reflected in average participant ratings of 6. After exclusion of this erroneous stimulus, it can be seen that the effect of pulse length (and associated potential “impulsivity”) does not appear significant. This might possibly partly be due to temporal masking effects.

Figure 7.3: The effect of pulse width on annoyance.

7.1 Conclusions

The preliminary sensitivity tests focused on the following parameters: modulation depth, pulse shape and pulse width. The annoyance ratings showed a possible systematic sensitivity to modulation depth/signal amplitude, but the effect from the increased signal energy was not separated from that of the increased modulation level in itself. A low sensitivity to pulse shape and/or pulse width was found.

It has been observed that realistic noise levels of garden noise were difficult to judge in a laboratory environment as the values between participants varied widely. Exact levels were felt to be useful and monitoring was therefore implemented for Sensitivity Test II. The range of $L_{Aeq}$ was additionally restricted to realistic levels which will be discussed in the context of Sensitivity Test II results in Section 8.

The test design for further stages of the project was aimed at finding out which other modulation parameters might affect annoyance, evaluating the effect of increasing signal energy, and whether sensitivity to modulation depth varies linearly with modulation depth or is governed by threshold behaviour.
8. Results of Sensitivity Test II

While Sensitivity Test I focussed on the temporal characteristics of the modulated signal, Sensitivity Test II was designed to address the effect of relative levels of signal components and the frequency content of the stimuli.

In contrast to Sensitivity Test I, participants made a record of the volume level when they adjusted the playback volume on a scale from 0-100% to a level at which they judged the garden noise to sound realistic. It should be noted that following the observations in the first test, the volume range available to participants had been reduced considerably in comparison to Sensitivity Test I to avoid unrealistic choices. The average adjustment for the GN was therefore 40±4.5% of the volume slider length with the lowest value at 30% and the highest occurring at 70% which indicates that the chosen range was well within the expected level for a garden and reproduces the finding that realistic noise levels have been difficult to judge. This was probably not helped by the fact that they can vary widely in reality. The average annoyance ratings for this garden noise were 2.95±0.64 with a minimum of 0 and a maximum of 6. All other stimuli were judged relative to the garden noise level.

The range of stimuli $L_{Aeq}$ that resulted from the adjustment of GN is shown in Figure 8.1. The figure also contains the 95% CI resulting from participant adjustments which span about 2 dB(A). This is small due to the limited choice available to participants. It can be seen that the quietest stimuli were reproduced at an average $L_{Aeq}$ of just above 28 dB(A). Note that the choice of x-axis in Figure 8.1 is only a convenient way to categorise the stimuli and that therefore the $L_{Aeq}$ are not per se a function of modulation depth.

The room background noise level in the headphones was measured using the HATS system and was between $L_{Aeq} = 30 - 35$ dB(A). In effect, it has to be assumed that the annoyance ratings for the quietest stimuli were affected by the room background noise although the modulation was always audible. The average $L_{Aeq}$ values are therefore specified for all figures in this section.

The wide range of background levels is due to a number of factors, firstly the noise in the room depended on how many computers were operated at a particular time, secondly the volume of the external soundcards had to be adjusted manually to about 25% of the available volume range, thirdly the headphone efficiency had to be estimated and assumed to be identical for all headphones.
In this test, three different ways of varying the modulation depth were investigated for two types of modulation: MFAM and RFAM (see Section 6.4.2). This involved varying in turns: the modulation peak level (MPL), masking level (ML) and their relative ratio (MD). MD was also kept constant in one set of stimuli to control for the effect of the overall LAeq. The masking noise type, modulation spectra (frequency range and shape) and modulation frequency were also varied.

### 8.1.1 Stimuli set I: Fixed masking noise level

Firstly, the modulation peak level (MPL) was increased with constant masking noise. Data are summarised in Table 8.1. In Figure 8.2, the mean annoyance score is shown as a function of MD for the two types of stimulus (MFAM and RFAM) and two types of GN. GN was part of the masking noise which also contained WTN with an amplitude ratio of 1:5, respectively.

In the figure the "unmodulated" stimulus was the respective type of GN on its own with a natural modulation depth of about 1 dB(A) for both types of GN. These GN stimuli served as reference sounds to compare with the AM stimuli.
The average annoyance for AM stimuli ranged between 3 and 4 and rose to a value of 8 for MD = 15 dB(A). 95% CI for the red curve span 0.3 - 1 points (half the error bar) on the 11 point rating scale for AM stimuli and 2 points for the GN (shown as MD = 0 dB(A)). Note however that increasing modulation amplitude contributed to the increase of annoyance toward higher MD because of the increased acoustic energy in the stimuli. This can be seen in Table 8.1. The table also shows that the high annoyance ratings for the GN coincide with large values of LAeq.

<table>
<thead>
<tr>
<th></th>
<th>MD, dB(A)</th>
<th>L_Aeq, dB(A)</th>
<th>Rating</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>GN1</td>
<td>MFAM</td>
<td>GN1</td>
<td>38</td>
<td>3.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>34</td>
<td>4.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
<td>38</td>
<td>5.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12</td>
<td>40</td>
<td>7.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>44</td>
<td>8.1</td>
</tr>
<tr>
<td></td>
<td>RFAM</td>
<td>GN1</td>
<td>38</td>
<td>3.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>34</td>
<td>4.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
<td>38</td>
<td>5.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12</td>
<td>40</td>
<td>7.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>44</td>
<td>8.1</td>
</tr>
<tr>
<td>GN2</td>
<td>MFAM</td>
<td>GN2</td>
<td>40</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>37</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
<td>38</td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11</td>
<td>41</td>
<td>7.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>14</td>
<td>43</td>
<td>8.4</td>
</tr>
<tr>
<td></td>
<td>RFAM</td>
<td>GN2</td>
<td>40</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>38</td>
<td>7.4</td>
</tr>
</tbody>
</table>

Table 8.1 Stimuli data for which modulation peak level (MPL) was varied and the masking noise kept constant. L_Aeq, 95% CI = ±1 dB(A).

Although the general trend both for MFAM and RFAM in Figure 8.2 is a similar total increase with MD/MPL, it seems that the MFAM sounds increase in annoyance faster with MD than the RFAM. It is therefore possible that the response to RFAM and MFAM is significantly
different especially given that the relative stimulus $L_{Aeq}$ were comparable as seen in Table 8.1.

![Figure 8.2: Annoyance rating for fixed background noise level and increase in MD (and peak level) (as indicated by inset) for RFAM and MFAM compared.](image)

**8.1.2 Stimuli set II: fixed modulation depth**

Secondly, the stimulus $L_{Aeq}$ was increased at constant MD. Data are summarised in Table 8.2. In Figure 8.3, the mean annoyance score is shown as a function of $L_{Aeq}$ for the two types of stimulus MFAM and RFAM and two types of GN.
<table>
<thead>
<tr>
<th></th>
<th>MD, dB(A)</th>
<th>$L_{Aeq}$, dB(A)</th>
<th>Rating</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GN1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MFAM</td>
<td>8</td>
<td>32</td>
<td>4.8</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>35</td>
<td>5.6</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>38</td>
<td>5.6</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>41</td>
<td>6.8</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>44</td>
<td>7.3</td>
<td>0.8</td>
</tr>
<tr>
<td>RFAM</td>
<td>2</td>
<td>28</td>
<td>3.0</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>31</td>
<td>3.7</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>34</td>
<td>4.9</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>37</td>
<td>5.6</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>41</td>
<td>6.4</td>
<td>0.6</td>
</tr>
<tr>
<td><strong>GN2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MFAM</td>
<td>8</td>
<td>32</td>
<td>5.0</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>35</td>
<td>5.8</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>38</td>
<td>6.5</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>41</td>
<td>7.4</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>44</td>
<td>7.5</td>
<td>0.6</td>
</tr>
<tr>
<td>RFAM</td>
<td>2</td>
<td>30</td>
<td>3.6</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>33</td>
<td>4.4</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>36</td>
<td>5.0</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>39</td>
<td>5.6</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>42</td>
<td>6.8</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Table 8.2 Stimuli data for which the modulation peak level (MPL) and the masking noise were varied simultaneously to keep the modulation depth constant for each AM type.

$L_{Aeq}$ 95% CI = ±1 dB(A)
Figure 8.3: Annoyance rating for fixed MD of 8 dB(A) for MFAM and 2 dB(A) for RFAM and increasing background noise and peak level (as indicated by inset) resulting in a systematic change of overall L\text{Aeq} in steps of 3 dB(A).

The average annoyance for the 4 groups of AM stimuli consistently increased with L\text{Aeq}. 95% CI for the red curve span 0.5 - 1 points (half an error bar) on the 11 point rating scale for AM stimuli. MFAM ratings are higher than RFAM ratings. However the MD levels for the stimuli types are different too. Both levels of modulation were the same before A-weighting but turned out to be significantly different in the MD metric after A-weighting with MD = 2 dB(A) for RFAM stimuli and MD = 8 dB(A) for MFAM stimuli. This difference results from the different frequency spectra for RFAM and MFAM. Indeed, the MFAM stimuli has significantly more energy in region 600-1kHz which is near the peak of the A-weighting filter: see Section 17.3. The ratings for the two types of GN were very similar for this set of stimuli.

8.1.3 Stimuli set III: Fixed peak level

In a third set of stimuli the peak level was kept constant and MD was increased by decreasing the masking noise level. Data are summarised in Table 8.3. In Figure 8.4, the mean annoyance score is shown as a function of MD for the two types of stimulus (MFAM and RFAM) and two types of GN.
<table>
<thead>
<tr>
<th>MD, dB(A)</th>
<th>L_{Aeq}, dB(A)</th>
<th>Rating</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>GN1</td>
<td>MFAM</td>
<td>GN1</td>
<td>38</td>
</tr>
<tr>
<td>5</td>
<td>37</td>
<td>5.3</td>
<td>0.8</td>
</tr>
<tr>
<td>8</td>
<td>38</td>
<td>5.6</td>
<td>0.9</td>
</tr>
<tr>
<td>12</td>
<td>37</td>
<td>6.5</td>
<td>0.7</td>
</tr>
<tr>
<td>15</td>
<td>38</td>
<td>6.7</td>
<td>1.1</td>
</tr>
<tr>
<td>RFAM</td>
<td>GN1</td>
<td>38</td>
<td>3.6</td>
</tr>
<tr>
<td>1</td>
<td>37</td>
<td>4.2</td>
<td>0.9</td>
</tr>
<tr>
<td>2</td>
<td>34</td>
<td>4.9</td>
<td>0.7</td>
</tr>
<tr>
<td>4</td>
<td>33</td>
<td>5.1</td>
<td>0.9</td>
</tr>
<tr>
<td>6</td>
<td>31</td>
<td>5.2</td>
<td>0.7</td>
</tr>
<tr>
<td>GN2</td>
<td>MFAM</td>
<td>GN2</td>
<td>40</td>
</tr>
<tr>
<td>5</td>
<td>40</td>
<td>5.6</td>
<td>1.0</td>
</tr>
<tr>
<td>8</td>
<td>38</td>
<td>6.5</td>
<td>0.5</td>
</tr>
<tr>
<td>11</td>
<td>38</td>
<td>6.3</td>
<td>0.6</td>
</tr>
<tr>
<td>14</td>
<td>37</td>
<td>6.9</td>
<td>0.7</td>
</tr>
<tr>
<td>RFAM</td>
<td>GN2</td>
<td>40</td>
<td>4.7</td>
</tr>
<tr>
<td>1</td>
<td>38</td>
<td>4.6</td>
<td>0.9</td>
</tr>
<tr>
<td>2</td>
<td>36</td>
<td>5.0</td>
<td>0.8</td>
</tr>
<tr>
<td>3</td>
<td>34</td>
<td>5.9</td>
<td>0.6</td>
</tr>
<tr>
<td>5</td>
<td>32</td>
<td>6.0</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Table 8.3 Stimuli data for which the Modulation Depth was increased by decreasing the masking noise. MPL was kept constant. $L_{Aeq}$ 95% CI = ±1 dB(A)

Again the average annoyance for the 4 groups of AM stimuli consistently increased with $L_{Aeq}$. 95% CI are similar to the previous two graphs. In this graph the error bars overlap strongly and therefore the difference between RFAM and MFAM or GN1 and GN 2 is less clear than in the previous two graphs. For both RFAM and MFAM GN2 stimuli the increase levels off towards higher MD values. These were the stimuli with consistently decreasing $L_{Aeq}$ values. For the MFAM GN1 stimulus with its almost constant $L_{Aeq}$ the average annoyance ratings do increase steadily with increasing MD.
8.1.4 Comparison of sets I - III

Comparing the three stimuli sets the responses to the two types of stimuli, MFAM and RFAM, were very different. Some reasons for this have been pointed out but the relative effects on annoyance of $L_{Aeq}$ for the first and third stimuli sets and of MD for the second set remained unclear. Further testing was therefore required under more controlled test conditions to clarify the effect of modulation type on participant response.

The situation is similar for the role of GN noise. Figure 8.2 also shows that there was a systematic difference in the annoyance ratings of the stimuli with two difference garden noise types. While the stimuli with GN2 were on average about 1-2 dB(A) higher than the stimuli with GN1 (Table 8.1 Stimuli data for which modulation peak level (MPL) was varied and the masking noise kept constant. $L_{Aeq}$ 95% CI = ±1 dB(A).Table 8.1) this might not fully explain the increased annoyance ratings. Also the responses did not differ so clearly between the GN types in Figure 8.3 and Figure 8.4. It is therefore possible but not certain that the masking noise which was played at relatively low level (amplitude ratio between WTN masking and GN masking 5:1) could contribute significantly to the perception and the affective response to WTN. This would be expected as it is widely reported in the literature.
(e.g. [10] and [1]). Because GN varies widely both spatially and temporally it is however impossible to design a representative GN stimulus.

8.1.5 The role of $L_{\text{Aeq}}$ and MD compared

From the results in Figure 8.2 - Figure 8.4 it seems clear that major contributors to annoyance are the parameters $L_{\text{Aeq}}$ and MD. Therefore the average annoyance ratings for all stimuli have been plotted versus these parameters in Figure 8.5 a) and b) to get an impression about the strength of the correlation. When fitting a linear function through the data the slope of the line shows that the ratings increased on average faster within a typical range of $L_{\text{Aeq}}$ than within a typical range of MD values. The spread of the data around the fit was comparable for the two plots.
8.1.6 Stimuli set IV: spectral characteristics

In a fourth set of stimuli the frequency content namely the bandwidth and the frequency skew were changed for both AM types as shown in Table 8.4. Figure 8.6 shows the average annoyance rating as a function of pulse bandwidth. The variation in the average ratings are as small as 0.6 points on the rating scale for each of the AM types. It is therefore concluded that there is no significant dependence for annoyance on the bandwidth/frequency skew of
the modulation. MFAM ratings are higher than ratings of RFAM stimuli. This can be attributed to both the higher average L_{Aeq} and the higher MD value of the MFAM stimulus.

<table>
<thead>
<tr>
<th>BW, Hz</th>
<th>Skew, %</th>
<th>MD, dB(A)</th>
<th>L_{Aeq}, dB(A)</th>
<th>Rating</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>RFAM</td>
<td>300</td>
<td>2</td>
<td>35</td>
<td>5.6</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>2</td>
<td>34</td>
<td>4.9</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>2</td>
<td>36</td>
<td>5.2</td>
<td>0.9</td>
</tr>
<tr>
<td>MFAM</td>
<td>250</td>
<td>10</td>
<td>39</td>
<td>6.3</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>350</td>
<td>8</td>
<td>38</td>
<td>5.6</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>450</td>
<td>8</td>
<td>38</td>
<td>5.7</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Table 8.4 Stimuli data for which bandwidth was varied. L_{Aeq} 95% CI = ±1 dB(A)

Figure 8.6: Annoyance rating as a function of pulse bandwidth and frequency skew for RFAM and MFAM compared.

### 8.1.7 Stimuli set V: modulation frequency

The last set of stimuli explore the effect of modulation frequency on annoyance ratings using two modulation periods of 0.65 sec and 1.3 sec. Test data are summarised in Table 8.5

Figure 8.7 shows the average annoyance rating as a function of MD for both RFAM and MFAM stimuli. The stimuli with shorter modulation period are rated consistently higher than the ones with a 1.3 sec period. In fact the contour lines are very nearly parallel. It is not
surprising that the high frequency modulation which according to [9] increases fluctuation strength in this frequency range is therefore more annoying than the lower modulation frequency. The peak in fluctuation strength would be expected at a modulation period of 0.25 sec. The variation in the average ratings ranges from 0.7 to 1.1 and is therefore small for all stimuli. Because MD was varied by dropping the MN level the effects of MD and $L_{Aeq}$ might partly cancel each other out as seemed to be the case in Figure 8.4.

<table>
<thead>
<tr>
<th>Period, sec</th>
<th>MD, dB(A)</th>
<th>$L_{Aeq}$ dB(A)</th>
<th>Rating</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.65 RFAM</td>
<td>1</td>
<td>38</td>
<td>6.4</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>35</td>
<td>7.0</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>34</td>
<td>7.1</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>MFAM 5</td>
<td>40</td>
<td>7.6</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>39</td>
<td>7.8</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>38</td>
<td>8.5</td>
<td>1.2</td>
</tr>
<tr>
<td>1.3 RFAM</td>
<td>1</td>
<td>37</td>
<td>5.0</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>34</td>
<td>5.6</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>33</td>
<td>5.8</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>MFAM 5</td>
<td>37</td>
<td>6.1</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>38</td>
<td>6.3</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>37</td>
<td>7.2</td>
<td>1.1</td>
</tr>
</tbody>
</table>

Table 8.5 Stimuli data for two modulation frequencies (here expressed as modulation period). $L_{Aeq}$ 95% CI = ±1

Figure 8.7: Annoyance rating as a function of MD for two modulation frequencies and for RFAM and MFAM compared.
Figure 8.7 shows a distinct difference between the higher and lower modulation frequency but not a strong dependence on MD for the two different types of modulation. Within the model from [9] the fluctuation increases as the modulation frequency get closer to 4 Hz. Therefore it is not surprising that the annoyance is significantly higher for shorter modulation periods, i.e. higher modulation frequencies.

8.2 Conclusions

Although it seemed possible that in principle signal properties Modulation Depth, Modulation Peak Level, and Masking Level could be separated in their effect on annoyance, the main effects on annoyance were seen from varying the stimuli parameters $L_{Aeq}$ and MD. Therefore a more straightforward method seemed to be to fix the $L_{Aeq}$ for each set of stimuli. This method would also allow a direct comparison with previous studies. The exact bandwidth of the amplitude modulation seemed to have little effect on annoyance and it was therefore decided that these parameters would not be included in the final tests. Because the evidence on garden noise and AM type was not clear it was decided to initially focus on RFAM stimuli without GN but to include validation stimuli to part of the test for one type of garden noise and for MFAM. A systematic analysis of the role of modulation frequency would have been possible but because it is probably sufficiently described by the existing Fastl and Zwicker's metrics for fluctuation strength it was decided to focus on modulation at a fixed frequency of less than 1Hz, representative of typical of large modern wind turbines.

For the final tests it was therefore decided to use RFAM stimuli at 3 $L_{Aeq}$ levels of 30, 35, 40 dB(A) and 12 different MD values (1, 2, 2.5, 3, 3.5, 4, 4.5, 5, 6, 7, 9, 12 dB(A)). The validation studies included also a subset of MFAM stimuli and one with garden noise masking.
9. Results of Final Test

The final tests were conducted under tightly controlled conditions in a calibrated listening room to optimise the accuracy of modulation parameters and realistic reproduction of outdoor stimuli. During the test procedure two rating methods were used. The first was an 11 point annoyance rating scale for easy comparison with previous studies. The second was a comparative rating method modelled on a procedure used in [5]: An un-modulated wind turbine sound (ABBS) was adjusted in $L_{Aeq}$ to be as annoying as a modulated AM test stimulus that was based on the same spectrum as the ABBS. The procedure is described in more detail in Sections 6.5.2, 6.6.2 and 18.3. This adjustment procedure was used to directly answer the question how much the $L_{Aeq}$ of the ABBS needs to increase to be equally annoying to a quieter AM stimulus. This type of information has previously been inferred from absolute annoyance ratings and has led to widely different results.

To keep the tests as simple as possible and within a manageable time for the participants the results focussed initially (Sections 9.1 - 9.3) on RFAM stimuli with WT masking noise and without the addition of garden noise (parameters in bold in Table 6.3). The results of Validation Test I are presented in Section 9.4 for comparison to show whether significantly different responses are expected from MFAM stimuli or for the addition of low levels of garden noise. Section 9.5 addresses the question whether the perception of stimuli is significantly different when the masking noise level is kept constant in comparison to the method of the Final Test where MN levels are dropped with increasing MD to achieve constant $L_{Aeq}$. The stimuli generation and detailed choice of parameters are described in Table 6.3 Section 6 and Appendix V.

9.1 Rating distributions

Figure 9.1 shows an overview over the general rating behaviour of all participants and stimuli that were included in the Final Test. Part a) shows the rating distribution for the annoyance ratings on the 11 point rating scale. A polarised rating behaviour was observed where the ratings 0 (not at all annoyed) dominated and the number of ratings towards higher annoyance values generally decreased. This is expected as many stimuli were fairly quiet and the low modulation depths were included.
Part b) contains the L\textsubscript{Aeq} adjustments of the ABBS minus the L\textsubscript{Aeq} of the stimuli. In contrast Figure b) shows a near Gaussian distribution around the mean value of 2.3 dB(A). This is evidence that ABBS L\textsubscript{Aeq} were on average adjusted to higher values than the AM L\textsubscript{Aeq} and therefore AM stimuli (RFAM) were generally rated as being more annoying than the ABBS. Interestingly, there are negative values of up to -11 dB(A) among those ratings which might be an indication that participants found the adjustment task difficult.

![Figure 9.1 Distribution of ratings a) for absolute annoyance scale, b) for the difference in L\textsubscript{Aeq} between the unmodulated ABBS and AM stimuli.](image)

The rating behaviour for the validation tests is plotted in Figure 20.1 and Figure 21.1. The distributions are very similar which is a first indicator that validation test stimuli were perceived to be similarly annoying to stimuli in the final test.

### 9.2 Annoyance ratings grouped by lines of constant MD

Using the 11 point scale for absolute annoyance ratings in the final listening tests allowed plotting the annoyance ratings as a function of L\textsubscript{Aeq} in groups of MD (Figure 9.2, tabulated results in Table 23.1). This presentation is in a similar form to published results [15]. Figure 9.2 shows that mean annoyance ratings consistently increase with the L\textsubscript{Aeq} of the AM stimuli (RFAM). Un-modulated stimuli were clearly rated as less annoying than modulated stimuli. A systematic increase with modulation depth is also apparent although some of the ratings overlap especially at higher L\textsubscript{Aeq} values. This can be explained by results from [12] who found that it was difficult for listeners to correctly identify the change in modulation depth in a signal. Therefore when perception of these changes is difficult it is not surprising that annoyance ratings show similar inconsistency. The error bars denote 95% confidence intervals (CI). They are smaller than one point on the annoyance rating scale for low L\textsubscript{Aeq}. 
and low MD. At high $L_{\text{Aeq}}$ and MD the error bars span up to 2.2 points (25%) of the rating scale which is a large value but not unexpected for an attitudinal parameter like annoyance. The statistical significance of the result in the presence of large error bars is further discussed in the context of Figure 9.3.

Figure 9.2 Mean annoyance rating of AM test stimuli as a function of modulation depth. Solid lines are results from final test, dotted lines from the validation tests with reduced participant numbers. The legend specifies MD. See data in Table 22.1.

A similar study [15] showed results with similar general features like the strong increase in annoyance ratings with $L_{\text{Aeq}}$ and less pronounced and sometimes overlapping ratings with increasing modulation factor.

Because Lee et al. used a different metric for modulation depth their results cannot be directly compared. The authors did not compare ratings to un-modulated signals. Lee et al. used the standard 11 point scale according to [24]. They found minimum annoyance ratings of 1.5/2.5 and maximum annoyance ratings around 7/8 for two different tests, respectively. The minimum values in the current study are lower because stimuli with lower $L_{\text{Aeq}}$ values were included. The maximum values are similar to results in Figure 9.2 which is surprising because Lee et al. included $L_{\text{Aeq}}$ values of up to 55 dB(A) in comparison to the 45 dB(A) used in the current study. This can possibly be explained by the descriptors used for the maximum annoyance rating was "very annoyed" in the current study and "extremely annoyed" for the study by Lee et al.
9.3 Ratings as a function of modulation depth

Figure 9.3 Absolute annoyance ratings of AM stimuli as a function of modulation depth. Solid lines are results from final test, dotted lines from the validation tests with reduced participant numbers. The legend specifies the $L_{Aeq}$ of the test stimuli in dB(A). See data in Table 22.1.

Figure 9.3 shows the mean annoyance ratings as a function of modulation depth with isolines of $L_{Aeq}$ to bring out any MD related trends more clearly. Like in Figure 9.2 it can be seen that $L_{Aeq}$ levels clearly change the average annoyance ratings and at the lowest $L_{Aeq}$ the stimuli are the least annoying. In comparison modulation depth increased the mean ratings only slightly which given the large error bars is statistically insignificant. A clear onset of annoyance with modulation depth is not apparent from the Figure. 95% CI are large as expected for an attitudinal parameter like annoyance.

To assess the significance of increased annoyance ratings, statistical analysis using a GLM ANOVA (e.g. [25] or [26]) has been performed using SPSS™. The results suggest that $L_{Aeq}$ increases annoyance significantly whereas the modulation depth does not with current numbers of participants. Given the consistent increase of annoyance ratings with MD it seems likely that a small but significant effect would be found with a larger number of participants. Beyond 6 dB(A) the curves seem to flatten off for $L_{Aeq}$ of 25, 30 and 35 dB(A). A similar decrease albeit with much less data has been observed [16] for low frequency AM broadband noise. [16] then go on to interpret results from absolute annoyance ratings to find equivalent levels of unmodulated sound. A more direct approach was taken in this study by posing the question:
"To which L_{Aeq} would a typical broadband WTN have to be adjusted to be as annoying as an AM stimulus of a certain L_{Aeq} and MD?" Therefore the participants were asked to adjust in volume an Adaptive BroadBand Stimulus (ABBS) until it was as annoying as the modulated sound. The ABBS was identical to the AM stimulus at 0 dB(A) modulation depth.

![Figure 9.4 ABBS level adjustments in comparison to AM stimuli as a function of modulation depth – Solid lines are results from final test, dotted lines from the validation tests with reduced participant numbers. The legend specifies the L_{Aeq} of the test stimuli in dB(A).](image)

In that task the ABBS were adjusted to levels close to and generally slightly above the L_{Aeq} of the AM stimulus (Figure 9.4, Table 23.2) indicating that L_{Aeq} increases annoyance in accordance with Figure 9.2 and Figure 9.3. However, the ratings for increasing MD show a slightly different rating behaviour as the line of equal ABBS L_{Aeq} appear rather flat. The adjusted levels therefore did not increase with statistical significance between 2 and 12 dB(A) modulation depths. They also increased only slightly between 0 and 2 dB(A) modulation depth. Like in Figure 9.3 a clear onset of annoyance with modulation depth is therefore not apparent.

It would be easy to think that the results from the two rating procedures plotted in Figure 9.3 (small but consistent increase of annoyance rating with MD) and Figure 9.4 (no increase of adjusted levels with MD for most L_{Aeq}) are contradictory. However, it is worth pointing out that the tasks were very different in that one rated annoyance directly and the other an equivalent level of an unmodulated WTN. And the results in both, Sensitivity Test I and the Final Test have shown that annoyance increases more strongly with L_{Aeq} than with MD. So while annoyance might be consistently but slightly increasing with MD for an AM stimulus, an
unmodulated sound at an ABBS $L_{\text{Aeq}}$ as shown in Figure 9.4 might be sufficient to account for the increased annoyance from AM.

The adjustments for quieter stimuli tended to be larger than for louder stimuli as seen in Figure 9.5 (Table 23.3). That figure shows the adjustments as the difference between the ABBS $L_{\text{Aeq}}$ and the $L_{\text{Aeq}}$ of the AM stimulus. On average the adjustments are about 2.3 dB(A) and mean maximum adjustments exceed 5 dB(A) only for the quietest stimuli. With a range from 0.8 – 3.2 dB(A) the 95% CI are the same size of as in Figure 9.4 and only appear to be larger because of the different scale.

![Figure 9.5 Normalised relative annoyance ratings of AM stimuli as a function of modulation depth. Solid lines are results from final test, dotted lines from the validation tests with reduced participant numbers.](image)

At 0 dB(A) modulation depth the adjustments were expected to be around $L_{\text{Aeq}} = 0$ dB(A) too as the two stimuli were identical. This is however not the case. Quieter stimuli were adjusted to higher levels such as a 2 dB(A) higher adjustment than the 25 dB(A) AM stimulus. And for the louder stimuli the level adjustment was on average 2 dB(A) lower than the AM stimulus $L_{\text{Aeq}}$. This confirms a participant observation from Section 19.1 stating that levels were hard to judge. Also participants might have felt the need to always make adjustments in the belief that the AM stimuli must be different from the ABBS.
9.4 Validation test I

In Validation Test I the questions were addressed whether different rating behaviour was expected from stimuli that were also masked by garden noise and from MFAM stimuli. The results of rating distributions, absolute ratings and ABBS ratings are displayed in the Appendix, Section 20.

Figure 20.2 shows absolute annoyance ratings for stimuli without garden noise (top panels) and with garden noise (bottom panels) and for RFAM type stimuli (left panels) and MFAM type stimulus (right panels). For all four combinations the annoyance ratings were very similar. $L_{Aeq}$ levels clearly changed the average annoyance ratings whereas modulation depth increased the ratings only slightly. The increase of annoyance with modulation depth seemed steeper for the lowest $L_{Aeq}$ than for the highest when garden noise was added. It should be pointed out that GN was reproduced at $L_{Aeq} = 7.5$ dB(A) below the $L_{Aeq}$ of the AM test stimulus. It was therefore loud enough to change the character of the stimulus but too quiet to make the AM noise less audible. In reality there are often situations with high levels of GN that mask the AM stimulus partially or completely.

In agreement with the results from in previous sections a clear onset of annoyance with modulation depth is not apparent and the size of the 95% confidence intervals is comparable to RFAM stimuli without GN. Because of the similarity of the results the types of AM and the presence/absence of garden noise were not thought to produce different responses of statistical significance and the possible effects seen in Sensitivity Test II were most likely the result of poor control of the $L_{Aeq}$ and modulation parameters in the headphone reproduction.

9.5 Validation Test II

One concern with stimuli of constant $L_{Aeq}$ was that to keep the level constant with increasing MD the masking noise had to be reduced which might have led to changes in signal character. In Validation Test II (Section 21) a subgroup of nine participants therefore also rated a set of stimuli with the same MD levels and masking levels of 25, 30, 35 and 40 dB(A). They used the procedure of adjusting ABBS for this test because an equivalent result to Figure 9.5 could be produced using the total measured $L_{Aeq}$ of the stimuli to normalise the ABBS values. If these relative annoyance ratings changed significantly then this would be evidence of a perceptible change in signal character.
In general the rating behaviour of the participants shown in Figure 21.2 was very similar for the two sets of stimuli. Figure 21.2 a) and c) show the absolute ABBS \(L_{Aeq}\) for the constant stimulus \(L_{Aeq}\) and the constant masking noise \(L_{Aeq}\) stimuli, respectively. The monotonous increase of the rating with modulation depth is evidence that the participants adjusted the louder stimuli to slightly higher ABBS \(L_{Aeq}\) compared to a).

Figure 21.2 b) and d) show the difference between ABBS and RFAM \(L_{Aeq}\). Importantly, the increase of \(L_{Aeq}\) due to the increasing MD was measured and the correct total stimulus \(L_{Aeq}\) was used to calculate this difference. Therefore if the nature of the stimuli changed by reducing masking noise then a difference between b) and d) should be seen. However, within the 95% confidence intervals b) and d) are very similar which suggests that by the nature of the stimuli is not changed significantly in terms of annoyance when reducing the masking noise to retain the total \(L_{Aeq}\).

9.6 \(L_{A90}\) analysis

All sound levels have so far been expressed as \(L_{Aeq}\) values whereas another common measure is \(L_{A90}\). In Section 22, Figure 9.2 and Figure 9.5 have been compared to the respective \(L_{A90}\) equivalents. The increase in annoyance ratings with increasing MD is clearly visible in Figure 9.2 and in Figure 22.1 b). The difference between the two measures only becomes significant at \(MD \geq 9\) dB(A) when \(L_{A90}\) suggests that the contribution of AM to annoyance might be larger than suggested by the \(L_{Aeq}\) measure. This is because \(L_{A90}\) is lower by up to 7 dB(A) at MD = 12 dB(A). It should be noted though that MD has rarely been observed to exceed 10 dB(A) (see WPC).

Figure 22.2 shows normalised ABBS levels a) as \(L_{Aeq}\) and b) as \(L_{A90}\). Note that the legend identifies the "design" \(L_{Aeq}\) for each group of stimuli for both Figure 22.2 a) and b). When measured in \(L_{A90}\) the normalised ABBS increase almost linearly with MD although the higher levels suggest a flattening of the curve from an MD of about 3dB(A). In summary \(L_{A90}\) might be a suitable parameter to express annoyance ratings in the psychoacoustic context and should be investigated more closely in future studies.

9.7 Interpretation of results

In its adjustment procedure the current study did not follow the common approach to quote the percentage of annoyed listeners. While this is often a very useful method when the occurrence of this type of noise is common enough to enable a large scale survey study in
the affected neighbourhoods it is difficult to use in this context where the observations of AM are still too rare for such a study. The annoyance ratings derived from the laboratory study cannot be directly interpreted in these terms because the ratings are taken out of context so that absolute ratings can only be interpreted relative to each other.

9.8 Comparison of different metrics for modulation depths and fluctuation strength

The MD metric, based on review of short-term $L_{Aeq}$ levels, was principally used to design a representative set of test stimuli, but it is not necessarily one that particularly relates to subjective response; however, WPB1 pointed out the complexities and pitfalls with these types of metrics, both given the uncertainties in reading the peaks and troughs values and in their application to general, realistic signals. The procedure described in Section 17.4 uses an averaging process which will work reasonably well given that the stimuli are artificially generated and are consistent in time, but inevitably some uncertainty will remain.

The results above were therefore analysed using other, more robust and generalised metrics, in addition to the MD as evaluated from $L_{Aeq100ms}$ signals:

- Method 1 described in WPB1: Fourier transform of signal envelope, with/without signal low-pass filtering below 500 Hz, and noise-referenced (normalised). The second method described in WPB1 gave similar results and is not considered further.
- The main metric analysis method described in WPBF, which is similar to method 1 of WPB1 but with alternative normalisation factors (peak modulation in modulation spectrum)
- The psychoacoustics Fluctuation Strength Metric, based on [9], as evaluated in an implementation in the 01dB dBSonic software, either the calculated average or peak level of the calculated Fluctuation Strength over the 20 s stimuli recording.

The comparative values are detailed in Table 9.1 and Table 9.2.

12 [http://www.01db-metravib.com/nvh-instruments.477/dbsonic-psychoacoustic-software.558/?L=1](http://www.01db-metravib.com/nvh-instruments.477/dbsonic-psychoacoustic-software.558/?L=1)
### Table 9.1 Comparison of modulation magnitude values (dB) resulting from the metrics based on physical signal properties.

<table>
<thead>
<tr>
<th>MD ($L_{Aeq}$)</th>
<th>Main routine (WPBF)</th>
<th>WPB1 (full band, noise ref.)</th>
<th>WPB1, (0-500Hz, noise ref.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.6</td>
<td>7.3</td>
<td>4.8</td>
</tr>
<tr>
<td>2</td>
<td>1.0</td>
<td>10.8</td>
<td>9.2</td>
</tr>
<tr>
<td>2.5</td>
<td>1.4</td>
<td>15.3</td>
<td>13.1</td>
</tr>
<tr>
<td>3</td>
<td>2.0</td>
<td>19.1</td>
<td>17.1</td>
</tr>
<tr>
<td>3.5</td>
<td>2.3</td>
<td>20.3</td>
<td>18.0</td>
</tr>
<tr>
<td>4</td>
<td>3.1</td>
<td>22.8</td>
<td>20.5</td>
</tr>
<tr>
<td>4.5</td>
<td>3.3</td>
<td>23.5</td>
<td>21.5</td>
</tr>
<tr>
<td>5</td>
<td>3.8</td>
<td>25.2</td>
<td>23.0</td>
</tr>
<tr>
<td>6</td>
<td>4.8</td>
<td>27.4</td>
<td>25.1</td>
</tr>
<tr>
<td>7</td>
<td>5.7</td>
<td>29.9</td>
<td>27.5</td>
</tr>
<tr>
<td>9</td>
<td>7.8</td>
<td>33.8</td>
<td>31.4</td>
</tr>
<tr>
<td>12</td>
<td>11.2</td>
<td>39.2</td>
<td>36.5</td>
</tr>
</tbody>
</table>

### Table 9.2 Comparison of fluctuation strength values.

<table>
<thead>
<tr>
<th>MD(dB)</th>
<th>$L_{Aeq,100ms}$</th>
<th>Fluctuation strength (cVacil) 40 dB(A)</th>
<th>Fluctuation strength (cVacil) 30 dB(A)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>max</td>
<td>Mean</td>
</tr>
<tr>
<td>1</td>
<td>1.4</td>
<td>1.3</td>
<td>0.9</td>
</tr>
<tr>
<td>2</td>
<td>1.6</td>
<td>1.3</td>
<td>1.4</td>
</tr>
<tr>
<td>2.5</td>
<td>1.7</td>
<td>1.4</td>
<td>1.6</td>
</tr>
<tr>
<td>3</td>
<td>2.5</td>
<td>1.6</td>
<td>1.2</td>
</tr>
<tr>
<td>3.5</td>
<td>2.5</td>
<td>1.9</td>
<td>1.2</td>
</tr>
<tr>
<td>4</td>
<td>2.7</td>
<td>2</td>
<td>1.3</td>
</tr>
<tr>
<td>4.5</td>
<td>2.8</td>
<td>2.2</td>
<td>1.4</td>
</tr>
<tr>
<td>5</td>
<td>3.2</td>
<td>2.5</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>4.1</td>
<td>3</td>
<td>2.4</td>
</tr>
<tr>
<td>7</td>
<td>n/a</td>
<td>4.7</td>
<td>3.2</td>
</tr>
<tr>
<td>9</td>
<td>7.6</td>
<td>5.6</td>
<td>3.4</td>
</tr>
<tr>
<td>12</td>
<td>10.8</td>
<td>8.6</td>
<td>4.9</td>
</tr>
</tbody>
</table>
Figure 9.6 to Figure 9.8 show annoyance ratings for the sets of stimuli at $L_{Aeq} = 30$ and 40 dB(A) for the parameter modulation depth in the different metrics. The main effect is that different metrics basically move and compress the annoyance curve along the x-axis. While Figure 9.6 a) and b) have a similar range of 2 – 12 dB(A) and 1 – 11 dB respectively, the metrics from WPB1 extend up to modulation depths of 32 -39 dB and start at modulation depths between 4 and 11 dB (Figure 9.7). Other metrics from WPB1 gave very similar results and are therefore not shown.

If the perception based measure fluctuation strength which includes loudness rather than $L_{Aeq}$ was able to explain the annoyance ratings completely the two curves in Figure 9.8 should merge. The implementation of different loudness standards can also lead to uncertainties as shown in [27]. Merging curves are also not expected because affective participant response is also influenced by contextual and attitudinal factors. From all metrics related figures results the important conclusion that the consideration of any potential threshold or correction must be consistent with the metric from which the data was analysed.

![Figure 9.6 Comparison of MD ($L_{Aeq}$) and main WPF routine metrics on absolute annoyance.](image-url)
Figure 9.7 Comparison of WPB1 metric (noise-referenced) on absolute annoyance.

Figure 9.8 Comparison of psychoacoustic metrics on absolute annoyance.
10. Conclusions

Listening tests have been conducted to evaluate AM metrics in terms of their correlation with subjective listener response and to find a dose-response relation between the AM metric and the subjective annoyance response.

10.1 Sensitivity test results

In a pilot phase test stimuli were synthesised for a characteristic range of AM modulation parameters and outdoor listening scenarios. The sensitivity tests showed in accordance with previous literature that annoyance crucially depended on $L_{Aeq}$ and to a lesser extent on MD.

The use of A-weighting both for the level and the modulation depth lead to consistent results. In contrast plotting the annoyance ratings as a function of $L_{A90}$ as an alternative to $L_{Aeq}$ produced similar annoyance rating results up to MD = 6 dB(A) where $L_{A90}$ and $L_{Aeq}$ values are similar. Whether normalised ABBS as a function $L_{A90}$ gives a consistently linear dose response relation should be subject of future work.

Annoyance response did not change significantly for the temporal parameters pulse shape and pulse width at constant modulation frequency as well as the spectral parameters frequency skew and bandwidth of the modulation pulse. These parameters were subsequently fixed at realistic values.

Annoyance ratings did vary with modulation frequency in agreement with changes in fluctuation strengths predicted by the model in [9]. For this reason and because the modulation frequency between large modern wind turbines does not change a lot modulation frequency was also eliminated as a parameter.

In the sensitivity tests conflicting results arose from the use of the two modulation types MFAM and RFAM as well as the role of a low level of garden noise in the broadband MN. This was thought to be mainly due to the insufficiently controlled $L_{Aeq}$ in this set of tests. For this reason, the decision to let the participants choose a sound reproduction level that they regarded as realistic turned out not to be successful. Another factor was possibly the quality of the sound reproduction using headphones.
10.2 Final Test and Validation Tests

The final test which was conducted in the carefully controlled acoustic environment of the listening room there were therefore 3 sets of test sounds with the constant $L_{Aeq}$ of 30, 35, and 40 dB(A) for which the modulation depth was systematically varied from 0 to 12 dB(A) in increasing steps. After taking the effect of $L_{Aeq}$ which always dominated the annoyance rating into account, increases in modulation depth seemed to increase the annoyance rating slightly and consistently (monotonically), in agreement with previous research. However, the effect was not statistically significant because there was a large spread of ratings. The consistency of the increase for all $L_{Aeq}$ suggests that given a large enough group of participants it can possibly be shown that average annoyance rating increase slightly but consistently (monotonically) with modulation depth. The 95% CI are however expected to remain large because affective response varies between listeners. In contrast average ABBS $L_{Aeq}$ was constant from MD of about 3 dB(A). This answered the question how much louder would an equivalent unmodulated sound have to be to be equally annoying to a modulated sound. The adjustments were on average 1.7 dB(A) for a 40 dB(A) test sound and 3.5 dB(A) at 30 dB(A). Validation tests at two additional levels of 45 dB(A) and 25 dB(A) confirmed this trend. A clear onset of annoyance at a particular modulation depth could not be found for either of the two rating methods. The average ABBS adjustment for all stimuli was found to be 2.3 dB(A) higher than the test stimulus $L_{Aeq}$. When levels were measured as $L_{A90}$, results suggest that annoyance ratings were similar for MD of up to 6 dB(A) and generally increased with both, MD and $L_{A90}$. Because results for sets of stimuli with constant $L_{A90}$ and changing MD are not available simple average adjustments cannot be identified and further work would be necessary.

The comparison of the RFAM results without GN with MFAM ratings and the addition of GN for both modulation types in Validation Test I with a subgroup of 11 participants both the absolute annoyance ratings and ABBS $L_{Aeq}$ did not show significant different annoyance ratings for the different sets of stimuli. This suggests that the results of the Final Test can be generalised to a wider range of AM sounds than just the two chosen examples.

A similar result for Validation Test II when the masking noise (MN) was kept constant to avoid a possible change in stimulus character implies that the same is probably true for GN/MN as long as the level is low enough not to affect AM audibility.

In a last step the annoyance ratings were compared for 6 different metrics, four of them based on different physical definitions of modulation depth and 2 using the perceptive measure fluctuation strength. The comparison showed that the main effect of the physical metric is to change the range of modulation depths. The same stimuli would have a range of
0 – 12 dB(A) in the preliminary MD metric but 4 – 32 dB(A) in another metric. Fluctuation strength results showed a further step towards a metric that correlates with listener response but it was evident from the results that not even a perception based metric can ever account for contextual and attitudinal aspects of annoyance rating.

10.3 Scope and future work

This study has focussed on steady AM sounds with constant AM amplitude. In reality both the modulation amplitude and spectral characteristics can vary widely on time scales as short as a few seconds. The occurrence of AM has also been observed to be intermittent at times. While both phenomena will certainly affect annoyance it is with the current knowledge on AM not possible to define a representative set of stimuli to study listener perception of this phenomenon.

The listening tests were designed to allow relative comparisons between ratings both for the absolute ratings and for the ABBS adjusted ratings. It is therefore not advisable to compare the results directly to survey studies that were conducted in participants homes because of the contextual differences between the different types of study.
11. References

11.1 Reports from other work packages within the project


11.2 General literature


12. Glossary

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABBS</td>
<td>Adaptive BroadBand Stimulus: un-modulated broadband WTN noise with the same spectral shape as the un-modulated (0 dB) stimulus (masking noise without garden noise) that was used in the final test. The participants adjusted the level of the ABBS until it was equally annoying as the modulated wind turbine sound (<em>paired comparison method</em>).</td>
</tr>
<tr>
<td>AM</td>
<td>Amplitude modulation</td>
</tr>
<tr>
<td>Annoyance</td>
<td>An unpleasant mental state that is characterised by effects as irritation. It can be distracting and lead to frustration and anger.</td>
</tr>
<tr>
<td>Background Noise (BN)</td>
<td>Any noise present at the listener position that does not originate from the wind turbines</td>
</tr>
<tr>
<td>CABS</td>
<td>Controlled Acoustic Bass System (CABS), a special arrangement of subwoofers to minimise room modes.</td>
</tr>
<tr>
<td>95 % CI</td>
<td>A 95 % Confidence Interval (CI) is a statistical measure that provides an estimated range in which the rating is expected to fall in 95 % of all cases. It is calculated as the $1.96 * \text{standard deviation}/\sqrt{\text{number of ratings}}$.</td>
</tr>
<tr>
<td>Frequency skew</td>
<td>If the frequency distribution of a signal has unequal energy in either the higher or the lower frequency range it is said to be skewed. This is visualised in Figure 17.6 where the red curve &quot;leans&quot; to the left in contrast to Figure 17.7 where the red curve is symmetrical around its maximum value.</td>
</tr>
<tr>
<td>Garden Noise (GN)</td>
<td>Type of noise that is heard from outside a residence which in the context of this study is regarded to be the sum of vegetation and other outdoors background noise.</td>
</tr>
<tr>
<td>GLM ANOVA</td>
<td>Abbreviation for General Linear Model ANalysis Of VAriance. Standard statistical method used here to decide whether mean values are different or the same.</td>
</tr>
<tr>
<td>Masking Noise (MN)</td>
<td>Any noise that reduces or eliminates the audibility of a particular noise source. In this study the term is used for either WTN on its own or the combination of WTN and GN all or some of wind turbine noise, vegetation noise and background noise.</td>
</tr>
<tr>
<td>Term</td>
<td>Description</td>
</tr>
<tr>
<td>-------------------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Modulation depth parameter $\alpha$</td>
<td>A measure of the strength of amplitude modulation as defined in the annex to WPB1.</td>
</tr>
<tr>
<td>Modulation Depth MD</td>
<td>In this report, MD is derived from 100 ms averages of $L_{Aeq}$. The modulation depth is defined as the difference between the mean peak level and the mean trough level in the A-weighted RMS time series for any consecutive group of all pulses over the length of the test stimuli (Figure 17.8 and Figure 17.9).</td>
</tr>
<tr>
<td>MPL</td>
<td>Peak level of the modulated part of the signal (highest value in blue curves in Figure 6.1) (MPL)</td>
</tr>
<tr>
<td>Medium Frequency Amplitude Modulation (MFAM)</td>
<td>Wind turbine amplitude modulated sound with a frequency content centred between 500 and 1000 Hz. It can be described as a “swish”.</td>
</tr>
<tr>
<td>Reduced Frequency Modulation (RFAM)</td>
<td>Wind turbine amplitude modulated sound with a frequency content centred between 200 and 600 Hz. It can be described as a “swoosh” or “woomp”.</td>
</tr>
<tr>
<td>Rise time</td>
<td>Property of the triangular shaped envelope of a modulated signal that describes for how long the signal amplitude increases.</td>
</tr>
<tr>
<td>Saw tooth</td>
<td>Triangular shaped envelope of a modulated signal</td>
</tr>
<tr>
<td>Spectral shape</td>
<td>The range of frequencies contained in a sound</td>
</tr>
<tr>
<td>Time envelope</td>
<td>The shape of the modulation in a graph showing the modulated signal as a function of time. Red line in Figure 6.1.</td>
</tr>
<tr>
<td>Vegetation noise (VN)</td>
<td>Sound originating from vegetation and often masking wind turbine noise</td>
</tr>
</tbody>
</table>
13. **Appendix I: Participant recruitment documents**

13.1 *Advertisement Final Test I*

![University of Salford Logo]

**UNIVERSITY OF Salford NEWS RELEASE**

**Salford seeks paid volunteers for sound study**

Would you like to be involved in research that paves the way for reducing noise problems from the adoption of wind energy?

- Are you interested in issues of noise control?
- Do you get frustrated by noisy environments?
- Do you find fluctuating sounds annoying or bothersome?

The University of Salford’s Acoustics Research Centre is seeking volunteers for a study into the preference for and against different amounts of Amplitude Modulation (how much a sound fluctuates, or ‘comes and goes’, periodically) for a range of sounds/wind turbine sounds.

Participants will have their hearing tested, and then they will rate how annoying they find a series of sound samples in a living room environment. In total, participation will take approximately 2 hours.

**Eligible volunteers will be paid for their time.**

People who are over 18 years old and without hearing problems are asked to apply. Applicants will be asked some questions for screening purposes.

Testing will take place between ###/##/## and ####/####.

For more information or to apply contact Andrew King by emailing a.king@edu.salford.ac.uk or call 0161 295 4669.
LEND US YOUR EARS

Next Week 6th-9th of December 2011, the Acoustics Research Centre, based in the Newton Building, would like to invite you to take part in a subjective listening test, can you help?

The project aims to better our understanding of what makes noise from wind turbines a problem for residents near them.

The experiment starts with a basic hearing test. Then you to listen to a collection of wind turbine noises in a specially designed, surround-sound listening room and rate how annoying they would be to hear in your garden.

You will receive payment for participating.

In total the testing should take 90 minutes, however this can be broken up into shorter sessions if that is more convenient. Your participation would make a significant contribution to cutting edge research and it would be a great help to the researchers.

If you have a preference for living or spending time in the countryside then we would be particularly eager to hear from you.

If you have any questions, or would like to take part, please get in touch with Ben Piper at b.j.piper1@salford.ac.uk
13.3 Consent Form

Consent Form

Project : Comparative Annoyance from Amplitude Modulated Noise
Researcher : Benjamin Piper
Contact Details: researcher@salford.ac.uk
Supervisor : Sabine von Hünerhein
Contact Details: supervisor@salford.ac.uk

Thank you for agreeing to participate in this study, taking place on ..............................

This form outlines the objectives of the study and your involvement.

The objectives are:

- To measure how sensitive your hearing is.
- To compare how annoying you find different types of noise.

First we will test your hearing in an audiometric booth in which you will be asked to indicate when you can hear a tone by holding down a button. The testing is done on each ear individually over headphones. If your hearing is not sensitive enough, you may not continue the experiment.

In the second test you will sit in a listening room (designed similar to a living room) and will be asked to imagine you are at home, in the garden or living room whilst you listen to sounds and rate them on a scale of annoyance and by adjusting one until it is equally as annoying as another.

The levels of sound are quite low, so there is no risk to your hearing or your health. There will be regular breaks approximately every 30 to 40 minutes. However, if you feel tired or uncomfortable at any time or would like a break please press the ‘help’ button to pause the test and alert the researcher. The experiment should take no more than 2 hours in total.

The information gathered from this study will be used for no other purpose except the completion of this study and the publication of its results. The results of this test will be stored anonymously. **Your participation is voluntary — you have the right to withdraw at any time without giving any reason and your data will not be used.**
Please feel free to ask any questions at any time about the nature of the study and methods being used – the contact details are listed above.

☐ Please tick this box if you would like to be de-briefed after the current study.
☐ Please tick this box if you are happy to be contacted about participating in the future.

Participant: I agree to the terms

Name .................................................. Signature ............................................... Date ....................

Researcher: I agree to the terms

Name .................................................. Signature ............................................... Date .....................
14. Appendix II: Participant Screening for Final Tests

This section details the exact wording and layout of the screening form sent to prospective participants. The Noise Sensitivity Scale at the end is the short version of the Zimmer and Ellermeier Noise sensitivity scale [28]:

All information provided here will be kept confidential (only available in its raw form to project members) and shall not be published in any way that identifies the participant. Information shall only be kept if applicant participates.

<table>
<thead>
<tr>
<th>Forename:</th>
<th>Surname:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age:</td>
<td>Sex: Male / Female (Delete as appropriate)</td>
</tr>
<tr>
<td>Occupation:</td>
<td>Nationality:</td>
</tr>
</tbody>
</table>

Previous listening test experience
- **A lot** (participated in more than 5 tests)
- **Some** (participated in between 2 and 5 tests before)
- **A Little** (participated in 1 test before)
- **None** (never participated in a test before) (Delete as appropriate)

For the following questions, please give one answer by deleting the answers that do not apply to you.

**Q1. What best describes the area surrounding your home?**
- Inner city
- Suburb (eg. City outskirts)
- In the countryside
- Other (please specify) ..........................................................

**Q2. How content are you with the area surrounding your home?**
- Very unhappy
Unhappy
Neither unhappy or happy
Happy
Very Happy

If you wish you lived in a different area type, please answer Qs 3 and 4. If not, please go to Q5.

Q3. Which of the following area types do you wish you lived in?

Inner city
Suburb (eg. City outskirts)
In the countryside
Other (please specify) ……………………………………………………

Q4. How strong is your desire to live in the area selected in q.3?

Strong
Moderately Strong
Moderately Mild
Mild

Q5. How good is your hearing, in general?

Very good
Good
Moderate
Poor
Very Poor
Q6. Do you have any specific problems with your hearing?

Yes
No

If yes, please provide details in the space below

.........................................................
.........................................................
.........................................................
.........................................................
.........................................................

Now please complete the Noise Sensitivity Scale below. Show whether you agree fully, rather agree, rather disagree or fully disagree with each statement by putting a tick in the relevant box.

<table>
<thead>
<tr>
<th>Noise Sensitivity Scale</th>
<th>Agree fully</th>
<th>Rather agree</th>
<th>Rather disagree</th>
<th>Disagree fully</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. It is no fun keeping up a conversation while the radio is on.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. I tend to notice disturbing sounds later than do other persons.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. I avoid noisy pastimes such as going to soccer matches or fairs.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. I wake up at the slightest sound.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Even in noisy surroundings. I am able to work quickly and with concentration.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. On doing my shopping in the city. I hardly hear the street noise.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
7. After having passed an evening in a noisy pub
I feel drained.

8. When I want to fall asleep, hardly any sound can disturb me.

9. On weekends I like to be in quiet places.

Thank you very much. We will contact you soon about participation, which is scheduled to take place in April.

Figure 14.1 Zimmer-Elernermeier Questionnaire for the assessment of noise sensitivity

The items within the scale are scored: 1: 3-0, 2: 0-3, 3: 3-0, 4: 3-0, 5: 0-3, 6: 0-3, 7: 3-0, 8: 0-3, 9: 3-0 (scored left to right across response boxes).
15. Appendix III: Check lists for listening test procedures

15.1 Participant screening

- When an individual emails to show interest in taking part, email them back with thanks, and ask them to fill in the screening document you attach to your reply.
- If they do not reply within a couple of days, send reminder asking if they still want to take part.
- When they return the Screening document, input the results into password protected participant file:
  - To calculate the Noise Sensitivity Score, use Zimmer-Ellermeier scoresheet. This gives a list for the scores for each item of the NSS questionnaire. For each item, note the score in the corresponding box. Notice they either go 0-3 or 3-0 left to right. Add up the scores and multiply by 3.7 for the participant's NSS score.

Selection:

We are looking for people who either say they want to live in the countryside or already do live in the countryside. Obviously the preference is for people who have a stronger desire to live there, or are happy there.

Last time we found countryside dwellers and those wanting to had higher scores on the NSS than the other demographics, so I would say to aim for participants will scores between 40-80.
Pre-test setup routine

- Send reminder email to next day’s participants
- Update the respective password protected subject data files on the Listening room PC if any new participants are in that day, then run Compile_Participant_List.m in main folder.
- Go around outside of curtain, turning on all the mains sockets with plugs inserted (pretty much every socket!), checking that all the subs are on (little green indicator light on the side near the base. Check sound card is on too (and set to input -10 dBV).
- Turn on desktop PC & laptop for webcam.
  - On desktop, open DigiCheck twice, on each instance, press F3 and from the drop down menu labelled ‘Source’ select ‘Input’ for one and ‘Playback’ for the other. This tells you what is going in and what is going out of the sound card. Now open, MATLAB. Set the directory to ‘D:\ReUK_AM’
- On laptop, open Creative… This should automatically find the webcam and you can resize the stream to your liking
- Best to have just centre lights on in listening room.
- Turn off ventilation
- To check all 8030 As (Ambisonic ring) are on and set to correct levels:
  - turn on Norsonic, check battery.
  - Place Microphone in listener position (using bolt on string hanging from ceiling) and point at a speaker
  - run daily_connection_check.m
    - select speaker mic is facing, get ‘Volume’ bar to turn green, make sure chair is not in sound path
- Measure white noise or GN with SLM compare with intended.
15.2 Test procedure for each participant

- Meet participant
- Explain procedure, context, what annoyance means and how long each bit will be for that session
- Ask them to sign the consent form
- Take them to the audiometric booth,
- Perform audiometric test
- Present participant with paper instructions
- Take them to listening room.
- Ask participant whether they would like to have screen on right or left, and angle the seat and coffee table accordingly, make sure they are comfortable (ask if they would like a drink).
- Mention the ‘help’ button and that it allows them to break from testing if they wish.
- Select test m file and run, select scenario.
- Guide participant through one practice trial. Indicate the ‘Okay’ button to end practice when they are ready.
- Ask participant if they would like a break or a drink after finishing each block.
- If they finish a session, but have more to come back and do, make sure you have booked a 2nd session.
- After finishing all testing, debrief them on what the project aims are and how their data will be used, (i.e. mean levels of all participants will be evaluated to find the point where levels start to be influenced by modulation and above this point, how it influences it).
- Have them sign the payment receipt form and pay them.
15.3 Test protocol (quality assurance)

Test stimuli have been calibrated and calibrations evaluated during set-up periods. A daily routine ensured full functionality of the reproduction system. Stimuli were presented in random order or manually counter balanced to avoid fatigue bias. Reproducible communication was ensured through written instructions and a checklist for oral communication.

15.4 Participant selection criteria, quantity

Participants were mainly recruited from staff and students via the internal University communication channels. To widen the age range and background we also attempted to recruit participants from a rural area away from existing wind farms to avoid pre-sensitisation.
bias. Selection criteria were normal hearing tested by a standard audiometric procedure and that the participants are either living in the country side or want to live in the countryside. This is to take noise sensitivity into account. Noise sensitivity was also established by asking the volunteers to fill in a Zimmer-Ellermeier questionnaire.

16. Appendix IV: Sound Production System

16.1 Headphone calibration for Sensitivity Tests

![Filter frequencies](image)

**Figure 16.1** Filters used to correct for headphone (dotted green) and HATS (dotted red) measurement system response. The blue line is the intended response, the red the smoothed achieved response.

16.2 Final test

To minimise the influence of the room on the stimuli reproduction the listening room was calibrated following the procedure laid out in [5]. For the current tests the number of loudspeakers in the ambisonic ring was reduced to six instead of eight. The calibration results for each loudspeaker are plotted in Figure 16.2 - Figure 16.15. The graphs represent a narrow-band, detailed frequency analysis which represents the effective audio
reproduction of the system, for each loudspeaker. \( H(f) \) is the measured response and \( G(f) \) is the correction applied, and the difference between the two is then shown. Two sets of calibration data are shown, the first was for the first participant subgroup of final test and the second were used at the final stage of the final test.

### 16.2.1 Final Test, participant subgroup I

![Graphs showing loudspeaker response and correction](image)

**Figure 16.2 Left Loudspeaker Response and Correction**
Figure 16.3 Front Left Loudspeaker Response and Correction

Figure 16.4 Front Right Loudspeaker Response and Correction
Figure 16.5 – Right Loudspeaker Response and Correction

Figure 16.6 Back Right Loudspeaker Response and Correction
Figure 16.7 Back Left Loudspeaker Response and Correction

Figure 16.8 CABS Loudspeaker Response and Correction
16.2.2 Final Test, Subgroup II

Figure 16.9 Left Loudspeaker Response and Correction

Figure 16.10 Front Left Loudspeaker Response and Correction
Figure 16.11 Front Right Loudspeaker Response and Correction

Figure 16.12 Right Loudspeaker Response and Correction
Figure 16.13 Back Right Loudspeaker Response and Correction

Figure 16.14 Back Left Loudspeaker Response and Correction
Figure 16.15 CABS Loudspeaker Response and Correction
17. Appendix V: Stimuli Design Method

This appendix contains information on how the stimuli were created from different component parts and measurements of the final stimuli.

17.1 Stimuli Components Step I

The wind turbine noise signal was composed in three different steps as detailed in Sections 6.3 and 17. The MN consisted of un-modulated wind turbine noise (WTN) with and without garden noise (GN). These two noise types were created from third octave band data as detailed in [5]. Figure 17.1 shows the measured third octave spectra of these signals when played through the listening room reproduction system. All measurements were made with a Svantek 927 sound level meter (SLM) giving A-weighted RMS time history data based on a 100 ms integration time and a monophonic .wav file.

![Fig 17.1 Measured third-octave data for wind turbine and garden masking noises.](image)

In the Sensitivity Tests the L_Aeq of WTN corresponded to 44 dB(A) alone, GN to 46.2 dB(A) alone, and when combined at a ratio of 5:1 between WTN and GN respectively the combined nominal level was 49.8 dB(A). The ratio between the two levels was chosen
empirically in consultation with the members of the project team, which included some experienced “expert” listeners, when everybody listened to various stimuli in comparison to recordings from WPC. Absolute levels varied between participants as described in Section 6.6.1.

17.2 Step 2: Modulation for Sensitivity Tests I and II

The modulated noise signals were created using the model developed and described in WPB1.

Two types of signal were created for Sensitivity Tests I and II, one to represent RFAM and one to represent MFAM. Where not otherwise specified the basic parameters are shown in Table 17.1

<table>
<thead>
<tr>
<th>Centre Frequency (Hz)</th>
<th>Bandwidth – 3 dB (Hz)</th>
<th>Frequency Skew (%)</th>
<th>Pulse Width (s)</th>
<th>Envelope Rise time (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RFAM 350</td>
<td>400</td>
<td>33</td>
<td>0.2</td>
<td>70</td>
</tr>
<tr>
<td>MFAM 600</td>
<td>350</td>
<td>50</td>
<td>0.2</td>
<td>70</td>
</tr>
</tbody>
</table>

Table 17.1 MFAM and RFAM parameters used for stimuli in Sensitivity Tests.

Figure 17.2 and Figure 17.3 show the spectra and time-envelope of the ‘MFAM’ and ‘RFAM’ stimuli, without the background masking noise.

Figure 17.2: MFAM stimulus properties a) frequency envelope with centre frequency of 600 Hz and bandwidth of 350 Hz. b) time envelope with a rise and drop time of 70%.
Figure 17.3: RFAM stimulus properties a) frequency envelope with peak at 350 Hz, and bandwidth of 400 Hz. b) time envelope with a rise time of 70% and a drop time of 30%. Representations of two examples of finalised stimuli including the masking noise have been produced by White and are shown in Figure 17.4 and Figure 17.5.

Figure 17.4 Spectrogram of MFAM stimulus with Code Identifier AC. For details on parameter specification see Section 17.5.2.
17.3 Step 2: Modulation for Final Tests I and II

Two types of signal were created for Final Tests I and II, one to represent RFAM and one to represent MFAM. The parameters are shown in Table 17.2.

<table>
<thead>
<tr>
<th></th>
<th>Centre Frequency (Hz)</th>
<th>Bandwidth – 3 dB (Hz)</th>
<th>Frequency Skew (%)</th>
<th>Pulse Width (s)</th>
<th>Envelope Skew (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RFAM</td>
<td>300</td>
<td>180</td>
<td>33</td>
<td>0.2</td>
<td>70</td>
</tr>
<tr>
<td>MFAM</td>
<td>600</td>
<td>350</td>
<td>50</td>
<td>0.2</td>
<td>70</td>
</tr>
</tbody>
</table>

Table 17.2 Parameters for RFAM and MFAM signals for Final Test and validations.

The time and frequency content of these signals are shown in Figures 17.2 and 17.3.
Figure 17.6 Time and frequency content of RFAM signal used to create test stimuli (modulation pulses shown without masking noise).

Figure 17.7 Time and frequency content of MFAM signal used to create test stimuli (modulation pulses shown without masking noise).
17.4 Approach to Combining Stimuli Components to Achieve Target $L_{Aeq}$ and Modulation Depth

In an initial step, input levels for AM and MN components were estimated to achieve the desired representative range of stimuli. To guide this process, the modulation depth was calculated as the difference between the mean peak and the mean trough in the A-weighted RMS time series for any consecutive group of 12 pulses as 12 pulses occur in each 20 s loop. It is difficult to define the exact modulation depth below 3 dB(A) due to the variation in the masking noise therefore initially signals were created and measured for modulation depths of 3 dB(A) and above for an $L_{Aeq}$ of 40 dB(A). These were then measured at the listening position in the listening room and the ratios of the WTN and AM pulses where altered until the $L_{Aeq}$ and modulation depth was within ±0.25 dB(A) of the target. Figure 17.8 - Figure 17.10 show the measured time series for 12, 6 and 3 dB modulation depths, in that order. Note that the uncertainty of MD below 3 dB(A) is therefore larger.

Although the stimuli were generated artificially based on a fixed ratio of MN to AM pulses, the effects of random masking from the broadband nature of both components of the signal meant that, subjectively, the different pulses sounded subtly different from each other, and therefore the signal did not sound too artificial. This is reflected in the variations in short-term $L_{Aeq}$.

![Figure 17.8](image)

Figure 17.8 Measured time series for stimulus (24) containing a 12±0.25 dB(A) modulation depth and with an $L_{Aeq}$ of 40±0.15 dB(A).
Figure 17.9 Measured time series for stimulus (21) containing a $6 \pm 0.25$ dB(A) modulation depth and with an $L_{Aeq}$ of $40 \pm 0.15$ dB(A).

Figure 17.10 Measured time series for stimulus (16) containing a $3 \pm 0.25$ dB(A) modulation depth and with an $L_{Aeq}$ of $40 \pm 0.15$ dB(A).

Based on values used to create the stimuli with modulation depths of 3 dB(A) or above the stimuli with smaller modulation depths were created using a cubic fit to find the input levels, shown in Figure 17.11 for RFAM.
Figure 17.11 Cubic fit to Measured AM and un-modulated WTN values to create stimuli with an $L_{Aeq}$ of 40 dB(A).

These stimuli were measured to ensure the $L_{Aeq}$ was correct. It was then assumed that scaling all the input values up by 5 dB and down by 5 and 10 dB would give stimuli sets with $L_{Aeq}$ levels at 45, 35 and 30 dB(A). The stimuli were all measured to confirm this. The SLM had a noise floor of 20 dB(A) and showed non-linear behaviour below 25 dB(A) and therefore it is impossible from these measurements to confirm the accuracy of the stimuli with high modulation depths at 30 dB(A) and 35 dB(A). It is assumed they are correct because all the other stimuli scale in the expected manner.

This process was then repeated with added GN. For this set of stimuli continuous GN was independently played at $L_{Aeq} = 7.5$ dB below the $L_{Aeq}$ of the AM test stimulus in order not to significantly mask modulation depths of up to 12 dB(A).

17.5 Detailed list of stimuli parameters

17.5.1 Sensitivity Test I

Three aspects of the stimuli were varied; the modulation depth and the time envelope properties rise time percentage and pulse width based on the full width half maximum (FWHM). In the Sensitivity Tests modulation depths were different for RFAM and MFAM stimuli as initially a measure for modulation depth that was based on unweighted spectra
was used to design the stimuli. This **depth parameter** $\alpha$ is defined in WPB1. The equivalent values of MD are specified together with all other variable modulation parameters in Table 17.3 for Sensitivity Test I and in Table 17.4.

<table>
<thead>
<tr>
<th>ID</th>
<th>$\alpha$ (dB)</th>
<th>MD, dB(A)</th>
<th>Rise Time (%)</th>
<th>Pulse Width (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Garden</td>
<td>n/a</td>
<td>1.2</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>A</td>
<td>0</td>
<td>1.0</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>B</td>
<td>10.5</td>
<td>5.6</td>
<td>70</td>
<td>0.2</td>
</tr>
<tr>
<td>C</td>
<td>6</td>
<td>1.8</td>
<td>10</td>
<td>0.2</td>
</tr>
<tr>
<td>D</td>
<td>12</td>
<td>8.0</td>
<td>70</td>
<td>0.2</td>
</tr>
<tr>
<td>E</td>
<td>1.5</td>
<td>1.2</td>
<td>70</td>
<td>0.2</td>
</tr>
<tr>
<td>F</td>
<td>6</td>
<td>1.7</td>
<td>20</td>
<td>0.2</td>
</tr>
<tr>
<td>G</td>
<td>6</td>
<td>1.8</td>
<td>30</td>
<td>0.2</td>
</tr>
<tr>
<td>H</td>
<td>3</td>
<td>1.2</td>
<td>70</td>
<td>0.2</td>
</tr>
<tr>
<td>I</td>
<td>6</td>
<td>1.6</td>
<td>40</td>
<td>0.2</td>
</tr>
<tr>
<td>J</td>
<td>4.5</td>
<td>1.7</td>
<td>70</td>
<td>0.2</td>
</tr>
<tr>
<td>K</td>
<td>6</td>
<td>1.6</td>
<td>50</td>
<td>0.2</td>
</tr>
<tr>
<td>L</td>
<td>6</td>
<td>1.5</td>
<td>60</td>
<td>0.2</td>
</tr>
<tr>
<td>M</td>
<td>6</td>
<td>1.7</td>
<td>70</td>
<td>0.2</td>
</tr>
<tr>
<td>N</td>
<td>6</td>
<td>1.6</td>
<td>70</td>
<td>0.2</td>
</tr>
<tr>
<td>O</td>
<td>7.5</td>
<td>2.6</td>
<td>70</td>
<td>0.2</td>
</tr>
<tr>
<td>P</td>
<td>6</td>
<td>1.6</td>
<td>80</td>
<td>0.2</td>
</tr>
<tr>
<td>Q</td>
<td>6</td>
<td>1.6</td>
<td>90</td>
<td>0.2</td>
</tr>
<tr>
<td>R</td>
<td>9</td>
<td>4.1</td>
<td>70</td>
<td>0.2</td>
</tr>
<tr>
<td>S</td>
<td>6</td>
<td>1.7</td>
<td>70</td>
<td>0.15</td>
</tr>
<tr>
<td>T</td>
<td>6</td>
<td>1.6</td>
<td>70</td>
<td>0.1</td>
</tr>
<tr>
<td>U</td>
<td>6</td>
<td>1.7</td>
<td>70</td>
<td>0.25</td>
</tr>
<tr>
<td>V</td>
<td>6</td>
<td>1.7</td>
<td>70</td>
<td>0.2</td>
</tr>
<tr>
<td>W</td>
<td>6</td>
<td>1.9</td>
<td>70</td>
<td>0.35</td>
</tr>
<tr>
<td>X</td>
<td>6</td>
<td>1.3</td>
<td>70</td>
<td>0.3</td>
</tr>
<tr>
<td>Y</td>
<td>6</td>
<td>1.9</td>
<td>70</td>
<td>0.45</td>
</tr>
<tr>
<td>Z</td>
<td>6</td>
<td>2.0</td>
<td>70</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Table 17.3 Sensitivity Test I: Stimuli identifier and details on modulation parameters.

The order of stimuli for each varied aspect is as follows:

Modulation Order from 1.5dB : 12dB - E H J M O R B D
Rise Time Order from 10% : 90% - C F G I K L N P Q
Width Order from 0.1:0.45 - T S V U X W Z Y

The samples were generated using the first edition of the ISVR code four_G_model.m

### 17.5.2 Sensitivity Test II

AM time envelope was 0.2 s

<table>
<thead>
<tr>
<th>Stimulus ID</th>
<th>α</th>
<th>MD dB(A)</th>
<th>AM Period (s)</th>
<th>Bandwidth (Hz)</th>
<th>Peak Frequency (Hz)</th>
<th>Freq. Skew (%)</th>
<th>Rise (%)</th>
<th>BNL Fixed</th>
<th>Mod Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC</td>
<td>0</td>
<td>1</td>
<td>no</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VT</td>
<td>0</td>
<td>1</td>
<td>no</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AC</td>
<td>3</td>
<td>5</td>
<td>1.3</td>
<td>350</td>
<td>600</td>
<td>50</td>
<td>70</td>
<td>yes</td>
<td>MFAM</td>
</tr>
<tr>
<td>DN</td>
<td>3</td>
<td>5</td>
<td>0.65</td>
<td>350</td>
<td>600</td>
<td>50</td>
<td>70</td>
<td>no</td>
<td>MFAM</td>
</tr>
<tr>
<td>EF</td>
<td>3</td>
<td>5</td>
<td>1.3</td>
<td>350</td>
<td>600</td>
<td>50</td>
<td>70</td>
<td>no</td>
<td>MFAM</td>
</tr>
<tr>
<td>EH</td>
<td>3</td>
<td>1</td>
<td>0.65</td>
<td>400</td>
<td>300</td>
<td>70</td>
<td>70</td>
<td>no</td>
<td>RFAM</td>
</tr>
<tr>
<td>GN</td>
<td>3</td>
<td>5</td>
<td>1.3</td>
<td>350</td>
<td>600</td>
<td>50</td>
<td>70</td>
<td>no</td>
<td>MFAM</td>
</tr>
<tr>
<td>JM</td>
<td>3</td>
<td>5</td>
<td>1.3</td>
<td>350</td>
<td>600</td>
<td>50</td>
<td>70</td>
<td>yes</td>
<td>MFAM</td>
</tr>
<tr>
<td>QD</td>
<td>3</td>
<td>1</td>
<td>1.3</td>
<td>400</td>
<td>300</td>
<td>70</td>
<td>70</td>
<td>yes</td>
<td>RFAM</td>
</tr>
<tr>
<td>TH</td>
<td>3</td>
<td>1</td>
<td>1.3</td>
<td>400</td>
<td>300</td>
<td>70</td>
<td>70</td>
<td>no</td>
<td>MFAM</td>
</tr>
<tr>
<td>UK</td>
<td>3</td>
<td>1</td>
<td>1.3</td>
<td>400</td>
<td>300</td>
<td>70</td>
<td>70</td>
<td>yes</td>
<td>RFAM</td>
</tr>
<tr>
<td>XE</td>
<td>3</td>
<td>1</td>
<td>1.3</td>
<td>400</td>
<td>300</td>
<td>70</td>
<td>70</td>
<td>no</td>
<td>RFAM</td>
</tr>
<tr>
<td>AV</td>
<td>6</td>
<td>8</td>
<td>1.3</td>
<td>350</td>
<td>600</td>
<td>50</td>
<td>70</td>
<td>no</td>
<td>MFAM</td>
</tr>
<tr>
<td>AX</td>
<td>6</td>
<td>8</td>
<td>1.3</td>
<td>350</td>
<td>600</td>
<td>50</td>
<td>70</td>
<td>no</td>
<td>MFAM</td>
</tr>
<tr>
<td>BU</td>
<td>6</td>
<td>2</td>
<td>1.3</td>
<td>400</td>
<td>300</td>
<td>70</td>
<td>70</td>
<td>no</td>
<td>RFAM</td>
</tr>
<tr>
<td>CT</td>
<td>6</td>
<td>2</td>
<td>1.3</td>
<td>400</td>
<td>300</td>
<td>70</td>
<td>70</td>
<td>no</td>
<td>RFAM</td>
</tr>
<tr>
<td>CY</td>
<td>6</td>
<td>2</td>
<td>0.65</td>
<td>400</td>
<td>300</td>
<td>70</td>
<td>70</td>
<td>no</td>
<td>RFAM</td>
</tr>
<tr>
<td>DB</td>
<td>6</td>
<td>8</td>
<td>1.3</td>
<td>350</td>
<td>600</td>
<td>50</td>
<td>70</td>
<td>no</td>
<td>MFAM</td>
</tr>
<tr>
<td>EG</td>
<td>6</td>
<td>2</td>
<td>1.3</td>
<td>400</td>
<td>300</td>
<td>70</td>
<td>70</td>
<td>no</td>
<td>RFAM</td>
</tr>
<tr>
<td>FN</td>
<td>6</td>
<td>2</td>
<td>1.3</td>
<td>400</td>
<td>300</td>
<td>70</td>
<td>70</td>
<td>no</td>
<td>RFAM</td>
</tr>
<tr>
<td>GM</td>
<td>6</td>
<td>8</td>
<td>1.3</td>
<td>350</td>
<td>600</td>
<td>50</td>
<td>70</td>
<td>no</td>
<td>MFAM</td>
</tr>
<tr>
<td>JO</td>
<td>6</td>
<td>8</td>
<td>1.3</td>
<td>400</td>
<td>300</td>
<td>70</td>
<td>70</td>
<td>no</td>
<td>MFAM</td>
</tr>
<tr>
<td>KP</td>
<td>6</td>
<td>8</td>
<td>1.3</td>
<td>350</td>
<td>600</td>
<td>50</td>
<td>70</td>
<td>no</td>
<td>MFAM</td>
</tr>
<tr>
<td>NI</td>
<td>6</td>
<td>2</td>
<td>1.3</td>
<td>400</td>
<td>300</td>
<td>70</td>
<td>70</td>
<td>no</td>
<td>RFAM</td>
</tr>
<tr>
<td>QF</td>
<td>6</td>
<td>2</td>
<td>1.3</td>
<td>400</td>
<td>300</td>
<td>70</td>
<td>70</td>
<td>no</td>
<td>RFAM</td>
</tr>
<tr>
<td>QS</td>
<td>6</td>
<td>2</td>
<td>1.3</td>
<td>400</td>
<td>300</td>
<td>70</td>
<td>70</td>
<td>no</td>
<td>RFAM</td>
</tr>
<tr>
<td>RH</td>
<td>6</td>
<td>8</td>
<td>1.3</td>
<td>350</td>
<td>600</td>
<td>50</td>
<td>70</td>
<td>no</td>
<td>MFAM</td>
</tr>
<tr>
<td>RJ</td>
<td>6</td>
<td>9</td>
<td>0.65</td>
<td>350</td>
<td>600</td>
<td>50</td>
<td>70</td>
<td>no</td>
<td>MFAM</td>
</tr>
<tr>
<td>SB</td>
<td>6</td>
<td>10</td>
<td>1.3</td>
<td>250</td>
<td>600</td>
<td>30</td>
<td>70</td>
<td>no</td>
<td>MFAM</td>
</tr>
<tr>
<td>TJ</td>
<td>6</td>
<td>2</td>
<td>1.3</td>
<td>400</td>
<td>300</td>
<td>70</td>
<td>70</td>
<td>no</td>
<td>RFAM</td>
</tr>
<tr>
<td>UL</td>
<td>6</td>
<td>8</td>
<td>1.3</td>
<td>350</td>
<td>600</td>
<td>50</td>
<td>70</td>
<td>no</td>
<td>MFAM</td>
</tr>
<tr>
<td>VY</td>
<td>6</td>
<td>8</td>
<td>1.3</td>
<td>350</td>
<td>600</td>
<td>50</td>
<td>70</td>
<td>no</td>
<td>MFAM</td>
</tr>
<tr>
<td>WD</td>
<td>6</td>
<td>8</td>
<td>1.3</td>
<td>350</td>
<td>600</td>
<td>50</td>
<td>70</td>
<td>no</td>
<td>MFAM</td>
</tr>
<tr>
<td>WG</td>
<td>6</td>
<td>2</td>
<td>1.3</td>
<td>500</td>
<td>300</td>
<td>80</td>
<td>70</td>
<td>no</td>
<td>RFAM</td>
</tr>
<tr>
<td>XT</td>
<td>6</td>
<td>8</td>
<td>1.3</td>
<td>450</td>
<td>600</td>
<td>61</td>
<td>70</td>
<td>no</td>
<td>MFAM</td>
</tr>
<tr>
<td>YK</td>
<td>6</td>
<td>8</td>
<td>1.3</td>
<td>350</td>
<td>600</td>
<td>50</td>
<td>70</td>
<td>no</td>
<td>MFAM</td>
</tr>
<tr>
<td>ZR</td>
<td>6</td>
<td>2</td>
<td>1.3</td>
<td>300</td>
<td>300</td>
<td>67</td>
<td>70</td>
<td>no</td>
<td>RFAM</td>
</tr>
<tr>
<td>ZW</td>
<td>6</td>
<td>2</td>
<td>1.3</td>
<td>400</td>
<td>300</td>
<td>70</td>
<td>70</td>
<td>no</td>
<td>RFAM</td>
</tr>
<tr>
<td>BY</td>
<td>9</td>
<td>3</td>
<td>1.3</td>
<td>400</td>
<td>300</td>
<td>70</td>
<td>70</td>
<td>no</td>
<td>RFAM</td>
</tr>
<tr>
<td>CR</td>
<td>9</td>
<td>12</td>
<td>1.3</td>
<td>350</td>
<td>600</td>
<td>50</td>
<td>70</td>
<td>no</td>
<td>MFAM</td>
</tr>
<tr>
<td>DV</td>
<td>9</td>
<td>4</td>
<td>1.3</td>
<td>400</td>
<td>300</td>
<td>70</td>
<td>70</td>
<td>no</td>
<td>RFAM</td>
</tr>
<tr>
<td>FM</td>
<td>9</td>
<td>4</td>
<td>0.65</td>
<td>400</td>
<td>300</td>
<td>70</td>
<td>70</td>
<td>no</td>
<td>RFAM</td>
</tr>
</tbody>
</table>
Table 17.4 Sensitivity Test II: Stimuli identifier and details on modulation parameters.

<table>
<thead>
<tr>
<th>Stimulus ID</th>
<th>( \alpha ) dB</th>
<th>MD dB(A)</th>
<th>Mean LAeq dB(A)</th>
<th>95% CI L eq</th>
<th>Mean Annoyance rating</th>
<th>95% CI Annoyance</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>3</td>
<td>5</td>
<td>37</td>
<td>1</td>
<td>4.7</td>
<td>0.6</td>
</tr>
<tr>
<td>AV</td>
<td>6</td>
<td>8</td>
<td>44</td>
<td>1</td>
<td>7.5</td>
<td>0.6</td>
</tr>
<tr>
<td>AX</td>
<td>6</td>
<td>8</td>
<td>38</td>
<td>1</td>
<td>5.6</td>
<td>0.9</td>
</tr>
<tr>
<td>BU</td>
<td>6</td>
<td>2</td>
<td>30</td>
<td>1</td>
<td>3.6</td>
<td>0.6</td>
</tr>
<tr>
<td>BY</td>
<td>9</td>
<td>3</td>
<td>34</td>
<td>1</td>
<td>5.9</td>
<td>0.6</td>
</tr>
<tr>
<td>CR</td>
<td>9</td>
<td>12</td>
<td>37</td>
<td>1</td>
<td>6.5</td>
<td>0.7</td>
</tr>
<tr>
<td>CT</td>
<td>6</td>
<td>2</td>
<td>31</td>
<td>1</td>
<td>3.7</td>
<td>0.8</td>
</tr>
<tr>
<td>CY</td>
<td>6</td>
<td>2</td>
<td>35</td>
<td>1</td>
<td>6.3</td>
<td>0.8</td>
</tr>
<tr>
<td>DB</td>
<td>6</td>
<td>8</td>
<td>32</td>
<td>1</td>
<td>4.8</td>
<td>0.7</td>
</tr>
<tr>
<td>DN</td>
<td>3</td>
<td>5</td>
<td>40</td>
<td>1</td>
<td>6.8</td>
<td>0.9</td>
</tr>
<tr>
<td>DV</td>
<td>9</td>
<td>4</td>
<td>33</td>
<td>1</td>
<td>5.1</td>
<td>0.9</td>
</tr>
<tr>
<td>EF</td>
<td>3</td>
<td>5</td>
<td>37</td>
<td>1</td>
<td>5.3</td>
<td>0.8</td>
</tr>
<tr>
<td>EG</td>
<td>6</td>
<td>2</td>
<td>28</td>
<td>1</td>
<td>3.0</td>
<td>0.9</td>
</tr>
<tr>
<td>EH</td>
<td>3</td>
<td>1</td>
<td>38</td>
<td>1</td>
<td>5.6</td>
<td>1.1</td>
</tr>
<tr>
<td>FB</td>
<td>12</td>
<td>15</td>
<td>38</td>
<td>1</td>
<td>6.7</td>
<td>1.1</td>
</tr>
<tr>
<td>FM</td>
<td>9</td>
<td>4</td>
<td>34</td>
<td>1</td>
<td>6.3</td>
<td>1.3</td>
</tr>
<tr>
<td>FN</td>
<td>6</td>
<td>2</td>
<td>37</td>
<td>1</td>
<td>5.6</td>
<td>0.5</td>
</tr>
<tr>
<td>GM</td>
<td>6</td>
<td>8</td>
<td>44</td>
<td>1</td>
<td>7.3</td>
<td>0.8</td>
</tr>
<tr>
<td>GN</td>
<td>3</td>
<td>5</td>
<td>40</td>
<td>1</td>
<td>5.6</td>
<td>1.0</td>
</tr>
<tr>
<td>HM</td>
<td>12</td>
<td>5</td>
<td>32</td>
<td>1</td>
<td>6.0</td>
<td>0.7</td>
</tr>
<tr>
<td>IL</td>
<td>9</td>
<td>12</td>
<td>40</td>
<td>1</td>
<td>7.0</td>
<td>0.5</td>
</tr>
<tr>
<td>JM</td>
<td>3</td>
<td>5</td>
<td>34</td>
<td>1</td>
<td>4.6</td>
<td>0.9</td>
</tr>
<tr>
<td>JO</td>
<td>6</td>
<td>2</td>
<td>39</td>
<td>1</td>
<td>5.6</td>
<td>0.7</td>
</tr>
<tr>
<td>KO</td>
<td>12</td>
<td>6</td>
<td>36</td>
<td>1</td>
<td>7.1</td>
<td>0.7</td>
</tr>
<tr>
<td>KP</td>
<td>6</td>
<td>8</td>
<td>41</td>
<td>1</td>
<td>7.4</td>
<td>0.6</td>
</tr>
<tr>
<td>LP</td>
<td>12</td>
<td>15</td>
<td>44</td>
<td>1</td>
<td>8.1</td>
<td>0.6</td>
</tr>
<tr>
<td>MI</td>
<td>9</td>
<td>4</td>
<td>36</td>
<td>1</td>
<td>6.2</td>
<td>0.6</td>
</tr>
<tr>
<td>NI</td>
<td>6</td>
<td>2</td>
<td>33</td>
<td>1</td>
<td>4.4</td>
<td>0.7</td>
</tr>
<tr>
<td>NU</td>
<td>12</td>
<td>14</td>
<td>37</td>
<td>1</td>
<td>6.9</td>
<td>0.7</td>
</tr>
<tr>
<td>QD</td>
<td>3</td>
<td>1</td>
<td>35</td>
<td>1</td>
<td>3.9</td>
<td>1.0</td>
</tr>
<tr>
<td>QF</td>
<td>6</td>
<td>2</td>
<td>42</td>
<td>1</td>
<td>6.8</td>
<td>1.0</td>
</tr>
<tr>
<td>QS</td>
<td>6</td>
<td>2</td>
<td>34</td>
<td>1</td>
<td>4.9</td>
<td>0.7</td>
</tr>
<tr>
<td>QS</td>
<td>6</td>
<td>2</td>
<td>30</td>
<td>1</td>
<td>5.2</td>
<td>0.7</td>
</tr>
<tr>
<td>RG</td>
<td>12</td>
<td>6</td>
<td>35</td>
<td>1</td>
<td>5.6</td>
<td>0.7</td>
</tr>
</tbody>
</table>
The target stimuli parameters were 12 modulation depths (1, 2, 2.5, 3, 3.5, 4, 4.5, 5, 6, 7, 9 and 12 dB(A)) at 4 $L_{\text{Aeq}}$ levels (30, 35, 40 and 45 dB(A)) for RFAM and MFAM with and without the presence of an unchanging level of garden noise within the masking signal. The resulting 192 stimuli were split into groups of 12 where modulation depth increased with stimuli number. The details of each group are shown in Table 17.6.
17.5.4 Final Test, participant subgroup 2

The stimuli consist of 8 modulation depths at 4 $L_{Aeq}$ levels for RFAM without the presence of garden noise within the masking signal. This gives 32 stimuli split into the following groups of 8 where modulation depth increases with stimuli number.

Two sets of these stimuli were produced. The first set replicates stimuli from Final Test I with a fixed overall $L_{Aeq}$. The second set has a fixed masking level with the modulation signal being gradually increased giving an increase to the overall level. This was done for validation purposes so that it could be ensured that the nature of the stimuli did not change sufficiently to affect perception when MN levels were reduced. The results are presented in Section 20.

<table>
<thead>
<tr>
<th>Stimulus Number</th>
<th>Modulation Type</th>
<th>$L_{Aeq}$ dB(A)</th>
<th>GN Present?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-8</td>
<td>RFAM</td>
<td>40</td>
<td>No</td>
</tr>
<tr>
<td>9-16</td>
<td>RFAM</td>
<td>35</td>
<td>No</td>
</tr>
<tr>
<td>17-24</td>
<td>RFAM</td>
<td>30</td>
<td>No</td>
</tr>
<tr>
<td>25-32</td>
<td>RFAM</td>
<td>25</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 17.7 Final Test, participant subgroup 2: Stimuli order and details

The target modulation depths are 0, 2, 3, 4, 5, 6, 9, 12 dB(A) and are derived from the average difference between the peak and trough in the A-weighted RMS of the stimuli.
18. Appendix VI: Participant instruction documents

18.1 Sensitivity Test I

Subjective Annoyance Listening Tests:
- Listen to the sound 'garden', this is the sound of wind blowing through the leaves and branches of trees, try to adjust this to a level that you would hear in your garden (imagine your garden has trees in it even if it doesn't in reality). Between 0 and 10, with 0 being not at all and 10 being very annoying, how would you rate this sound if heard in your garden after a hard day's work.

- in the same context, and on the same scale, now rate sounds A-Z.
- you can give as many sounds the same rating as you like and you can re-listen to any of the sounds as many times as you like.
- Please listen in a random order (already set to 'shuffle')
- If you feel you cannot accurately rate a sound, please put N/A in the corresponding box.

Figure 18.1 Test sheet for Sensitivity Test I
18.2 Sensitivity Test II

Subjective Annoyance Listening Tests
- Listen to the sound 'garden', this is the sound of wind blowing through the leaves and branches of trees, try to adjust this to a level that you would hear in your garden (imagine your garden has trees and/or bushes in it, even if it doesn't in reality).
- Record the number that appears on the volume slider at your chosen level.

| Adjustment: 60% |

Between 0 and 10, with 0 being not at all and 10 being very annoying, how would you rate this sound if heard in your garden after a hard day's work?

| Garden: 4 |

In the same context, and on the same scale, now rate sounds A-C, press |<>< and >>| to move through the playlist randomly.

You can give as many sounds the same rating as you like and you can re-listen to any of the sounds as many times as you like. If you feel you cannot accurately rate a sound, please put N/A in the corresponding box.

<table>
<thead>
<tr>
<th>AC</th>
<th>FB</th>
<th>NU</th>
<th>VT</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>AV</td>
<td>FM</td>
<td>QD</td>
<td>VU</td>
<td>10</td>
</tr>
<tr>
<td>AX</td>
<td>FN</td>
<td>QF</td>
<td>VY</td>
<td>7</td>
</tr>
<tr>
<td>BU</td>
<td>GM</td>
<td>QS</td>
<td>WD</td>
<td>8</td>
</tr>
<tr>
<td>BY</td>
<td>GN</td>
<td>RG</td>
<td>WF</td>
<td>7</td>
</tr>
<tr>
<td>CR</td>
<td>HM</td>
<td>RH</td>
<td>WG</td>
<td>8</td>
</tr>
<tr>
<td>CT</td>
<td>IL</td>
<td>RJ</td>
<td>XE</td>
<td>4</td>
</tr>
<tr>
<td>CY</td>
<td>JM</td>
<td>SB</td>
<td>XR</td>
<td>8</td>
</tr>
<tr>
<td>DB</td>
<td>JO</td>
<td>SC</td>
<td>XT</td>
<td>7</td>
</tr>
<tr>
<td>DN</td>
<td>KO</td>
<td>SV</td>
<td>YJ</td>
<td>6</td>
</tr>
<tr>
<td>DV</td>
<td>KP</td>
<td>TH</td>
<td>YK</td>
<td>4</td>
</tr>
<tr>
<td>EF</td>
<td>LP</td>
<td>TJ</td>
<td>ZE</td>
<td>8</td>
</tr>
<tr>
<td>EG</td>
<td>MI</td>
<td>UK</td>
<td>ZR</td>
<td>7</td>
</tr>
<tr>
<td>EH</td>
<td>NI</td>
<td>UL</td>
<td>ZW</td>
<td>6</td>
</tr>
</tbody>
</table>

Figure 18.2 Test sheet Sensitivity Test II
18.3 Final Test I and II

Instructions

Thank you for participating in this study. It is designed to investigate if fluctuations in Wind Turbine noise have an effect on how annoying the noise is.

Please sit facing the touch-screen, try not to move your head around too much, as the sounds you will hear are tailored to the centre point of the room.

Annoyance is an attribute that is heavily dependent on context. Therefore, we will be asking you to imagine you are hearing the sounds in specific situations. Try to imagine you are in your garden, relaxing and trying to enjoy your free time. The first sound you hear is the sound of wind in trees and bushes. This sound reflects how windy it is in your garden, so imagine there is moderate breeze.

Now, whilst you maintain this mental image, press ‘Begin’ and a control panel will appear. The ‘Test Sound’ button will be initially selected, this plays the reference sound for a minimum of 7 seconds. Listen to it until you can confidently rate how annoying this sound would be to hear in the imagined scenario. Use the slider on-screen to indicate this rating.

Now press the ‘Reference Sound’ button, this stops the test sound and begins the reference sound. Again, try to imagine how annoying this sound would be to hear in imagined scenario in your garden. Press the plus or minus buttons to change the level of part of the sound until it is of equal annoyance to the test sound. You can toggle between the two sounds until you are satisfied with your response, but please do not spend too long or think too hard about your answer as an initial answer is often the most natural. Press ‘Next’ when you are ready to move onto the next trial.

Please remember, your goal should always be to compare annoyance, if the sounds were heard at home, in your garden. Make sure that you are not simply adjusting the reference sound to equally loud as the test sound unless this also happens to be the point of equal annoyance.

Figure 18.3 Instruction sheet for Final Test and Validation
19. Appendix VII: Participant and observer comments

19.1 Participant observations

- Sounds were perceived by a number of participants to be very similar
- It was suggested for future experiments to use the descriptor ‘Intrusive’ which was one participant’s interpretation of the term annoyance.
- It was recommended to introduce timescales together with the rating on how annoyed participants were; i.e. Not at all annoying = I could sit and listen to this all day; Very annoying = This would annoy me within a few minutes. Alternatively, a specific imagined time duration was thought to be useful
- Some participants felt that different answers could be given for the same stimulus on two different instances. – Possibly a lack of consistency in context elicitation.
- One participant mentioned that the swish was reminiscent of prenatal ultrasounds, and as such was a pleasant sound! Had to make sure they were clear as to what wind turbines were and that the context was in the garden. In the participant’s individual results, this attitude is apparent as the increase in modulation led to a decrease in annoyance and equal annoyance level.

19.2 Observer comments

- 1 participant provided very polarised responses, either not at all annoying or very annoying. This highlights the problem that each participant’s range of realistic answers is not quantified, an approximation maybe to use Z-scores, or divide by measured range? Also brings about the dilemma of whether to tell participants to use the full range (currently done), or let them do what comes naturally.
- 1 participant had very narrow range on annoyance slider, around ‘not at all’. Also did not understand what annoyance meant, had to explain. Possibly language barrier.
20. **Appendix VIII: Results of validation test 1**

20.1 *Rating distributions*

![Graphs showing rating distributions](image)

Figure 20.1 Distribution of ratings a) for absolute annoyance scale, b) for the level difference between the ABBS and the AM stimuli with and without garden noise, mean = 2.2 dB(A), minimum rating = -11 dB(A).
20.2 Absolute Ratings

Figure 20.2 Absolute annoyance ratings as a function of modulation depth for four different scenarios. The legend specifies the $L_{Aeq}$ of the test stimuli in dB(A).
20.3 ABBS results

Figure 20.3 Absolute ABBS $L_{Aeq}$ as a function of modulation depth for two types of modulation and in the presence and absence of masking garden noise.
Figure 20.4 ABBS -AM LAeq as a function of modulation depth for two types of modulation (RFAM left, MFAM right) and in the presence (bottom) and absence (top) of masking garden noise. The legend specifies the LAeq of the AM stimuli in dB(A).

The general features of Figure 20.4 a) -d) are very similar within the 95 % CI. Using two types of AM is not likely to produce different responses of statistical significance whereas the presence/absence of garden noise might become significant for the quieter stimuli for a larger sample of participants.
21. Appendix IX: Results of Validation Test II

One concern with stimuli of constant $L_{Aeq}$ was that to keep the level constant with increasing MD the masking noise had to be reduced which might have led to changes in signal character. In Validation Test II a subgroup of nine participants therefore also rated a set of stimuli with the same MD levels and masking levels of 25, 30, 35 and 40 dB(A). They used the procedure of adjusting ABBS for this test.

21.1 Rating distributions

![Figure 21.1 Distribution of ratings for the level difference between the ABBS and the AM stimuli with and without garden noise, mean = 2.6 dB(A), minimum rating = -15 dB(A). Absolute ratings were not recorded for this validation.](image)

21.2 ABBS results

In general the rating behaviour of the participants shown in Figure 21.2 was very similar for the two sets of stimuli.

Figure 21.2 a) and c) show the absolute ABBS $L_{Aeq}$ for the constant stimulus $L_{Aeq}$ and the constant masking noise $L_{Aeq}$ stimuli, respectively. The monotonous increase of the rating with modulation depth is evidence that the participants adjusted the louder stimuli to slightly higher ABBS $L_{Aeq}$ compared to a).
Figure 21.2 Comparison of equal annoyance ratings between stimuli with constant overall $L_{Aeq}$ (top) and constant masking noise with increasing $L_{Aeq}$ as a function of MD (bottom). Note that the legend has therefore a different meaning for top and bottom graphs. Left panel: absolute ABBS $L_{Aeq}$, right panel: ABBS-AM $L_{Aeq}$

Figure 21.2 b) and d) show the difference between ABBS and AM $L_{Aeq}$. Importantly, the increase of $L_{Aeq}$ due to the increasing MD was measured and the correct total stimulus $L_{Aeq}$ was used to calculate this difference. Therefore if the nature of the stimuli changed by reducing masking noise then a difference between b) and d) should be seen. However, within the 95 % confidence intervals b) and d) are very similar which suggests that by the nature of the stimuli is not changed significantly in terms of annoyance when reducing the masking noise to retain the total $L_{Aeq}$.
22. Appendix X: Annoyance ratings as a function of $L_{90}$

<table>
<thead>
<tr>
<th>$L_{A50}$ MD</th>
<th>$L_{A50}$</th>
<th>$L_{A10}$</th>
<th>$L_{A90}$</th>
<th>$L_{A50} - L_{A90}$</th>
<th>$L_{A10} - L_{A90}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>30dB(A)-0dB(A)</td>
<td>29.3</td>
<td>29.7</td>
<td>28.8</td>
<td>0.5</td>
<td>0.9</td>
</tr>
<tr>
<td>30dB(A)-2dB(A)</td>
<td>29.5</td>
<td>30.1</td>
<td>28.8</td>
<td>0.7</td>
<td>1.3</td>
</tr>
<tr>
<td>30dB(A)-3dB(A)</td>
<td>29.5</td>
<td>30.5</td>
<td>28.5</td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td>30dB(A)-4dB(A)</td>
<td>29.2</td>
<td>30.7</td>
<td>27.9</td>
<td>1.3</td>
<td>2.8</td>
</tr>
<tr>
<td>30dB(A)-5dB(A)</td>
<td>29.6</td>
<td>31.6</td>
<td>27.7</td>
<td>1.9</td>
<td>3.9</td>
</tr>
<tr>
<td>30dB(A)-6dB(A)</td>
<td>29.4</td>
<td>31.9</td>
<td>27.2</td>
<td>2.2</td>
<td>4.7</td>
</tr>
<tr>
<td>30dB(A)-9dB(A)</td>
<td>29.8</td>
<td>33.1</td>
<td>26.0</td>
<td>3.8</td>
<td>7.1</td>
</tr>
<tr>
<td>30dB(A)-12dB(A)</td>
<td>29.6</td>
<td>33.4</td>
<td>23.6</td>
<td>6.0</td>
<td>9.8</td>
</tr>
</tbody>
</table>

Table 22.1 Measured $L_A$ metrics for nominal 30 dB(A) AM stimuli
Figure 22.1 Annoyance ratings as a function of L90 b) in comparison to ratings as a function of $L_{A_{eq}}$ a) (identical to Figure 9.2)
Figure 22.2 ABBS ratings normalised by a) $L_{Aeq}$ (identical to Figure 9.5), b) $L_{A90}$
### 23. Appendix XI: Data tables

#### 23.1 Final Test composite figures

<table>
<thead>
<tr>
<th>Modulation Depth, dB(A)</th>
<th>RFAM L$_{Aeq}$</th>
<th>Annoyance Rating</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>45</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>2</td>
<td>45</td>
<td>4.72</td>
<td>0.93</td>
</tr>
<tr>
<td>3</td>
<td>45</td>
<td>5.22</td>
<td>1.25</td>
</tr>
<tr>
<td>4</td>
<td>45</td>
<td>6.17</td>
<td>1.04</td>
</tr>
<tr>
<td>5</td>
<td>45</td>
<td>5.48</td>
<td>1.16</td>
</tr>
<tr>
<td>6</td>
<td>45</td>
<td>6.05</td>
<td>1.18</td>
</tr>
<tr>
<td>9</td>
<td>45</td>
<td>5.72</td>
<td>1.10</td>
</tr>
<tr>
<td>12</td>
<td>45</td>
<td>6.05</td>
<td>1.18</td>
</tr>
<tr>
<td>0</td>
<td>40</td>
<td>2.81</td>
<td>1.04</td>
</tr>
<tr>
<td>2</td>
<td>40</td>
<td>3.52</td>
<td>1.00</td>
</tr>
<tr>
<td>3</td>
<td>40</td>
<td>3.78</td>
<td>1.07</td>
</tr>
<tr>
<td>4</td>
<td>40</td>
<td>3.67</td>
<td>1.00</td>
</tr>
<tr>
<td>5</td>
<td>40</td>
<td>4.41</td>
<td>1.00</td>
</tr>
<tr>
<td>6</td>
<td>40</td>
<td>4.17</td>
<td>1.05</td>
</tr>
<tr>
<td>9</td>
<td>40</td>
<td>4.86</td>
<td>1.34</td>
</tr>
<tr>
<td>12</td>
<td>40</td>
<td>5.71</td>
<td>1.38</td>
</tr>
<tr>
<td>0</td>
<td>35</td>
<td>0.65</td>
<td>0.44</td>
</tr>
<tr>
<td>2</td>
<td>35</td>
<td>1.64</td>
<td>0.73</td>
</tr>
<tr>
<td>3</td>
<td>35</td>
<td>2.12</td>
<td>0.62</td>
</tr>
<tr>
<td>4</td>
<td>35</td>
<td>2.22</td>
<td>0.66</td>
</tr>
<tr>
<td>5</td>
<td>35</td>
<td>2.36</td>
<td>0.85</td>
</tr>
<tr>
<td>6</td>
<td>35</td>
<td>3.31</td>
<td>0.98</td>
</tr>
<tr>
<td>9</td>
<td>35</td>
<td>3.79</td>
<td>1.24</td>
</tr>
<tr>
<td>12</td>
<td>35</td>
<td>3.97</td>
<td>1.26</td>
</tr>
<tr>
<td>0</td>
<td>30</td>
<td>0.09</td>
<td>0.12</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>1.18</td>
<td>0.77</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>1.42</td>
<td>0.51</td>
</tr>
<tr>
<td>4</td>
<td>30</td>
<td>1.54</td>
<td>0.63</td>
</tr>
<tr>
<td>5</td>
<td>30</td>
<td>1.80</td>
<td>0.62</td>
</tr>
<tr>
<td>6</td>
<td>30</td>
<td>2.56</td>
<td>0.86</td>
</tr>
<tr>
<td>9</td>
<td>30</td>
<td>2.74</td>
<td>1.05</td>
</tr>
<tr>
<td>12</td>
<td>30</td>
<td>3.46</td>
<td>1.12</td>
</tr>
<tr>
<td>0</td>
<td>25</td>
<td>0.11</td>
<td>0.14</td>
</tr>
<tr>
<td>2</td>
<td>25</td>
<td>0.13</td>
<td>0.08</td>
</tr>
<tr>
<td>3</td>
<td>25</td>
<td>0.48</td>
<td>0.29</td>
</tr>
<tr>
<td>4</td>
<td>25</td>
<td>0.58</td>
<td>0.34</td>
</tr>
<tr>
<td>5</td>
<td>25</td>
<td>1.40</td>
<td>0.58</td>
</tr>
<tr>
<td>6</td>
<td>25</td>
<td>1.23</td>
<td>0.48</td>
</tr>
<tr>
<td>9</td>
<td>25</td>
<td>1.69</td>
<td>0.84</td>
</tr>
<tr>
<td>12</td>
<td>25</td>
<td>2.89</td>
<td>1.27</td>
</tr>
</tbody>
</table>

Table 23.1 Annoyance rating data for Figure 9.2 and Figure 9.3. Note that the unmodulated stimulus was not included for L$_{Aeq}$ = 45 dB(A).
<table>
<thead>
<tr>
<th>Modulation Depth, dB(A)</th>
<th>RFAM $L_{Aeq}$</th>
<th>ABBS $L_{Aeq}$</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>45</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>2</td>
<td>45</td>
<td>46</td>
<td>1.0</td>
</tr>
<tr>
<td>3</td>
<td>45</td>
<td>46</td>
<td>1.1</td>
</tr>
<tr>
<td>4</td>
<td>45</td>
<td>46</td>
<td>0.8</td>
</tr>
<tr>
<td>5</td>
<td>45</td>
<td>46</td>
<td>1.4</td>
</tr>
<tr>
<td>6</td>
<td>45</td>
<td>46</td>
<td>1.7</td>
</tr>
<tr>
<td>9</td>
<td>45</td>
<td>45</td>
<td>1.8</td>
</tr>
<tr>
<td>12</td>
<td>45</td>
<td>46</td>
<td>1.8</td>
</tr>
<tr>
<td>0</td>
<td>40</td>
<td>38</td>
<td>1.4</td>
</tr>
<tr>
<td>2</td>
<td>40</td>
<td>41</td>
<td>1.3</td>
</tr>
<tr>
<td>3</td>
<td>40</td>
<td>41</td>
<td>0.9</td>
</tr>
<tr>
<td>4</td>
<td>40</td>
<td>42</td>
<td>1.6</td>
</tr>
<tr>
<td>5</td>
<td>40</td>
<td>42</td>
<td>1.7</td>
</tr>
<tr>
<td>6</td>
<td>40</td>
<td>42</td>
<td>1.7</td>
</tr>
<tr>
<td>9</td>
<td>40</td>
<td>42</td>
<td>2.4</td>
</tr>
<tr>
<td>12</td>
<td>40</td>
<td>42</td>
<td>2.6</td>
</tr>
<tr>
<td>0</td>
<td>35</td>
<td>34</td>
<td>1.4</td>
</tr>
<tr>
<td>2</td>
<td>35</td>
<td>36</td>
<td>1.2</td>
</tr>
<tr>
<td>3</td>
<td>35</td>
<td>38</td>
<td>2.4</td>
</tr>
<tr>
<td>4</td>
<td>35</td>
<td>37</td>
<td>2.4</td>
</tr>
<tr>
<td>5</td>
<td>35</td>
<td>37</td>
<td>1.7</td>
</tr>
<tr>
<td>6</td>
<td>35</td>
<td>38</td>
<td>1.6</td>
</tr>
<tr>
<td>9</td>
<td>35</td>
<td>39</td>
<td>2.6</td>
</tr>
<tr>
<td>12</td>
<td>35</td>
<td>37</td>
<td>2.5</td>
</tr>
<tr>
<td>0</td>
<td>30</td>
<td>30</td>
<td>1.2</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>33</td>
<td>1.4</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>33</td>
<td>1.4</td>
</tr>
<tr>
<td>4</td>
<td>30</td>
<td>33</td>
<td>1.4</td>
</tr>
<tr>
<td>5</td>
<td>30</td>
<td>34</td>
<td>2.2</td>
</tr>
<tr>
<td>6</td>
<td>30</td>
<td>34</td>
<td>1.6</td>
</tr>
<tr>
<td>9</td>
<td>30</td>
<td>34</td>
<td>3.2</td>
</tr>
<tr>
<td>12</td>
<td>30</td>
<td>34</td>
<td>2.6</td>
</tr>
<tr>
<td>0</td>
<td>25</td>
<td>26</td>
<td>1.5</td>
</tr>
<tr>
<td>2</td>
<td>25</td>
<td>28</td>
<td>1.0</td>
</tr>
<tr>
<td>3</td>
<td>25</td>
<td>30</td>
<td>2.1</td>
</tr>
<tr>
<td>4</td>
<td>25</td>
<td>30</td>
<td>2.1</td>
</tr>
<tr>
<td>5</td>
<td>25</td>
<td>30</td>
<td>2.5</td>
</tr>
<tr>
<td>6</td>
<td>25</td>
<td>29</td>
<td>2.8</td>
</tr>
<tr>
<td>9</td>
<td>25</td>
<td>31</td>
<td>2.4</td>
</tr>
<tr>
<td>12</td>
<td>25</td>
<td>32</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Table 23.2 Data for Figure 9.4. - Note that the unmodulated stimulus was not included for $L_{Aeq} = 45$ dB(A).
<table>
<thead>
<tr>
<th>Modulation Depth, dB(A)</th>
<th>RFAM $L_{Aeq}$</th>
<th>ABBSS - RFAM $L_{Aeq}$</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>45</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>2</td>
<td>45</td>
<td>0.7</td>
<td>1.0</td>
</tr>
<tr>
<td>3</td>
<td>45</td>
<td>0.9</td>
<td>1.1</td>
</tr>
<tr>
<td>4</td>
<td>45</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>5</td>
<td>45</td>
<td>0.7</td>
<td>1.4</td>
</tr>
<tr>
<td>6</td>
<td>45</td>
<td>0.7</td>
<td>1.7</td>
</tr>
<tr>
<td>9</td>
<td>45</td>
<td>0.1</td>
<td>1.8</td>
</tr>
<tr>
<td>12</td>
<td>45</td>
<td>1.1</td>
<td>1.8</td>
</tr>
<tr>
<td>0</td>
<td>40</td>
<td>-2.5</td>
<td>1.4</td>
</tr>
<tr>
<td>2</td>
<td>40</td>
<td>1.2</td>
<td>1.3</td>
</tr>
<tr>
<td>3</td>
<td>40</td>
<td>1.3</td>
<td>0.9</td>
</tr>
<tr>
<td>4</td>
<td>40</td>
<td>1.6</td>
<td>1.6</td>
</tr>
<tr>
<td>5</td>
<td>40</td>
<td>1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>6</td>
<td>40</td>
<td>1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>9</td>
<td>40</td>
<td>1.8</td>
<td>2.4</td>
</tr>
<tr>
<td>12</td>
<td>40</td>
<td>1.6</td>
<td>2.6</td>
</tr>
<tr>
<td>0</td>
<td>35</td>
<td>-1.4</td>
<td>1.4</td>
</tr>
<tr>
<td>2</td>
<td>35</td>
<td>0.8</td>
<td>1.2</td>
</tr>
<tr>
<td>3</td>
<td>35</td>
<td>2.6</td>
<td>2.4</td>
</tr>
<tr>
<td>4</td>
<td>35</td>
<td>2.4</td>
<td>2.4</td>
</tr>
<tr>
<td>5</td>
<td>35</td>
<td>2.4</td>
<td>1.7</td>
</tr>
<tr>
<td>6</td>
<td>35</td>
<td>2.7</td>
<td>1.6</td>
</tr>
<tr>
<td>9</td>
<td>35</td>
<td>3.7</td>
<td>2.6</td>
</tr>
<tr>
<td>12</td>
<td>35</td>
<td>2.3</td>
<td>2.5</td>
</tr>
<tr>
<td>0</td>
<td>30</td>
<td>0.5</td>
<td>1.2</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>2.6</td>
<td>1.4</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>3.0</td>
<td>1.4</td>
</tr>
<tr>
<td>4</td>
<td>30</td>
<td>3.0</td>
<td>3.2</td>
</tr>
<tr>
<td>5</td>
<td>30</td>
<td>3.7</td>
<td>2.2</td>
</tr>
<tr>
<td>6</td>
<td>30</td>
<td>3.5</td>
<td>1.6</td>
</tr>
<tr>
<td>9</td>
<td>30</td>
<td>4.3</td>
<td>3.2</td>
</tr>
<tr>
<td>12</td>
<td>30</td>
<td>3.6</td>
<td>2.6</td>
</tr>
<tr>
<td>0</td>
<td>25</td>
<td>1.1</td>
<td>1.5</td>
</tr>
<tr>
<td>2</td>
<td>25</td>
<td>2.6</td>
<td>1.0</td>
</tr>
<tr>
<td>3</td>
<td>25</td>
<td>5.0</td>
<td>2.1</td>
</tr>
<tr>
<td>4</td>
<td>25</td>
<td>4.5</td>
<td>2.5</td>
</tr>
<tr>
<td>5</td>
<td>25</td>
<td>5.3</td>
<td>2.4</td>
</tr>
<tr>
<td>6</td>
<td>25</td>
<td>4.2</td>
<td>2.8</td>
</tr>
<tr>
<td>9</td>
<td>25</td>
<td>5.5</td>
<td>2.4</td>
</tr>
<tr>
<td>12</td>
<td>25</td>
<td>6.9</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Table 23.3 Data for Figure 9.5 - Note that the unmodulated stimulus was not included for $L_{Aeq} = 45$ dB(A).
Work Package C
Collation and analysis of existing acoustic recordings

Hoare Lea Acoustics
Wind Turbine Amplitude Modulation: Research to Improve Understanding as to its Cause & Effect

Work Package C (WPC) - Collation and Analysis of Existing Acoustic Recordings
WIND TURBINE AMPLITUDE MODULATION: RESEARCH TO IMPROVE UNDERSTANDING AS TO ITS CAUSE & EFFECT
WPC - COLLATION AND ANALYSIS OF EXISTING ACOUSTIC RECORDINGS

Andrew Bullmore, Matthew Cand
HOARE LEA Acoustics
140 Aztec West Business Park
Almondsbury
Bristol
BS32 4TX

Tel: 01454 201 020
Fax: 01454 201 704

Audit Sheet

<table>
<thead>
<tr>
<th>Revision</th>
<th>Description</th>
<th>Date</th>
<th>Issued by</th>
<th>Reviewed by</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Draft for comment</td>
<td>30/11/2011</td>
<td>MMC</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Revision following comments</td>
<td>13/01/2012</td>
<td>MMC</td>
<td>AB</td>
</tr>
<tr>
<td>3</td>
<td>Minor consistency updates</td>
<td>09/03/2012</td>
<td>MMC</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Update following comments</td>
<td>10/04/2012</td>
<td>MMC</td>
<td>AB</td>
</tr>
</tbody>
</table>
Executive Summary

The objective of Work Package C was to collate and assess existing evidence, and in particular available recorded samples of wind turbine noise containing amplitude modulation, in order to provide input to the research on further understanding the cause and effect of amplitude modulated wind turbine noise. A review of the available and published evidence was therefore undertaken at the outset of the project in order to provide some initial steer to the project overall. The review then continued throughout the project as further information became available. In order to maximise the usefulness to the research, relevant data was proactively sought from the wind turbine noise community. The data acquired was reviewed and analysed. Relevant existing data which had been acquired prior to the commencement of the project, and the analysis of this data made by members of the project team, was also used to allow prompt progress to be made towards achieving the project aims within the required timescales. The results of these analyses, and a selection of the audio samples used as the basis for these analyses, were used as an input to other work packages. A review of the available evidence and literature was also undertaken.

This Non-Technical Summary contains an overview of the report and its conclusions. No reliance should be placed on the content of this Non-Technical Summary until this report has been read in its entirety.
1 INTRODUCTION

1.1.1 The work presented in this report is part of project funded by RenewableUK and entitled ‘Wind Turbine Amplitude Modulation: Research to Improve Understanding as to its Cause & Effect’. The project comprises a total of six separate work packages. The outcome results of each of the work packages have separately resulted in their own dedicated final reports. A seventh work package, WPF, has produced an overarching final report in which the key findings across the separate work packages have been collated and discussed.

1.1.2 This is the final report of Work Package WPC: ‘collation and analysis of existing acoustic recordings’.

1.1.3 Wind turbine aerodynamic noise, by which is meant the noise produced by the rotating wind turbine blades, includes a steady component as well as, in some circumstances, a periodically fluctuating, or amplitude modulated (AM), component. However, AM may take different forms. One form of AM, commonly referred to as ‘blade swish’, is an inherent feature of the operation of all wind turbines. It can be explained by well understood mechanisms, it being the result of the directivity characteristics of the noise created by the air flowing over a turbine blade as it rotates. Because this type of AM is an inherent feature of the operation of wind turbines, whose origin can be explained and modelled, the present project adopts as its definition the term ‘normal amplitude modulation’ (NAM). The key driver for the project, however, is the recognition that some AM exhibits characteristics that fall outside those expected of NAM. Such characteristics include a greater depth of modulation, different directivity patterns or a changed noise character. For this reason the present project adopts as its definition the term ‘other amplitude modulation’, or ‘OAM’, for all observations of AM that lie outside that expected of NAM.

1.1.4 In recent years public concern has grown about the potential annoyance from wind turbine OAM noise. This concern has resulted in an increased interest to establish how AM, and in particular OAM, occurs, how it can be better defined and measured, and how it is generally perceived and responded to. It is the answers to these questions that the present project seeks to address.

1.1.5 To provide input to this research, it was identified early on that real-world acoustic data would be required as a key input. To allow prompt progress and to maximise the ability to achieve the project aims within the required timescales, it was considered essential to make use of relevant existing data. This existing data included both that acquired previously by some members of the project team and data available within the wind energy community as a whole. The latter data was proactively sought by the project team. In this manner, acoustic data became available to the project which had been collected for a wide variety of purposes. This constituted Work Package C of the current project, which was undertaken by Hoare Lea Acoustics.

1.1.6 As part of Work Package C of the project, the aforementioned acoustic data and associated recordings were analysed and any relevant observations collated. This provided the required input to other key elements of the project:

- Work Package A – Fundamental Research into the Causes of Amplitude Modulation

2 APPROACH AND METHODOLOGY

2.1 Review of available evidence

2.1.1 At the project outset, a review of the current knowledge and experience of AM was undertaken in order to provide a starting point for investigations. This review collated existing knowledge and reviewed any further studies or information since the work undertaken in 2007 by the
One of the complicating factors of the present study is that wind turbine noise generally only becomes an issue where it adversely affects residential neighbours to wind farms. The issue as to whether or not a particular wind farm may cause problematic noise therefore generally relies on the reliable and consistent reporting of its effects by those living in the vicinity of the wind farm. The review and interpretation of available information is complicated by the difficulty in establishing the relevance of reported experiences and disturbances of wind farm neighbours from wind turbine noise, and in particular the relevance of the widely varying descriptions used by those reporting it. The potential issue of relating subjective descriptions to actual effects applies particularly to the specific subject of Amplitude Modulation noise from wind farms, especially when it is appreciated that this potential feature of the noise may vary and/or take different forms, each of which may be self-reported using different descriptors across different subjects.

Previous research [2] undertaken in 2006 following reports of disturbance from a limited number of wind farms in the UK, reportedly from low-frequency noise, identified that in these cases the complaints were, in fact, more likely related to increased level of amplitude modulation of the blade passing noise. Although the blade passing frequencies at which the wind farm noise may modulate are relatively low (of the order of one Hertz), this does not mean that the noise itself directly contains such low or infrasound frequencies.

In comparison, a 2010 study [3] commissioned by the Danish Energy Authority to study low-frequency noise from large wind turbines identified the presence of low-frequency tones associated with the operation of mechanical components in a prototype turbine as the source of reported annoyance from a wind farm neighbour. As a result, the research focussed in detail on the study of the subjective response to tonal noise. So in that study as well, a specific feature of the noise was identified as the source of the reported annoyance.

These considerations are complicated to a degree by the historical presence of infrasound in downwind turbine designs due to blade flow/tower interaction effects, which have now been effectively designed out of modern turbines through the use of upwind designs. The above-referenced studies, as well as more recent research [4] presented in 2011, have confirmed that there is no significant level of infrasound emitted from modern wind turbines.

The foregoing findings highlight the difficulties in interpreting subjective descriptions of noise, in particular by non-specialised observers, which includes the majority of wind farm neighbours. Experience has shown that a process of undertaking objective measurements and recordings, and then comparing and relating the experiences of those exposed to noise with objective data (if possible directly) is often necessary to clarify the cause of these complaints with the required degree of certainty. Reported disturbances from wind turbine noise, even after discounting non-acoustic factors, may just as likely be due to excessive overall levels of noise and/or significant tonal components rather than being related to AM. Acoustic evidence available from situations where complaints have arisen from effects other than AM are therefore of no relevance to the present project, even though the subjective descriptions assigned to such data may initially have led the project team to investigate the reported noise further.

In circumstances when tones are present in the noise emissions from wind turbines, this may be described using terms such as ‘rumble’ or ‘pulsing’ which may be interpreted as describing modulation of the aerodynamic noise, when this is not the case. In specific situations, tonal noise emissions have been found to vary in time (i.e. modulate at the blade passing frequency) as the mechanical source producing this tone varies along with the blade loading, but this was in cases of significant tonal emissions which can be readily assessed using methods to evaluate (non-stationary) tones [5]. This was therefore excluded from the scope of the current project.
2.2 Terminology and conclusions

2.2.1 As a result of the review outlined in Appendix A, the use of the term ‘AM’ was also perceived as introducing a degree of confusion. This term strictly relates to amplitude modulated noise, which could be used as a characteristic for several other sources of ambient noise. It is in particular an intrinsic feature of the noise emitted at source from wind turbines due to their rotation, but it has also sometimes been used as a short-hand to refer to cases where this modulation was found to be increased, enhanced or more prominent than expected at receptor locations. For example, the 2007 study\(^1\) by the University of Salford was based on a survey of reported disturbances from wind farm noise, but focused on reports in which the modulation was characterised by ‘a sharper attack and a more clearly defined character than usual’, which it defined as ‘AM’. Some observers have claimed, having reviewed the data from this research, that it underestimated the occurrence of amplitude modulation, but this interpretation is based on a wider definition of the term ‘AM’ than the one used by the authors of the report.

2.2.2 It is therefore important to distinguish between the ‘normal’ AM (NAM) which is understood to be an inherent feature of wind turbine noise, and ‘other’ instances of AM which have different characteristics.

2.2.3 The literature review undertaken identified research on this feature of the noise, from the early turbine designs in the late 90s, to recent noise models on larger, modern turbine designs, which can predict the modulation of the noise at source in normal conditions and were satisfactorily validated using near-field measurements. Therefore the mechanism explaining the ‘normal’ modulation of turbine noise and its characteristics is well understood, being a result of the directivity of the noise generated at the trailing edge noise of the blade as it rotates.

2.2.4 This could then be separated from the reports of ‘other’ types of AM (OAM)\(^1\) which could not be easily defined or understood using the theory outline above. There was at the outset of this project little agreement on:

- how this could be defined exactly, given that observations and reports were inconclusive;
- its causes, frequency of occurrence and degrees of severity, which could be due, or at least exacerbated by, the limited data and limited reports of the phenomenon, which creates a level of uncertainty.

2.2.5 There was also a lack of results or consensus on:

- how modulation translates to the far-field (i.e. at significant distances from the turbines, say at distances of 10 rotor diameters from the turbines);
- modulation metrics and subjective response.

2.3 Data sources

2.3.1 In view of the above review, data and information was sought to provide input to the other elements of the present RenewableUK AM research project, thereby maximising its potential value and provide as complete as possible a view of the subject, providing additional certainty where possible.

2.3.2 The project team (lead by Hoare Lea Acoustics) sought to approach third parties with a view to compiling a database of wind farm acoustic recordings, including different types of AM. This included:

- researchers
- acousticians and consultants
- wind farm operators and developers

\(^1\) The ‘Introduction and Project Overview’ (Section 1) to WPF contains a more detailed discussion concerning the definitions of NAM and OAM
The UK Government
advocacy groups and other interested parties

In particular, such an appeal was made as part of the presentation by the project team of a paper [6] at the 2011 Wind Turbine Noise Conference in Rome, which was attended by a great number of interested parties in the field.

Appendix B includes the data specification which was issued to third parties following initial contacts. It describes the requested acoustic data types, sometimes in order of preference as all may not be available, accessible or transferable. It also suggested relevant non-acoustic information which would assist in analysing the data.

A targeted search of relevant information and recordings available on the internet was also made, albeit bearing in mind that that significant caution should be exercised when considering the often limited information available for such data sources, along with the lack of quality control often associated with it.

The data measured on behalf of the UK Government as part of a previous research project on this subject, the 2006 study by Hayes McKenzie Partnership for the UK Department of Trade and Industry (DTI), was also sought and obtained from the Department of Energy and Climate Change.

In addition to seeking data from third parties, use was made of data held by members of the project team, including several long term measurements at a number of UK sites (in England, Wales and Scotland, across a range of terrains and turbine types and for both internal and external measurement locations) which were identified as being relevant to the current Work Package.

2.4 Data content and type

Experience has shown that measurements of wind turbine AM (of all kinds) can be challenging, particularly when considering measurements in the far-field.

Wind turbine noise, due to its relatively low levels, is often masked to at least some degree by ambient noise, even in relatively quiet rural locations, due to the presence of a variety of other noise sources associated with natural effects and with animal and human activities, although the latter tend to diminish during evening and night-time periods.

In addition, the temporal characteristics of AM noise make the acquisition of meaningful acoustic data which can be directly related to wind turbine AM even more prone to corruption by extraneous noise. In particular, the more usual level metrics (L_{Aeq}, L_{A90}) or temporal resolution (minutes, hours) implemented by traditional averaging sound level meters to assess overall levels of wind turbine noise or other steady sources of noise, are inadequate. This is because, whilst metrics that average noise over longer periods (such as the 10 minute average L_{A90,10min}) traditionally used to measure wind turbine overall noise levels) are effective at removing the effects of intermittent extraneous noise from the measured noise levels, they also remove shorter term effects that may be related to the wind turbine noise itself. This includes any AM, which for modern, large scale wind turbines typically occurs at a modulation rate of 1 second or less. As a consequence, measurements with an increased temporal resolution of significantly below 1 second, and typically closer to 0.1 second, are required in order to resolve AM effects. The problem here is that these shorter term measured levels then become prone to corruption by other extraneous short term noise, such as may be caused by bird song, livestock, passing cars, agricultural activities, etc. The shorter term measured noise levels can then either be characterised by overall A-weighted levels, or analysed in more detailed in terms of individual frequencies bands (such as 1/1 or 1/3 octave bands), with concurrent audio recordings providing the fullest record of the characteristics of the noise (and also, where necessary, enabling the positive subjective separation of turbine noise from extraneous noise). Collecting
2.4.4 Meteorological and turbine operational data allow the measured acoustic data to be related to the source conditions and atmospheric conditions. Any such data was sought, where available, as part of the work package. It must be recognised, however, that current practice is for wind data to be collected at a single height and location (typically the turbine hub height) with statistical information being based around 10 minute intervals. In recent years, remote meteorological scanning systems (SODAR or LIDAR) have become more widely used, allowing increased spatial sampling with measurement at different heights. Increased resolution in time is also possible with these systems. Notwithstanding the potential limitations of existing data even when available, obtaining site-specific meteorological and operational data often requires the collaboration of the wind farm operator and may not always be available to third parties. In the absence of other data, indicative area-wide meteorological information can be considered.

2.4.5 Where available, information on the wind farm sites in question was also collated including: site topography; turbine details, etc. Details of any associated complaints can also provide a useful guide to the analysis, provided one is mindful of the difficulties outlined above.

3 DATA OBTAINED AND ANALYSIS

3.1 Analysis of data and samples supplied

3.1.1 Following the request made according to the above procedure, a number of data packages were obtained from the sources identified.

3.1.2 The quality and quantity of the data acquired varied from clearly labelled and calibrated acoustic measurements to simple audio samples with very limited supporting information. Even in the latter case, it was nonetheless possible to analyse the character of the noise, but some questions remained as to the exact conditions of the measurements which could have affected the data collected to a more or less significant degree. Because of the recognised challenges involved in collecting long-term audio data outlined above, some of the quality of the audio files acquired was limited, particularly in historical recordings. Any such deficiencies were taken into account when interpreting the data.

3.1.3 In other cases, the data requested was not obtained despite follow-up requests, but overall a good return rate is considered to have been achieved, particularly given the challenging nature of the subject and the implications in terms of confidentiality requirements.

3.1.4 The study focused on the data received which was considered relevant to the current project. Some of the data acquired, such as that from some wind farm sites in Australia, did not seem to contain elevated levels of modulation when reviewed both subjectively using amplified playback and objectively using detailed signal analysis. The analysis did, however, in some cases reveal the presence of low-frequency tones which may have been the cause of the reported disturbance. Earlier in this report, the difficulties in interpreting the subjective descriptions of noise features were highlighted. Methods for tonal noise analysis have been developed and standardised in the recent years [5], but remain technically complex and require specialised knowledge and experience to apply. Similarly the subjective response to tonal noise has received extensive study, but this feature can be difficult to discern directly for the untrained ear. Therefore, claims of reported significant modulation, when little was audible could, in some cases, be ascribed to misinterpretation of subjective descriptions of the noise, or to the erroneous use of tools such as Fourier analysis which may appear to show some modulation where this may, in fact, more likely be due to artefacts of the processing.
3.1.5 Appendix C presents illustrative results of the analysis of the frequency content and time evolution of representative samples of the data considered in the project. The samples shown typically correspond to the clearest periods of modulation observed within the dataset and/or reported as corresponding to complaint conditions, for illustrative purposes. This may not however be representative of the nature of the noise experience for other periods or indeed for the majority of the time in some cases.

3.1.6 The following sections outline the key datasets analysed, a sample of which are illustrated in Appendix C.

**Van den Berg – Journal of Sound and Vibration article - 2004**

3.1.7 F. van den Berg supplied an audio recording of approximately 10 minutes’ duration. This corresponded to the period of modulation shown in a 2004 article in the Journal of Sound and Vibration [7] (Figure 8 in this article). This article described the measurement of modulated wind turbine sound ‘with an impulsive character’: see Appendix A. Measurements were made in the vicinity of a wind farm comprising 17 pitch-regulated, variable speed turbines, on relatively flat terrain. This recording was measured 750 m away from the nearest turbine of the wind farm in question, and approximately 2m from a reflective surface. The audio sample was supplied with a low-pass filtered applied above 1kHz to exclude the corrupting influence of background sources.

**The Measurement of Low Frequency Noise at Three UK Wind Farms (for the DTI)**

3.1.8 The full set of measurement data obtained at the three sites considered in the 2006 study by Hayes McKenzie Partnership (HMP) for the UK Department of Trade and Industry (DTI) was obtained. The project report details the measurements which were made in response to noise-related complaints at certain properties around three UK wind-farms, with measurements at various locations both inside and outside the properties concerned, which were related to complaint logs for the monitoring period.

3.1.9 Appendix C presents samples for the first two sites, from periods highlighted in the report. For the third site, the data corresponding to the period highlighted was not available due to a hardware failure; the data for this site was reported to be affected by significant levels of water-course noise which limited the clarity of the recordings. The other series of measurements are, however, considered sufficiently representative based on the report for this project.

3.1.10 Site 1 comprised seven fixed-speed pitch-regulated wind turbines, installed on hilly terrain. In easterly wind conditions, which were associated with the complaints, three of the turbines, the closest to the dwelling studied, tended to experience inappropriate wind conditions due to a local terrain feature. A noise reduction management system was therefore implemented to curtail the operation of some of the turbines in the wind conditions associated with the complaints, but this was not operating during the measurements. The analysis in Appendix C is shown for the external (free-field) measurement location, for the period highlighted in the HMP report (page 84 Annex 2).

3.1.11 Site 2 comprised sixteen stall-regulated wind turbines, located on a plateau amongst a rolling terrain. The measurements undertaken comprised internal and external (free-field) locations at a dwelling, which was located in a relatively sheltered hollow. The analysis shown in Appendix C was for one of the two periods highlighted in the HMP report (page 89 Annex 2) and in which the resident activated the recording system during the monthly measurement period.

**Internet audio sample**

3.1.12 Appendix C presents the analysis of an audio sample obtained from the internet [8], the sample being described as being representative of the experience of residential neighbours to a particular wind farm. There was very limited information available on the recording location,
equipment used etc.), which would assist in evaluating its quality, but it was reportedly made at a residential property and therefore in the far-field of the turbines. Some influence of unknown source (non-turbine related) was evident at higher frequencies (>1kHz), but the analysis shows clear levels of modulation of the noise at times.

**Australia/New Zealand + USA data**

3.1.13 As outlined in 3.1.4, the data received from various sources often did not contain significant levels of audible modulation. An example period is shown in Appendix C when a low level of modulation or rumbling is audible, although the exact conditions of the measurement were unclear. In some of the other recordings, the measurement appeared to have been made in the near-field of the turbines, where swish is expected to be experienced, but this would not necessarily be representative of conditions in the far-field.

**D. Bowdler near-field recording**

3.1.14 D. Bowdler supplied [9] a 25 second audio sample measured at the foot of a pitch-regulated wind turbine, approximately 45 degrees from a cross-wind direction. In the sample, a transition in the character of the modulating noise is clearly audible and apparent in the spectrogram between two different types of modulation, with the latter period having a clearly increased content at lower frequencies (in the 100 to 600Hz region). This sample is considered in WPA2 in further detail.

‘Other’ AM

3.1.15 This sample shows a spectrogram and time history for a period of ‘other’ AM, measured at a free-field location in the far-field of a wind farm site (>800m from the turbines), during a quiet period where little other sources of ambient noise were present. The terrain was relatively flat and the wind farm comprised several pitch-regulated machines. The modulation is dominated by frequencies in the region of 200-600Hz.

**3.2 Summary of sample analysis**

3.2.1 A representative selection of audio samples obtained was issued to the project team in the form of audio files. This information was used as input to inform those leading the other work packages.

3.2.2 Although the data was sometimes difficult to interpret due to interference from spurious sources of noise and natural variability, both of which are inherent to the analysis of wind turbine noise in the far-field, the analysis suggested that in periods of clear modulation, the observed far-field data fell broadly into two types of categories with differing spectral content:

A. A-weighted levels dominated by the 500-800Hz region;  
B. A-weighted levels dominated by the 200-600Hz region, with a slight-low frequency bias (peaking around 300Hz)

3.2.3 For the first category, this frequency range is consistent with existing literature on modulated ‘swish’ noise from wind turbines, associated with trailing edge noise from the turbine blades: this was therefore labelled as ‘mid-frequency AM’ (MFAM). The second category is different and was therefore labelled as ‘reduced-frequency AM (RFAM)’.

3.2.4 It was also observed that the frequency at which the sound modulated typically varied between 0.8Hz (for modern machines) and 1.3Hz (for older models), which is consistent with the rotational rate of the turbines.
3.3 Overview of other field experience

3.3.1 The experience of members of the project team was also considered, based on measurements undertaken at sites where ‘other’ AM was observed in the far-field. This followed complaints from the neighbouring residents of the sites in question. The observations made were not considered typical of past experience around other wind farm sites, hence the use of the ‘other AM’ category. Due to client confidentiality, it was not possible to circulate details and results of these measurements, but some general analysis results were discussed to support the progress of the research project.

3.3.2 At these sites, periods of modulation were measured in the far-field of the turbines (i.e. distances of 500 to 1km) in which the character and frequency content of the modulation noise was of a similar character to that shown in Appendix C as ‘other AM’, although the influence of background sources of noise often represented a complicating factor.

3.3.3 During periods of modulation, short-term changes in measured A-weighted noise levels of 5dB(A) or more could be observed at times, increasing to up to 10 dB(A) in exceptional cases. The modulation was dominated by frequencies in the 100-400 Hz region when measured internally, extending up to 600Hz externally but dominated by the 300 Hz region.

3.3.4 This feature was observed to be intermittent and often experienced for limited proportion of the total time, which is consistent with previously reported analysis [1]. But when present it can, at times, persist (to varying degrees) for extended periods of several minutes or hours.

3.3.5 Periods of modulation were in some cases associated with certain wind conditions (wind speeds and/or wind direction), although this dependence could be complex. It could generally not be established whether this was because the noise feature ceased to be generated or whether it was because the ambient conditions changed, leading to the noise being masked in the far-field. Further correlation with other operational parameters, apart from those indicating the turbine was generating, was generally inconclusive.

3.3.6 Based on the available data and the above analysis of the different instances reported, no common factors could be associated with different instances of site features or layout characteristic, topography, wind shear characteristics, turbine model and/or type, turbine proximity, turbine height or turbine proportions.

3.3.7 The foregoing experience, including the often contradictory evidence, led to the conclusion that the measurement parameters typically available for wind farm studies could not provide the required degree of evidence to directly identify potential causes for increased or atypical levels of modulation. It was the conclusion of the research group that a more extensive measurement survey and a detailed study of on-blade generation mechanisms was necessary to reach firmer conclusions.

2 See WPF for a further discussion on the lack of absolute definition of modulation depth. These indicative values refer to the typical peak-to-trough changes in A-weighted $L_{eq,T}$ levels, where $T$ is close to 100ms.
4 CONCLUSION

4.1.1 The objective of Work Package C was to collate and assess existing evidence, and in particular available recorded samples of wind turbine noise containing amplitude modulation, in order to provide input to the research on further understanding the cause and effect of amplitude modulated wind turbine noise. A review of the available and published evidence was therefore undertaken at the outset of the project in order to provide some initial steer to the project overall. The review then continued throughout the project as further information became available. In order to maximise the usefulness to the research, relevant data was proactively sought from the wind turbine noise community. The data acquired was reviewed and analysed. Relevant existing data which had been acquired prior to the commencement of the project, and the analysis of this data made by members of the project team, was also used to allow prompt progress to be made towards achieving the project aims within the required timescales. The results of these analyses, and a selection of the audio samples used as the basis for these analyses, were used as an input to other work packages.
5 REFERENCES


APPENDICES

Appendix A – Review of available literature and information
This appendix includes a brief review of current knowledge and experience of AM: relevant and available studies in the scientific and technical literature, as well as relevant reports of disturbance or complaints from wind turbines, focusing mainly in the UK but including as well available international experience.

A1) UK

ETSU-R-97

The ETSU-R-97 report [A1] noted that blade swish, defined as a rhythmic modulation of the aerodynamic noise of the turbines, can be audible in some circumstances by wind farm neighbours at typical separation distances. It suggested that it might be due to directivity of trailing edge noise, dependent on blade profile and tip speed, and it was described as being dominated by high frequencies: 800 – 1000 Hz and above. It will be more apparent closer to the turbines, with typical variations of 2-3 dB(A) in A-weighted levels, but with stronger variations in some frequency bands. But with increasing observer distance, because of atmospheric absorption, this modulation becomes less pronounced. As the relative contribution of background noise will also generally increase, this would reduce the prominence of the ‘swish’. The document reports variations in swish levels between different turbines, as well as site-specific variations for the same turbine type.

ETSU-R-97 on page 68 contains further descriptions of AM:

'This modulation of blade noise may result in a variation of the overall A-weighted noise level by as much as 3dB(A) (peak to trough) when measured close to a wind turbine. As distance from the wind farm increases, this depth of modulation would be expected to decrease because of atmospheric absorption […]. However, it has been found that positions close to reflective surfaces may result in an increase in the modulation depth […]. If there are more than two hard, reflective surfaces, then the increase in modulation depth may be as much as +/- 6dB(A) (peak to trough).'

Due to standing wave effects from reflection from building structures, the modulation in specific frequency bands can increase significantly.

The noise limits defined within ETSU-R-97 were established on the basis that they took account of the noise from wind turbines containing a certain level of AM, but the report also suggested that it would be useful to undertake further work to understand and assess this feature of wind turbine noise.

Additional UK research

A report for ETSU in the UK in 1999 [A2] monitored turbine noise at close range of what would currently be considered a relatively small turbine (32 m to the hub). It concluded that ‘the experimentally observed modulation [measured close to the turbine] is due to a combination of tower shadow effects as the blades pass the tower plus the preferential radiation of noise into some directions in preference to others.’ It should be noted that that this ‘shadow effect’ was a predominantly a shielding mechanism rather than a blade-tower interaction effect, the test turbine being of the upwind type.

The modulation observed above 1 kHz, which was more marked than at 500 Hz and below, was found to be strongly correlated to yaw error, but not with wind shear or turbulence intensity, and only weakly correlated with wind speed.

Jiggins [A3] measured turbine swish from several wind farm sites in some detail, both at close range and further away from several wind turbine sites. The turbines studied were also relatively small in size compared to more recent machines.

He noted variations in the time between peaks, which may have been due to the contributions of different turbines. Variations in time in the depth of the modulation (observed in a limited
First Site

A.21 Several complaints were received from 4 locations: ‘Loud/noisy’, ‘rhythmic’ ‘thumping’, ‘sometimes overlapping’, ‘like a washing machine’. No complaints were recorded following remedial works in 2004, which we understand comprised the addition of serrated edges to the turbine blades. The Salford analysis suggests that the weather conditions in which the AM was found to occur would be present on average around 15% of the time.

Second Site

A.22 In the report by the local authority, AM was described as being ‘like train in next field’ and ‘percussive’ with what was termed the ‘Van Den Berg effect (i.e. AM) apparent occasionally’. This is thought to refer to the results published by Van Den Berg which are described below. ‘The characteristics of the noise -chopping, whoomphing etc- are very noticeable even at levels below 35dB(A). An example: LA90 34dB, noise judged to be a nuisance at 600m UPWIND of turbines.’ A consultant considered the nature of the topography i.e. landform sloping downwards from the turbines contributed to the characteristics of the noise. Measurements ‘have indicated that third octave band levels when complaints were received before the implementation of wind turbine control features, indicated level changes of 12–15dB.’

A.23 A ‘library’ of conditions leading to complaints was arduously built up and noise management system put in place. Complaints have reduced dramatically since this system was put in place. It was found that ‘AM occurred specifically for Easterly winds and for speeds from the cut-in speed, of around 5m/s, up to 10 m/s measured at a height of 10m above ground level’. Specifically, ‘AM on this site was associated with three specific wind turbines. To alleviate the problem, a turbine control system was programmed to shut down these three machines for wind directions between 55° and 130°.’

A.24 Wind shear effects associated with conditions of high atmospheric stability can be dismissed as a cause there, as they were found to be very limited at the site based on local anemometry measurements. However, the Salford report did note that ‘topographical effects result in some wind turbines being ‘unsure’ as to the wind direction. This is caused by the wind turbine wind vane being influenced by the wind direction at the hub height of the rotor but the wind direction at the lower arc of the rotor may be from a different direction.’ This may have resulted in elevated angles of attack of the flow on the blades.

Third Site

A.25 One complainant describes periods of operation when amplitude modulation of the aerodynamic noise (AM) is clearly audible inside and outside the building. The Salford report notes that this occurred when the wind direction was in a narrow sector, and the wind speed in a given range (neither very high or very low). Analysis of long-term anemometry data led the authors to conclude that the range of conditions associated with AM would be expected to occur for 7% of the year on average.

Fourth Site

A.26 The noise character was described as AM, with ‘swoosh swish’ and ‘beating (rhythmic)’. During the site visit, council representatives reportedly experienced audible blade noise ‘whoosh’.
Bowdler review

A.27 Bowdler [A8] reviews the state of knowledge at the time of the article to assist with further work on the subject. He notes that the general descriptions of AM in refs [A1] and [A2] are consistent with the subsequent work of Oerlemans and Scheper [A9], which showed that the directivity of the trailing edge noise from the blade, combined with the Doppler amplification effect of the blade movement, would explain the ‘normal’ swishing noise of a turbine. More recent research by these authors [A10] has validated this model using measurements, and shown that ‘for both cross-wind directions, the average level is lower than in the up- and downwind directions, but the variation in level is larger.’

A.28 Bowdler describes his observation that, in a crosswind direction the swish reduces, and that the ‘maximum modulation’ is experienced at 45 degrees from the crosswind direction. In the model of Oerlemans and Scheper, at 45 degrees from crosswind there is a combination of both high absolute noise level and deeper modulation.

A.29 He argues that effects of radiation directivity may not always decrease with increased separation distance in some situations, in particular at 45 degrees from downwind, because of the shadowing effect from the tower in one case. He also considers that the Oerlemans model can be interpreted as describing normal turbine swish as opposed to the other types of AM.

A.30 Bowdler also reviews the complaints related to AM at Deeping St Nicholas and proposes a likely correlation of specific ‘thump’ occurrences to the 45-degrees-from-crosswind conditions discussed above; however this interpretation need to be taken with caution because of uncertainties as to the exact wind direction reference used. Bowdler also discusses the Wharrels Hill site but notes that ‘thump’ was not observed there.

A2) Europe

A.31 As noted in Reference [A5], European regulations on wind turbine noise are generally stated in terms of maximum dB(A) noise levels and make no explicit allowances for AM, although some national standards provide methods for rating characteristics such as impulsivity.

Van den Berg publications

A.32 Van den Berg [A11] has described measurements at a 30MW, 17-turbine wind farm located on the Dutch-German border. One of the main findings of this research was that measured sound levels were higher than predicted at set 10 m height wind speeds because of wind shear effects, which are now well-recognised and incorporated in the study of wind farms in the UK according to best practice.

A.33 But another of the reported main findings is that ‘wind turbines can produce sound with an impulsive character.’ The ‘thumping’ nature of the wind turbine sound was observed in some occasions, and the author suggested that this must have contributed to the annoyance of the residents. The example illustrated in the article shows a modulation of up to 5 dB(A) (peak to trough) measured at 750 m from the nearest turbine, 2 m away from a reflective surface and in the middle of the night. Pulses of depth 3-4 dB occurred for dozen of seconds with the worst cases impulses for no more than ~3 s; they are also described as more ‘pronounced and annoying’ at higher rotational speeds. The noise level graph shown exhibits an impulsive shape. The frequency and conditions of occurrence are not described.

A.34 Van den Berg distinguishes the normal ‘swish’, which can be heard during most conditions and other types, such as the more pronounced ‘thump’ described in the paper. Van den Berg has stated that he did not consider the form of the turbine layout (i.e. turbines in line or ‘randomly’ laid out) was not more likely to lead to ‘impulsiveness’ (verbal evidence at the Bald Hills Wind Farm Project hearing, as reported in Ref. [A12]).

A.35 The varying depth of modulation reported in the JSV article was attributed by the author to short periods of synchronisation in phase of the rotation of the dominant turbines (closest to the measurement location). He speculated that this emission of pulses would not be apparent in measurements of single turbines, because of his proposed synchronisation effect. The author
also suggests that the interaction of the blade passing the tower influences the character of the noise.

A.36 Bowdler in [A8] casts some doubt on this analysis as the modulation depth would not increase if turbines become in phase. Examining this hypothesis in his review, Bowdler notes that: “it is perhaps more correct to suggest not that, when turbine noises are in phase the level increases, but rather that when they are out of phase the modulation is reduced because they average each other out’. Bowdler also notes that in modern upwind turbine configurations, blade-tower interaction effects have been shown [A9] to be marginal acoustically. Bowdler notes that in other publications, Van den Berg has attributed AM clapping or beating to wind velocity differentials across the turbine rotor associated with wind shear, and Bowdler suggests similar differentials could occur with turbulence of meteorological or topographical origin.

Finland - Di Napoli

A.37 In 2009, Di Napoli presented [A13] measurements made at single, isolated 1 MW turbine (66 m hub height, pitch regulated), located approximately 750 m from holiday houses in Finland. Measurement made at a point 530 m from the turbine showed some AM, with levels generally varying with wind speed but some periods of clear, apparently impulsive peaks at blade passing frequency, with a worst-case amplitude of 5 dB peak-to-trough for at least a few seconds.

A.38 The author describes this as generally occurring as wind speed decreased or stopped accelerating, and reports observing it to a certain degree during most of the recording on the day of the measurements. Some ‘notches’ or double-pulses were apparent at times. These results indicate that whilst turbine-turbine interaction may be a contributory factor in some cases, it is not the only potential cause of AM effects.

A.39 In 2011 the same author reported [A14] measurements at different distances from a wind farm in Finland consisting of 5 stall-regulated 600kW turbines. He reports levels of modulation in the far-field, most notably in downwind directions, at distances of 500m to up to 2km. The results appear to show the modulation increasing and then decreasing as the measurement location moved from the near-field to the far-field. Some example periods of modulation are illustrated by the time-evolution of A-weighted levels with time.

Other

A.40 Legarth [A15] notes that for modern turbines, the modulation was dominated by the frequencies in the range of 350 to 700Hz, based on recordings made at distances of 1.5 to 3 hub heights. This is compared to studies in 1996, with smaller turbines, where it was found that the dominating frequencies were closer to 1kHz. Legarth notes that the rotating speed for larger machines also tends to be smaller.

A.41 Lundmark [A16] states that some complaints have been registered in Sweden concerning ‘swish/whoosh’ noises from wind turbines ‘of a certain type under some meteorological conditions’, but no further details are provided. Data is shown for short periods of audible modulation at a particular site, but it is stated that this did not correspond to ‘serious complaints’.

A3) Australia

A.42 A 2006 review of the subject [A17] concluded that there were little publicly available records of complaints from large modern wind farms at the time, with the exception of the Toora Wind Farm, located in South Gippsland Shire Council, Victoria, Australia.

A.43 A report by Fowler [A12] notes that residents near Toora have reportedly complained about the audible rhythmic noise, and the turbine blade rotation being ‘clearly audible’. The author of the latter report therefore argues that a 5 dB penalty should be added for ‘special audible characteristics’ which was specified in the New Zealand standard NZ6808:1998 [A18] applicable at the time. But it is not clear however if this modulation was typical of turbines or if some enhanced modulation was experienced at this site. The author might apply this penalty to all wind turbines according to his interpretation of the NZ standard, due to the inherent character of the wind turbine noise.
A.44 Another recent review [A19] suggests that, based on the available information, the general inclusion of this penalty for all wind farm schemes would not be justified. It cites the first draft of the Australian National Wind Farm Development Guidelines [A20] for which excessive swish is referred to as one of the potential Special Audible Characteristics (or SACs), but recommends for example that 'with the exception of tonality, the assessment of SACs will not be carried out during the noise impact assessment phase, that is, pre-construction'.

A.45 The wind farm at Waubra (Victoria) is another site which has received some attention in the press as some residents have complaining about the health effects impacts of wind turbine noise. The descriptions from some residents include: 'when in sync, every minute or two you can hear 3-4 big wooshes that you can actually feel'; '[you] feel that you have motion sickness'; 'I wake up 5-6 times at night'.

A.46 A report by Thorne for one of the residents [A21] has described 'pulsing at low frequency' which some residents believe is at the origin of their problems. However, the frequency of occurrence of this feature was not determined. It is not therefore known whether this modulation was a continuous feature of the site which would then potentially warrant a penalty for 'special audible characteristics'. The author suggests that this 'rumble/thump' may be caused by the downstream wake from adjacent turbines or by interaction of the blade with the tower. The available measurement data did not demonstrate clear evidence of strong modulation at far-field locations.

A4) New Zealand

A.47 West Wind, Meridian’s wind farm near Wellington, comprises 62 turbines on elevated hills with valleys either side. It was officially opened in April 2009. Since then, the company’s been dealing with complaints from people living in the adjacent Makara Valley, as reported in the media.

A.48 Ref [A21] quotes one resident as saying: '[we] get the low frequency thump/whump inside the house, is very similar to a truck driving past or boy racers sub-woofer 100m away […] we have no line of sight [sic] turbines and the closest one is 1.35km away. […] The sound is extremely ‘penetrating’ and while we have a new house with insulation and double glazing, the low frequency modulation is still very evident in the dead of night. It is actually less obvious outside as the ambient noise screens out the sound.' The ‘rumble/thump’ is reportedly heard just before or after wind gusts.

A.49 The planning conditions for the West Wind project [A22] require a penalty of 5 dB be added for ‘special audible characteristics’, such as tonality or ‘audible modulation’. The text then goes on to clarify that ‘a test for modulation is if the measured peak to trough levels exceed 5 dBA on a regularly varying basis or if the spectral characteristics, third octave band levels, exhibit a peak to trough variation that exceeds 6dB on a regular basis in respect of the blade pass frequency’. The recently revised New Zealand standard NZS6808:2010 has a test for modulation that is similar to those conditions.

A.50 A noise compliance report published by the operator [A23] describes measurements undertaken at various locations around the wind farm. It showed clear levels of tonality in the measured turbine noise. Mitigation measures are described which aimed to reduce the tonal noise emissions by changing the operation of the turbines. The presence of these tones was said to explain the audibility of the wind farm even at relatively large separation distances.

A.51 The report then goes on to consider amplitude modulation. It argues that (in theory) during ‘high power conditions’, the use of turbine blade pitch adjustment may lead to aerodynamic noise becoming more audible at receiver locations, and that this may be more easily perceived in sheltered rather than exposed locations. Following an analysis of complaint records (mentioning ‘whoosh’) and a review of the measurements, the report concludes that audible modulation has only found been found to occur for very short periods, i.e. no more than 5 seconds in a 1 minute recording, and on no regular basis. Although some modulation which met one of the tests of the condition (>6 dB change in the 160 Hz octave band), this was for such brief intervals that it was considered inappropriate to apply a penalty for this characteristic.
A.52 A subsequent report [A24] notes that following the progressive implementation of mitigation measures across the wind farm (between February and April 2010), tonality levels and the number of complaints from residents both reduced significantly.

References for Appendix A


[A23] M. Hayes, P. Botha, Project West Wind Wind Farm, Noise Compliance Assessment, 17th March 2010

[A24] P. Botha, Project West Wind Wind Farm Noise Compliance Assessment, 14th September 2010
Appendix B – Data request – specification issued
The issue of amplitude modulated noise (often referred to as ‘blade swish’ or ‘AM’) arising from the operation of wind turbines is presently receiving a high focus of attention. Whilst the acceptability of audible noise from wind turbines continues to be the subject of considerable debate, the specific issue of AM has come to the fore following the publication of a number of studies claiming that the existence of such noise may result in an enhanced possibility of adverse effects, both in terms of subjective response and in terms of direct adverse health effects. A research project is underway, 100% funded by RenewableUK, which aims to improve understanding of the phenomenon.

It would be most interesting to test any model or metric on real-world data. This process can be greatly accelerated by making use of data that already exists within the wind energy community, i.e. acoustic data that has been collected for other purposes. The project team is seeking to approach other researchers and acousticians with a view to compiling a database of wind farm acoustic recordings, including AM in some cases. The following describes requested data types, sometimes in order of preference as all may not be available, accessible or transferable.

Confidentiality

The data would of course be used in a confidential manner, and assurances can be given in this respect if required. If there are problems relating to commercial confidentiality, this would be addressed by removing any meta-data enabling identification of the data source if required.

Contributions would be acknowledged in publications (unless otherwise requested).

General data and site description

Identification of the site is not essential. A general description of the wind farm would be more interesting, including:

- Type of turbines and power regulation used (pitch or stall regulation, variable speed etc)
- Number and size of turbines (exact or approximate)
- Age or status of wind farm (construction year / status)
- If any noise complaints: description of situation (resolved, ongoing, scale?)

Data

The data may cover an extended period or simply sample representative periods.

Acoustic data

In order of preference:

- Audio data:
  - Uncompressed and/or calibrated long-term recordings
  - Compressed samples
  - Source: sound level meter or hand-held recorder, microphone etc.
  - Calibrated level if available
- Noise levels:
  - Short-term sampling rate LAeq or LAfast data (for example 100ms sample rate)
  - Third-octave band data: short term as above or averaged over short-term intervals (less than 5 minutes)
  - Source: class 1 or 2 sound level meter, analyser, etc
- Description:
  - Measurement position: distance from turbines, environment
  - Measurement type: close to the ground, on tripod/ground board, wind shield present etc.
  - Environment: Internal/external, proximity of reflective surfaces, walls etc, trees or other sources
Non-acoustic data

- **Anemometry information**: wind speed/direction at hub height and/or different heights, mast or LIDAR/SODAR. If not available, approximate or subjective description of conditions during measurement period
- **Turbine operational data**: full operational records of turbine status (power, yaw, nacelle wind speed etc). If not available, approximate or subjective description of status during measurement period
- **Subjective descriptions** of noise from measurement operator or from complainants (if any)

Format

- For audio data an uncompressed format (WAV or similar) is preferred, but if not available or difficult, compressed samples (MP3 or similar) would be useful.
- For acoustic data, a spreadsheet or similar text output format would be useful, but proprietary instrument or software data may be processed directly.
- Data may be transmitted by email if not extensive in size, otherwise CD/DVD or web transfer may be arranged
Appendix C – Sample data analysis

This appendix presents illustrative results of the analysis of the frequency content and time evolution of representative samples of the data considered in the present work package C. The samples shown typically correspond to the clearest periods of modulation observed within the dataset and/or reported as corresponding to complaint conditions, for illustrative purposes. This may not however be representative of the nature of the noise experience for other periods or indeed for the majority of the time in some cases.

For each of the illustrative periods, two analysis graphs are shown:

- A spectrogram analysis is shown for frequencies up to 2kHz. In some cases (as indicated), the spectrogram is shown A-weighted. These spectrograms are a graphical representation of the evolution of the frequency content of the signal over time.
- A time history of the evolution of A-weighted $L_{eq}$ levels with time, both for the signal as acquired and when low-pass filtered to retain only lower frequencies (up to 500Hz or up to 230Hz). This was derived from the audio signal, but as calibration data was not always available, this is not shown on an absolute scale of measured noise levels. The vertical scale mark corresponds to 5dB increments.
Fig. C1) Van Den Berg sample – Journal of Sound and Vibration article – extract: a) spectrogram (linear) and b) noise levels history (arbitrary scale) 100ms resolution, with increasing filtering

Note: the modulation frequency when present is close to a rate of 1Hz.
Fig. C2) DTI LFN study – Site 1 - extract: a) spectrogram (linear) and b) noise levels history (arbitrary scale) 100ms resolution, with increasing filtering.

Note: the modulation frequency when present is close to a rate of 1.4Hz.
Fig. C3) DTI LFN study – Site 2: a) spectrogram (linear) and b) noise levels history (arbitrary scale) 100ms resolution, with increasing filtering, both measured externally, free-field location; c) comparison between external/internal recording for a concurrent time period

Note: the modulation frequency, when present, is close to a rate of 1.3-1.4Hz.
WIND TURBINE AMPLITUDE MODULATION: RESEARCH TO IMPROVE UNDERSTANDING AS TO ITS CAUSE & EFFECT
WPC - COLLATION AND ANALYSIS OF EXISTING ACOUSTIC RECORDINGS
APPENDIX C SAMPLE DATA ANALYSIS

c)
Fig. C4) ‘Other’ AM (measured externally, free-field location): a) spectrogram (A-weighted) and b) noise levels history (arbitrary scale) 100ms resolution, with increasing filtering.

Note: the modulation frequency, when present, is close at a rate of 0.8Hz.
Fig. C5) Bowdler Near-field measurements: a) spectrogram (linear) and b) noise levels history (arbitrary scale) 100ms resolution, with increasing filtering.

Note: the modulation frequency is unclear but appears close to a rate of 0.8Hz.
Fig. C6) **Web-sourced audio:** a) spectrogram (linear) and b) noise levels history (arbitrary scale) 100ms resolution, with increasing filtering

**Note:** the modulation frequency is unclear but appears close to a rate of 0.8Hz.
Fig. C7) Sample data from Australian site: a) spectrogram (A-weighted) and b) noise levels history (arbitrary scale) 100ms resolution, with increasing filtering.

Note: some light modulation is just audible, at a rate of around 0.8Hz.
Work Package D
Measurement and analysis of new acoustic recordings
Hoare Lea Acoustics
Wind Turbine Amplitude Modulation: Research to Improve Understanding as to its Cause & Effect

Work Package D (WPD) - Measurement and Analysis of New Acoustic Recordings
WIND TURBINE AMPLITUDE MODULATION: RESEARCH TO IMPROVE UNDERSTANDING AS TO ITS CAUSE & EFFECT
WPD - MEASUREMENT AND ANALYSIS OF NEW ACOUSTIC RECORDINGS

Matthew Cand, Andrew Bullmore, Ben Wilson
HOARE LEA Acoustics
140 Aztec West Business Park
Almondsbury
Bristol
BS32 4TX

Tel: 01454 201 020
Fax: 01454 201 704

Audit Sheet

<table>
<thead>
<tr>
<th>Revision</th>
<th>Description</th>
<th>Date</th>
<th>Issued by</th>
<th>Reviewed by</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Draft for comment</td>
<td>23/03/2012</td>
<td>MMC</td>
<td>AJB</td>
</tr>
<tr>
<td>2</td>
<td>Update following comments</td>
<td>11/04/2012</td>
<td>MMC</td>
<td></td>
</tr>
</tbody>
</table>
EXECUTIVE SUMMARY

In the light of the expected key characteristics of Other AM (OAM) noise, and in particular the notable differences between OAM and Normal AM (NAM), the present project has involved targeted measurements across three separate wind farm sites in order to attempt to measure OAM and to confirm its expected characteristics. The measurements undertaken at the three separate sites adopted a very different approach in order to attempt to extract different information:

- **At Site A** measurements were undertaken at residential dwellings where AM noise issues had been reported by the residents. Noise measurements were undertaken at two dwellings in the absence of any other operational data from the wind farm and the data obtained used to test the AM metric routine developed;

- **At Site B** detailed measurements of noise at multiple locations around the test turbines, meteorological conditions and turbine operational data were undertaken on a wind farm site. The opportunity was provided for the switching on and off of various turbine combinations, but no control was provided for manually varying the operational parameters of the turbines.

- **At Site C** multiple noise measurements were undertaken around a test turbine (located within an operational wind farm) together with turbine operational data. The opportunity was provided to manually control the blade pitch settings of the test turbine away from its optimal design setting such that the effects on noise output of inducing full or partial stall could be established.

When present, the presence of OAM was able to be detected and rated effectively using the techniques developed in other parts of the current project. More general time-averaged metrics based on a 10-minute interval analysis, which are generally used to assess overall levels of wind turbine noise could not effectively discriminate the presence of modulation.

Based on the various measurement results, and particularly those at Site B, it has been concluded that the general characteristics of other OAM noise are consistent with the expected directivity and spectral characteristics of transitory stall noise, thus exhibiting a significantly increased effect in the downwind direction from the wind turbine.

In the far-field, instances of clear OAM were associated with the downwind direction and were reduced in the cross-wind direction. The effects in the near-field were more difficult to discern, although the expected presence of NAM was clearly characterised by higher modulation depths of up to 5 dB in the cross-wind direction.

The instance of OAM levels in the far-field were strongly variable and did not seem to be simply associated with the existence of certain meteorological conditions. In terms of the various hypotheses that have historically been as possible causal mechanisms for other AM, whilst the results could not generally rule out any of these as potential contributory factors, they did confirm the ability of OAM to exist in situations where the factors are known not to contribute. In summary, significant OAM was positively identified under conditions of:

- low wind shear;
- low wind veer;
- uniform turbulence;
- single operational turbines (i.e. no interaction effects);
- on both flat and hilly sites;
- turbines with high tower to rotor diameter ratios.
The only positively identified association between the occurrence of OAM and the operational characteristics of the turbines was that, in the detailed measurements undertaken at site B, OAM only occurred when active power generation was occurring, and it also appeared to be sometimes exacerbated during periods when changes in the estimated relative angle of attack of the blades also occurred.

Other source mechanisms may be at play. It is conceivable that particular blade designs could experience partial blade stall in certain conditions without the influence of non-uniform inflow conditions to trigger it. For example, aeroelasticity effects may vary the blade geometry in such a way that it departs significantly from its design conditions. There is, however, very limited information available to study this in the current state of knowledge.
1 INTRODUCTION AND SCOPE

1.1 Introduction

1.1.1 The work presented in this report is part of a project funded by RenewableUK and entitled ‘Wind Turbine Amplitude Modulation: Research to Improve Understanding as to its Cause & Effect’. The project comprises a total of six separate work packages. The outcome results of each of the work packages have separately resulted in their own dedicated final reports. A seventh work package, WPF, has produced an overarching final report in which the key findings across the separate work packages have been collated and discussed.

1.1.2 This is the final report of Work Package WPD: ‘Measurement and analysis of new acoustic recordings’.

1.1.3 Wind turbine aerodynamic noise, by which is meant the noise produced by the rotating wind turbine blades, includes a steady component as well as, in some circumstances, a periodically fluctuating, or amplitude modulated (AM), component. However, AM may take different forms. One form of AM, commonly referred to as ‘blade swish’, is an inherent feature of the operation of all wind turbines. It can be explained by well understood mechanisms, it being the result of the directivity characteristics of the noise created by the air flowing over a turbine blade as it rotates. Because this type of AM is an inherent feature of the operation of wind turbines, whose origin can be explained and modelled, the present project adopts as its definition the term ‘normal amplitude modulation’ (NAM). The key driver for the project, however, is the recognition that some AM exhibits characteristics that fall outside those expected of NAM. Such characteristics include a greater depth of modulation, different directivity patterns or a changed noise character. For this reason the present project adopts as its definition the term ‘other amplitude modulation’, or ‘OAM’, for all observations of AM that lie outside that expected of NAM.

1.1.4 In recent years public concern has grown about the potential annoyance from wind turbine OAM noise. This concern has resulted in an increased interest to establish how AM, and in particular OAM, occurs, how it can be better defined and measured, and how it is generally perceived and responded to. It is the answers to these questions that the present project seeks to address.

1.2 Scope

1.2.1 Based largely on the outcome of other Work Packages, a programme of measurements was derived in order to collect supplementary acoustic and audio data. The aim of this data was to supplement the data already available from the database developed under Work Package C, as well as to provide detailed supporting information of the type that has been observed as often being lacking from the previously available data obtained from other sources. It was the conclusion of the research group that a more extensive measurement survey and a detailed (but indirect) study of on-blade generation mechanisms was necessary to reach firmer conclusions.

1.2.2 The scope and methodology of this part of the project evolved significantly with time. It was initially conceived, at the project outset, that additional measurements would be undertaken as part of Work Package D at up to seven separate sites, the original aim being to collect additional recordings to those of work package C, but using an essentially similar approach. However, as the project progressed, it was determined that, rather than simply acquire more examples of AM audio recordings in the far-field, more detailed supporting information, such as better defined meteorological information and turbine operational information was crucial to obtaining an improved understanding of the subject. This was because recordings acquired to date were not sufficient to prove or disprove the different mechanisms identified.

1.2.3 It has also been the experience of the project team that, even at those wind farm sites where AM has been reported or identified to be an issue, its occurrence may be relatively infrequent.
The approach adopted was therefore to focus on a more limited number of sites but to undertake more extensive and detailed measurements than originally envisaged at each of these sites, using a variety of strategies and taking into account the findings of other work packages.

One of the benefits of the originally envisaged approach to the measurements to be undertaken under work package D was that recordings could be taken at any accessible location without necessarily the need for approval from any involved parties. However, the downside to this approach was quickly recognised to be the subsequent inability to access relevant supporting information. The revised approach required the direct involvement of wind farm operators if the necessary supporting information was to be made available. The benefits of the revised approach were determined to far outweigh any drawbacks, although it had to be accepted that one of the drawbacks was the significantly extended time required to arrange site access and to adequately address confidentiality considerations. Also, many logistical and technical challenges were associated with the more detailed and innovative nature of some of the measurements proposed, some of which required working in close collaboration with wind turbine manufacturers in addition to the wind farm operators. This led to some delay to the overall project programme but, as previously stated, the value of the additional measurements which were undertaken were deemed to more than outweigh any adverse timing issues.

It was also therefore not expected that the measurements undertaken as part of this work package would offer more evidence into the frequency of occurrence across the country of the phenomenon, but it was considered preferable to focus on acquiring further insight on the characteristics of ‘other AM’ and its potential causes.

A staged approach was taken in which different approaches were employed at different sites in order to achieve separate aims, as summarised below.

Site A involved measurements that were most similar to wind turbine noise immission (far-field) measurements, as generally undertaken following the guidance of ETSU-R-97. However, in accordance with the expected requirements for the measurement of any modulation, high-resolution data including audio recordings were also collected as part of these works. Recordings were made at two residential properties neighbouring a wind farm site for which residents at the measured properties had been complaining about the noise from the wind farm, with investigations currently underway (by others) to assess the complaints further. Access was granted to the two properties which enabled detailed measurements to be made at suitable external locations over a period of several weeks.

Site B comprised a location where the existence of OAM had been positively identified. Efforts were therefore focused on undertaking a detailed series of measurements, allowing a study of conditions in which varying levels of AM were experienced and at different locations relative to the turbines. This also involved capturing detailed anemometry measurements and turbine operational data at a high resolution. The schedule and requirements of the measurement campaign were based on the theoretical considerations and requirements outlined in the WPA2 report, in as much as practical and budgetary conditions reasonably allowed. These measurements were significantly more detailed than those generally undertaken for immission measurements of wind turbine noise but were nevertheless still limited to some degree through practical constraints.

Site C involved targeted measurements on an operational wind farm site using novel techniques to investigate the influence of turbine operational parameters on the character of the AM noise produced, as informed by the results of the other work packages in this project. In particular, the hypothesis raised in WPA1 and WPA2 that partial blade stall may lead to increased levels of modulation at large distance downwind warranted particular investigation. Considering this, the influence of a turbine's pitch regulation system was considered a crucial
element to be tested. Designing a measurement campaign capable of addressing the foregoing
issues required detailed cooperation with turbine manufacturers, especially as a detailed
knowledge of the blade geometry and control system operation of commercial wind turbines is
generally not freely available due to confidentiality considerations. It was agreed with the turbine
manufacturer to undertake tests in which the pitch of the turbine was controlled directly in order
to attempt to trigger detached (stalled) flow on the blade, and to assess the relative impact on
far-field noise, and in particular the potential for varying pitch angles to induce or control
amplitude modulation. The project team is not aware of such investigations having been
undertaken previously.

1.2.11 Each of the measurements surveys undertaken and associated results will then be described in
turn.
2 SITE A – MEASUREMENT AT RESIDENTIAL LOCATIONS

2.1 Introduction

2.1.1 This phase of the measurement was most similar to wind turbine noise immission (far-field) measurements generally undertaken in current practice, following in particular the guidance of ETSU-R-97. However, in accordance with the expected requirements for the measurement of any modulation, high-resolution data including frequency and audio data were collected as part of these works.

2.1.2 These recordings were made at two residential properties neighbouring a wind farm site: referred to herein as locations 1 and 2. We understand that residents at these properties had been complaining about the noise from the wind farm and that investigations are currently underway to assess this further. Access was granted to the two properties for measurements to be made at suitable external locations over a period of several weeks.

2.1.3 The aim was to collect additional audio recordings of AM if at all possible. The limitations of such an exercise were recognised amongst the project team, particularly in terms of the potential for detailed investigations of the causal mechanisms of AM. It was nonetheless thought useful on balance to attempt to collect additional recordings, even in the absence of detailed supporting operational and meteorological data, as this would add to the current database of work package C and provide further data, this time from a wind farm with an alleged noise issue, on which to implement some of the techniques discussed in other parts of the project.

2.1.4 Recordings were made at an external location within the curtilage of each residential properties. No detailed turbine operational or meteorological data was available, but reference was made to observations made by residents, as well as the broad meteorological conditions available for the area from public sources.

2.1.5 The surveyed properties were situated less than 1km from the nearest turbines of a relatively large wind farm site. This site comprises more than 10 turbines which have a rotor diameter in excess of 80m. The turbines are located on a plateau, amongst a generally hilly terrain, with the surveyed residential properties located in a valley situated lower down. Due to the hilly nature of the area it was thought unlikely that the level of atmospheric wind shear would be high, although the terrain itself will provide a level of shelter from the wind. The area was rural and fairly isolated with low levels of traffic noise or other ambient sources. Each location experienced varying amounts of shelter from the wind, with location 1 situated further down the valley than location 2, the latter of which was more elevated by approximately 40m relative to the former and therefore tended to experience stronger winds.

2.2 Survey set up and description

2.2.1 Measurements were undertaken for slightly less than 3 weeks at free-field locations chosen, in consultation with the residents, to minimise the impact of reflections from building surfaces as well as noise from water-courses located in the area which would tend to mask the noise from the turbines.

2.2.2 At each of the survey locations, the noise measurements system used were capable of monitoring overall noise levels and could also provide periodic audio recordings. The chosen noise measurement system was one based around a 01dB Blue Solo sound level meter used in conjunction with a low power embedded computer running the 01dB “dBTrig” measurement software. This sound level meter system accords with the requirements of a Type 1 sound level meter. The sound level meter and computer were housed in an environmental enclosure and included a battery back-up power supply with a low voltage charge fed from the mains electricity supply.
2.2.3 The measurements system recorded data correctly during the entire survey period, except for the second system which stopped recording audio samples for a period of 4 days partly through the survey, due to a software fault. The microphone system was mounted on a pole attached to the side of the environmental enclosure with an installed microphone height of 1.2 m. A two layer windshield system was used to reduce wind induced noise on the microphone. The system comprised a 01dB BAP21S outdoor microphone protection system which incorporates rain protection and a small diameter foam wind screen. The secondary windshield (the second layer of the two layer arrangement) was custom made from open cell foam approximately 25 mm thickness formed as a domed cylinder 170 mm diameter and 300 mm high. A lower disc of 40 mm thick open cell foam formed total enclosure of the primary windshield. The outer windshield was designed following the guidance given in the report Noise Measurements in Windy Conditions [1] which indicates that the insertion loss of this type of windshield assembly is likely to be less than ±1 dB between 50 Hz and 5 kHz and so not a significant factor on the measured results.

2.2.4 The measurement system was set to log continuous and contiguous periods of both $L_{eq}$ and $L_{Aeq}$, the 'A' weighted, 'Fast' time weighted sound pressure level, as well as filtered 1/3 octave band levels between 20 and 20kHz, every tenth of a second. From these logged values, longer term indices values may be calculated by a post-processing procedure in the 01dB dBTrait software. In addition the system was configured to provide regular audio recordings of two minutes duration with each recording start spaced at intervals of ten minutes and with an audio sampling rate of 25.6 kHz (10 kHz audio bandwidth). The clock on the computer was set to disable ‘daylight saving’ and synchronised with Greenwich Mean Time (GMT) using a global positioning system receiver.

2.3 Measurement analysis – introduction

2.3.1 In a preliminary phase, the review of notes provided by the resident at location 1 focused the analysis on some periods in which ‘other AM’ may have been experienced. Some of the likely relevant descriptions included "(loud) whoomping", "(deep) thumping", "beating". Indications were that these periods often seemed to correspond to situations when the location was downwind of the wind farm. At other times descriptions included "rumble" or "roaring" which seemed less relevant to the analysis of AM and may represent more general wind turbine noise.

2.3.2 Figure 2.1 below shows a graph of the variation of the measured short-term $L_{eq,100ms}$ levels for a sample day-time period of less than 2 minutes in which the influence of noise from the turbines, including AM, was identified. Some short periodic patterns of relatively regular modulation of noise at a rate of slightly less than 1 Hz are visible in the trace of A-weighted levels as a function of time. One such AM period is highlighted in red, with a period with reduced modulation marked in blue, and a period of likely reduced wind turbine noise marked in green (denoted "background", although a residual influence of the wind farm could not be excluded). These descriptions were reinforced by a subjective review of the audio sample recorded for this period.
The corresponding average spectra are then shown in Figure 2.2 using the same colour reference for the periods highlighted, along with instantaneous spectra corresponding to a clear peak and trough of the modulation. It can be seen that the modulation itself is dominated by the region between 300 Hz and 1 KHz. The slight "dip" observed in this region at 500Hz could be caused by interference due to ground reflection and/or propagation effects (see WPA2) which would therefore be location-specific. A similar but stronger dip is observed around 200 Hz, with some modulation energy between 80 and 160Hz: these frequencies would be characteristic of the presence of stall according to WPA1 [2]. The 1/3 octave band frequencies dominating the A-weighted modulation spectrum were at 315, 400 and 630Hz.
2.4 Towards a systematic analysis

2.4.1 Whilst, for some periods such as the one shown in the above Figure 2.1, the evolution of the short-term A-weighed levels exhibit a clear pattern during periods of audible modulation, this is not always the case. WPF discusses further the difficulties associated with the subjective interpretation of such short-term variations in levels. Even such a "visual" identification of periods of modulation was not possible without ambiguities or risk of subjective interpretations. The systematic review of the time-history of levels, in no more than 5 or 10 minute periods at a time, would not really be feasible in practice, particularly when considering the often sporadic and intermittent character of the AM, as well as the strong dependence on weather conditions and the potential influence of extraneous noise at typical noise sensitive receiver distances.

2.4.2 The variability of the short-term levels and modulation levels, for other periods, is illustrated by the following figure showing the evolution of 100ms $L_{Aeq}$ levels. Even during periods in which audible modulation tended to be noted, periods of clearer modulations often lasted for periods of typically only a few (5 to 10) seconds. Any subjective review of $L_{Aeq,100ms}$ or similar may therefore miss such short modulation periods. A systematic analysis using the Fourier analysis techniques such as those described in WPB1 and WPF, which automatically and more objectively identify modulation at the expected modulation frequency, therefore seems to offer a preferred approach.

2.4.3 Furthermore, the modulation may not be so clearly apparent from the A-weighted levels because of noise from other sources either masking the variations on A-weighted or creating complex patterns in which regular variations at blade passing frequency may not be evident (see below). As discussed in WPB1, filtering the input signal into more restricted range in which the wind turbine modulation is considered likely to dominate will assist in the analysis. The WPB1 report explains that the analysis in a restricted frequency band means the assumption of uniform "white" noise, on which the Fourier analysis is based, is then more representative. A potential practical downside to this approach, however, is that it requires more detailed information to be captured and analysed: this is considered in the next section.

2.5 Practical considerations

2.5.1 In a "best-practice" wind farm acoustic immission measurement set-up, 2 minutes of audio recording would often be made every 10 minutes, as this allows a tonal analysis to be made in accordance with ETSU-R-97. This sampling period will often not match a particular period of interest. See for example Figure 2.3, in which only the first 2 minutes had a corresponding audio recording, and which experiences varying levels of modulation. The difference between the $L_{Aeq,10min}$ and the $L_{A90,10min}$ for this period was 1.8dB(A), which is considered typical for wind turbine noise [3].

2.5.2 Even limiting the effective audio recording rate to 20% in this way: using a 25.6kHz audio sampling rate for a single channel represents about 1.7Gb of audio data per day of recording. Full audio recording would represent more than 8 Gb of data per day. This amount of data recording also increases the risk of hardware/software failure of the equipment. Even if the audio sampling rate is reduced significantly, this still represents significant technological and practical constraints.

2.5.3 Therefore a systematic analysis based on 1/3 octave band data appears more practical. Recording 1/3 octave band data at a 10Hz sampling rate should represent significantly less data requirements (less than 50Mb per day). This represents a practical way of implementing the techniques described in WPB1 and WPF.

2.5.4 Any audio recordings, if present, would then provide a useful way of subjectively evaluating the nature of particular events which are visible from the audio trace as part of verification procedures.
2.5.5 As a minimum, data with a sufficiently short time resolution (i.e. significantly less than the expected blade passing period of typically 1 Hz, thus indicating a data capture resolution of 8 times a second or more) should be recorded. This will not be the case for many standard integrating sound level meters which only record average and statistical indices over longer periods, but it was done for the present survey.

![Graph of L_{Aeq,100ms} vs Time](image)

**Figure 2.3** – sample time history (min:sec) of variation in short-term L_{Aeq,100ms} levels for a 5min measurement period

2.6 Automated AM analysis

2.6.1 An entire period of more than 24 hours measured at location 1 was systematically analysed, as descriptions by the resident seemed to suggest the presence of clear AM. This was made between 21:00 one evening to 24:00 the next day (27 hours in total).

2.6.2 This measured data was analysed using the main AM metric routine described in Work Package F (WPF), which is based on objective analysis techniques described in WPB1. The routine is based on a Fourier analysis of the noise signal envelope, either for the A-weighted signal or for a specific 1/3 octave band, implemented in the MATLAB software. WPF Annex C shows that using this implementation, the value of the peak in the modulation spectrum at the modulation frequency (in this case, the blade passing frequency of the turbine or BPF) results in a representative measure of the modulation magnitude. The normalisation used means that values are comparable to the typical peak-to-trough variation in short-term A-weighted levels (typically 1 dB lower, unless the analysis is restricted to a specific representative 1/3 octave band).

2.6.3 The MATLAB implementation of the main AM metric routine described in WPF was first applied to short-term A-weighted levels: the full set of recorded L_{Aeq,100ms} levels was separated into contiguous blocks of 10s of data which were then analysed. The modulation spectra obtained do exhibit evidence of modulation which is likely to be associated with the operation of the turbines, particularly during the quieter evening and night periods. During day-time periods, despite the relatively rural and isolated nature of the area, some spurious sources of noise appeared to affect the analysis.
2.6.4 For example, the evolution of the modulation spectrum with time between 09:00am to 12:00am is shown in Figure 2.4. A spectral peak at a fundamental modulation frequency close to 0.8 Hz is apparent as expected, but at times modulated signals at lower frequencies appear on the graph, but these are unlikely to be related to the operation of the turbines. The worst-case peak appears for block 622 (10:43:30), and a review of the measurements at this time show this is caused by a short squeal/whistle noise (around 3kHz).

2.6.5 In cases such as these, spurious signals influence the spectrum of a large range of "modulation" frequencies, and so even if only the spectral peaks close to the expected modulation frequency (in this case 0.8Hz) are retained, the values may not always be representative of actual wind turbine modulation except in quieter conditions. Nevertheless, the potential for false negatives remains relatively low compared to methods involving a visual inspection of $L_{Aeq100ms}$ levels.

Figure 2.4 – Evolution over a period of 3 hours (09:00 to 12:00) of the calculated modulation spectrum based on the $L_{Aeq100ms}$ levels (for contiguous 10s data blocks) at location 1

2.6.6 The same analysis was therefore applied to the measured time history of the 315Hz 1/3 octave band (with a 100ms resolution). The analysis of each block of 3 hours of data for this single 1/3 octave band took less than 5 minutes using a PC with a 64-bits 2.7GHz processor with the MATLAB software, and this could probably be optimised further. This therefore represents a feasible analysis method even for large sets of data, particularly as reports from residents and analysis of any available complaint diaries can often assist further in refining the analysis period, in line with the approach described in ETSU-R-97.

2.6.7 The evolution with time of the modulation spectrum derived from the 315Hz data, for the first three hours (21:00 to 00:00), is shown in Figure 2.5. A clear peak at a fundamental modulation frequency close to 0.8 Hz is apparent, as well as (more faintly) the first harmonic at 1.6 Hz at times. Sometimes faint peaks at lower or higher modulation frequencies are apparent, but these spurious peaks are relatively less prominent than for the A-weighted data.

2.6.8 The consistent presence of such a peak in the spectrum, over long-term periods, is characteristic of wind turbine noise as:
the modulation frequency is consistent with the expected rotational speed of turbines, in particular those of three-bladed machines of the size present at site A;

this type of noise is relatively constant in time, over periods of minutes or hours in response to general wind conditions, as opposed to short-term spurious sources which might influence the spectrum for only brief periods or at specific times of the day.

2.6.9 On this basis, the analysis procedure determines the amplitude of peaks in the modulation spectrum at frequencies close to the assumed typical blade passing frequency (BPF) of 0.8Hz: the time evolution of this metric for the full analysis period is shown in Figure 2.6.

2.6.10 The resulting statistics of the prevalence of occurrence of periods of relatively high modulation is stated in Table 2.1, for the entire 27 hour period.

<table>
<thead>
<tr>
<th>Location 1</th>
<th>&gt;3dB</th>
<th>6%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&gt;4dB</td>
<td>1%</td>
</tr>
<tr>
<td></td>
<td>&gt;5dB</td>
<td>0.3%</td>
</tr>
</tbody>
</table>

Table 2.1— proportion of 10s analysis period, over the entire 27h period of Figure 2.6, for which the calculated AM rating at BPF exceeded set values (315Hz 1/3 octave band)

2.6.11 A sample check of some of the relatively high values identified from this systematic analysis confirmed that they corresponded to periods of clear modulation likely to be associated with the wind farm: see for example Figure 2.7, which corresponded to the period (23:02) associated with the period (23:01 to 23:02), which appears dominated by wind turbine noise, the difference between L_{Aeq,1min} and the L_{A90,1min} was 2.3 dB, which is typical of general wind turbine noise [3].

2.6.12 The values of AM rating obtained for the 315Hz 1/3 octave band were generally higher than for the A-weighted analysis only, by about 1 to 1.5dB, which is comparable to the analysis shown in WPF for a series of artificial stimuli. This analysis showed that, for the representative AM stimuli used in WPB2, the dB values obtained from the main AM metric routine were comparable to those determined from the variations in short-term L_{Aeq} (and labelled “MD” in WPB2): approximately 1dB lower when using the A-weighted signal envelope, and similar values when considering the dominant 1/3 octave band (315Hz).
Figure 2.5 – Evolution over a period of 3 hours of the calculated modulation spectrum based on the 315Hz 1/3 octave band (for contiguous 10s data blocks) at location 1.

Figure 2.6 – Evolution over a period of more than 24h of the calculated AM peak close to BPF based on the 315Hz 1/3 octave band at location 1.
WIND TURBINE AMPLITUDE MODULATION: RESEARCH TO IMPROVE UNDERSTANDING AS TO ITS CAUSE & EFFECT
WPD - MEASUREMENT AND ANALYSIS OF NEW ACOUSTIC RECORDINGS

Figure 2.7–time history of variation in short-term $L_{Aeq100ms}$ and 315Hz 1/3 octave-band levels at location 1 for a period identified from the worst-case peak shown in Figure 2.6.

2.7 Comparative analysis

2.7.1 The analysis was also conducted for another octave band for comparison purposes: this was done for 630Hz following the analysis presented in Figure 2.2. As illustrated in Figure 2.8, comparable or lower values of modulation were obtained for this frequency band, and the analysis made for 315Hz is therefore considered to be more representative.
As suggested in WPB1, this type of Fourier analysis could usefully be conducted over a wider range of 1/3 octave bands in parallel, such as in the work of Vos [4], or for narrow-bands as in WPB1 or the work of Lee et al. [5]. It may then be desirable to combine the individual results using a weighting function (such as A-weighting). This will naturally tend to reinforce modulation occurring at similar frequencies over a range of frequency bands. This was not implemented in this work due to timescale constraints, but the analysis above shows that implementation on a well-chosen octave band is representative and minimises the influence of background sources.

Finally, we can compare the analysis for the first three-hour period made at location 1 to the period measured simultaneously at location 2: see Figure 2.9. Table 2.2 shows the associated relative proportion of the 10s samples analysed for which the calculated modulation rating exceeded set values. Both illustrate that the effective modulation was reduced at location 2, which is consistent with its more exposed character as the increased masking from the wind will tend to mask the wind turbine noise and periods of AM, as was observed on site.

It can also be seen from Figure 2.9 that some periods of clear modulation were experienced at location 2 and not location 1, and this was verified by the review of such periods: see Figure 2.10 below, which highlights short periods of modulation which correspond to isolated peaks of Figure 2.9. This suggests the potential influence of propagation effects, as both locations are more than 400 m apart.
Table 2.2 – proportion of 10s analysis period, over the three-hour period of Figure 2.9 (21:00 to 00:00), for which the AM rating at BPF exceeded set values (315Hz 1/3 octave band)

<table>
<thead>
<tr>
<th>AM Rating</th>
<th>Location1</th>
<th>Location2</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;3dB</td>
<td>9%</td>
<td>5%</td>
</tr>
<tr>
<td>&gt;4dB</td>
<td>2%</td>
<td>1%</td>
</tr>
<tr>
<td>&gt;5dB</td>
<td>1%</td>
<td>0%</td>
</tr>
</tbody>
</table>

Figure 2.9 – Evolution over a period of 3h (21:00 to 00:00) of the calculated AM peak close to BPF based on the 315Hz 1/3 octave band, for locations 1 and 2.

Figure 2.10- time history of variation in short-term L_{Aeq100ms} levels at location 2 for two periods identified from peaks near 22:46 in the graph of Figure 2.9.
2.8 Analysis in reported “quieter” conditions

2.8.1 The next period analysed was for a day which was described as “quiet”, in which the locations were thought to be upwind of the turbines, but conditions were not completely calm. A similar analysis of the 315Hz 1/3 octave band data was undertaken for a period of 9 hours (between 03:00 and 09:00). The full history of the value of modulation peaks close to 0.8Hz is shown in Figure 2.11.

2.8.2 The “modulation” values are generally very low, and the isolated “peaks” visible on the graph can be associated with spurious sources, most likely due to short term events from, for example, machinery or vehicle noise. This is most clearly visible if the full modulation spectra are considered: see for example Figure 2.12. This can be confirmed through the available audio records. There is no clear, consistent modulation trend here in the data (in comparison with Figure 2.5 for example) and periods of elevated levels are isolated and not consistent with the expected pattern from the wind turbines. This analysis is therefore consistent with the subjective reports from the residents.

Figure 2.11 – Evolution over a period of 9h on a “quiet” day of the calculated AM peak close to BPF based on the 315Hz 1/3 octave band at location 1.
Although not exhaustive, the analysis undertaken suggests that varying levels of ‘other AM’ can be experienced at the locations surveyed when situated broadly downwind of some of the nearest turbines.

The analysis has shown that AM analysis techniques such as those described in WPB1 and WPF can be meaningfully applied to large datasets and can detect and characterise the measured AM even in complex rural environments in which wind turbine noise can often be difficult to detect (let alone characterise in detail). The use of measured data in specific 1/3 octave band characteristic of the modulation allows most spurious sources to be efficiently excluded from the analysis, without the excessive practical difficulties involved with continuous audio recordings.

These techniques have been shown to identify clear levels of AM through the consistent presence of a characteristic peak in the modulation spectrum corresponding to the blade passing frequency. The evolution of the amplitude of the peak in the spectrum has been shown to be representative of the depth of the modulation over the analysis period (10s intervals). This metric is also consistent with subjective response as assessed in WPB2. As shown in WPF Annex C, for simple signals the levels obtained with a dominant 1/3 octave band are similar to measures of peak-to-trough levels determined from short-term $L_{Aeq}$ levels.

This then allowed a statistical analysis of the variability of AM at different times, which was done for some example representative periods of more than 24 hours. The analysis undertaken at the second location identified that the AM was less significant because of the location’s more exposed character, this being consistent with subjective impressions gained by the project team whilst on site. In “quieter”, upwind conditions, the characteristic peak in the spectrum was not present with the rated peak AM levels consistently lying below 2 or 3 dB.
3 SITE B – DETAILED IMMISSION AND PROPAGATION MEASUREMENTS

3.1 Introduction

3.1.1 Measurements were made at a site where ‘Other AM’ was experienced. Efforts were therefore focused on undertaking a detailed series of measurements, allowing a study of conditions in which varying levels of AM were experienced in different conditions and at different distances from the turbines. This also involved capturing detailed anemometry measurements and turbine operational data at a high resolution.

3.1.2 The schedule and requirements of the measurement campaign were based on the theoretical considerations and requirements outlined in the WPA2 report, in as much as practical and budgetary conditions reasonably allowed.

3.1.3 These measurements were significantly more detailed than those generally undertaken for immission measurements of wind turbine noise, both in current practice and in the literature, but were nevertheless still limited to some degree through practical constraints.

3.2 Survey set up and description

3.2.1 The wind farm site comprised more than 5 turbines, which are pitch-regulated, variable speed machines located in a relatively flat landscape. Due to the flat nature of the area, this site was known to experience elevated (although not atypical) levels of wind shear during evening and night-time periods due to atmospheric stability levels. Despite its rural nature, the area nonetheless experienced higher levels of background noise sources than site A, such as distant traffic noise and occasional agricultural activity, particularly during day-time periods.

3.2.2 The testing procedure focused on a group of three turbines (labelled T1 to T3), as represented on Figure 3.1. Other turbines were located at increasing distance from the instruments and did not generally appear to have a significant influence on the measurements. There was limited amount of vegetation surrounding the measurement locations, which were mostly located on bare agricultural land: therefore the impact of this type of wind-induced noise was limited.

3.2.3 The survey was conducted over a period of more than 6 weeks. It first comprised three free-standing sound level meters placed at different distances from the turbines: these were labelled P1 to P3 and are indicated on Figure 3.1. Part way through the survey, P3 was moved to a new location at an increased distance from the turbines (from location P3a to P3b on Figure 1). This move was possible following the relaxation of associated constraints on the measurement site. The layout was chosen to determine the propagation and directivity of the AM in different wind conditions, allowing for practical considerations. Two key wind directions are identified (Figure 3.1):

- In Wind Direction 1 (WD1), P1 and P2 are downwind of T1, and P3a/b is crosswind
- In Wind Direction 2 (WD2), P1 and P2 are crosswind, and P3a/b is downwind of T2/3

3.2.4 The measurement system used for locations P1 to P3 was one based around a Rion NL 52 sound level meter. This sound level meter system accords with the requirements of a Type 1 sound level meter and was housed in an environmental enclosure and included a battery power supply capable of running the system for at least two weeks. They included WS15 windshield systems which were designed to offer significant reduction of wind-induced noise. Each system was capable of logging overall noise levels, including in short time intervals of 100ms, over a period of many weeks. Periodic audio recordings were made, although this was limited to the space on the 32 GB memory card housed in the meter. The systems were configured to provide regular audio recordings of one minute duration, with each recording start spaced at intervals of ten minutes and with an audio sampling rate of 12 kHz (6 kHz audio bandwidth).
WIND TURBINE AMPLITUDE MODULATION: RESEARCH TO IMPROVE UNDERSTANDING AS TO ITS CAUSE & EFFECT
WPD - MEASUREMENT AND ANALYSIS OF NEW ACOUSTIC RECORDINGS

Figure 3.1– Diagram representing the layout of the measurements at site B (turbines in blue, sound level meters in red and ground-board systems in green)

<table>
<thead>
<tr>
<th></th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>302</td>
<td>613</td>
<td>916</td>
</tr>
<tr>
<td>P2</td>
<td>601</td>
<td>903</td>
<td>1199</td>
</tr>
<tr>
<td>P3a</td>
<td>299</td>
<td>302</td>
<td>539</td>
</tr>
<tr>
<td>P3b</td>
<td>874</td>
<td>845</td>
<td></td>
</tr>
<tr>
<td>B1</td>
<td>82</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B2</td>
<td>44</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B3</td>
<td>77</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1 – Distances (in meters) between the different turbines and sound level meters

3.2.5 In addition to these systems, additional sound level meters were placed in closer proximity of the turbines: labelled B1 to B3 on Figure 3.1. These comprised systems similar to those used for the measurements of site A but which were connected to ground-board mounted microphone and primary/secondary windshields. This was based on the advice of the IEC 61400-11:2003 standard [6] although the measurements were not strictly compliant with standard requirements: the aim was to identify relative source levels and character rather than undertake a formal sound power test. These systems included a mains-powered PC connected to a 01dB Blue Solo sound level meter, with large hard drive capacity. $L_{eq}$ as well as filtered 1/3 octave band levels between 20 and 20kHz, were recorded every tenth of a second.
the system was configured to provide regular audio recordings of two minutes duration with each recording start spaced at intervals of two and a half minutes, with an audio sampling rate of 25.6 kHz (10 kHz audio bandwidth).

3.2.6 The measurements systems installed therefore covered three regions, which can be broadly characterised by comparing the distance with the turbine’s Rotor Diameter (RD) as in WPA1:
- the near-field at ~1RD: locations B1 to B3
- the mid-field at ~3RD: locations P1/P3a
- the far-field at ~10RD: locations P2/P3b

3.2.7 A LIDAR (Light Detection And Ranging) remote sensing device was installed at a location which was approximately 100 m upwind of the turbines considered during all of the analysis periods, and was therefore thought to provide a reasonable representation of turbine inflow conditions. This remote sensing system measured wind speeds and directions at different heights representative of those covered by the turbine rotor, with a resolution of approximately 3s. This data could then be reduced in statistics for periods of 10 minutes as standard. Figure 3.2 illustrates the heights measured which were representative of those covered by the rotor (and above). This provided a significantly increased spatial resolution than that provided by the meteorological mast installed on the site which measured wind speed and direction at two heights only (hub and bottom).

![Diagram illustrating the heights measured by the LIDAR scanning system (red line) in relation to the turbines](image)

3.2.8 In addition, dedicated data loggers were prepared by HLA in order to capture turbine operational data with a resolution of 1 second. This is in comparison to the 10 minute resolution data otherwise generally available as standard from the turbines’ Supervisory Control And Data Acquisition (SCADA) system. It was therefore possible for these three turbines to obtain data on their respective power generation, rotor/generator rotational speed, yaw (turbine orientation) and wind speeds (measured at hub height) with a 1s resolution. These were directly derived from the control system of turbines T1 and T2 using information supplied by the turbine manufacturer.

3.2.9 All HLA noise and turbine measurements systems were set to the same time reference by their synchronisation with Greenwich Mean Time (GMT). This was achieved through the use of a global positioning system (GPS) receiver. The synchronisation times were regularly verified during the site visits for data downloads and equipment calibrations as obtaining excellent time synchronisation was considered key to the measurements required in this instance.
3.3 Analysis approach

3.3.1 A preliminary analysis determined that some periods of other AM were experienced in conditions which were effectively downwind from the turbines studied. In lower winds, the turbines were operating very little or not at all, and in the windier periods the influence of wind noise represented a complicating factor despite taking reasonable precautions to minimise it. These considerations therefore restricted the analysis to medium wind speeds and certain key wind directions.

3.3.2 The analysis also focused on evening and night-time periods, where recordings were least likely to experience corruption from ambient sources of noise other than the wind farm, such as distant traffic or other human-related activities.

3.3.3 The chosen approach was to undertake a detailed analysis of five key periods, for which specific wind directions were experienced (typically within 15 to 20 degrees):

- Wind direction WD1 (3 periods)
- Wind direction WD2 (2 periods), for the latter part of the survey when the third sound level meter was moved from P3a to P3b.

3.3.4 For the latter case, this allowed a comparable analysis between the far-field locations P2 (crosswind) and P3b (downwind), as they were located at a similar distance from the turbines. Considering different wind directions also meant that the near-field locations B1-B3 experienced a range of different relative orientations of the wind turbine.

3.4 Metric analysis

3.4.1 As for site A above, a systematic analysis was undertaken using the AM analysis routine described, based on the measured $L_{Aeq,100ms}$ levels measured at locations 1 to 3, in blocks of 10 seconds. The technique used is the same as above and described in section 2.6. Analysis of filtered 1/3 octave band data was not possible because of equipment limitations, but as the analysis was restricted to quieter evening and night-time periods, the data contamination by spurious sources was limited, and a review of the calculated modulation spectra did allow the exclusion of short periods clearly affected by other sources.

3.4.2 Furthermore, it was possible to undertake a precise discrimination of the data through verification of the expected modulation frequency. The rotational speed of the turbine was measured in 1s resolution using a dedicated acquisition system, and therefore the expected modulation rate (at Blade Passing Frequency (BPF)) could be deduced from the turbine RPM by $BPF = \frac{RPM \times 3}{60}$.

3.4.3 For each of the analysed 10 s periods, a local peak in the modulation spectrum was sought in the region 0.4 Hz to 1.2 Hz (based on the expected typical rotational rate for the turbine at site B). The corresponding frequency of this peak was then checked against the calculated BPF for the corresponding period as supplied by the logger on the nearest turbine, and rejected if more than 0.05 Hz apart. This tended to exclude periods of spurious low modulation, as for periods of high modulation the correct modulation rate was correctly identified. The modulation amplitude rating is then shown only for the points retained.
3.5 Wind direction 1 (WD1) – period 1 (evening)

3.5.1 An example of a period of relatively high modulation experienced at the two downwind locations (P1 and P2) is shown in Figure 3.4. The levels measured in the near-field on a ground-board at location B3, which was downwind of the turbine in this case, are also shown. A spectrogram analysis of the frequency content of the audio sample corresponding to this period is shown in Figure 3.5 to Figure 3.6. It should be remembered when comparing the various traces included on Figure 3.4 that the timescales are absolute and no compensation has been made for propagation delays between the various measurement locations.

3.5.2 It can be seen that a large variability in the modulation is experienced, even within the period above which representative of a typical worst-case in terms of modulation. The modulation at the far-field location (P2) was of increased depth compared to both the mid-field and near-field locations. The near-field modulation appears relatively constant in comparison to that measured at further distance from the turbine which varies significantly.

3.5.3 Although the general reduction in average levels between locations P1 and P2 was consistent with the increased distance from the turbines, the modulation peaks did not seem to have decreased in the same way. From the spectrograms below it appears that:
- the modulation in A-weighted levels at locations P1 and P2 was generally dominated by frequencies between 200 and 600 Hz;
- the modulation peaks do attenuate in the same way as troughs between 300 m (approximately 3RD) and 600 m (approx. 10RD).

3.5.4 This could be due to a number of effects, or combination of effects, including the relative attenuation of these frequencies in the mid-field, the variable influence of source directivity with distance, or propagation effects. For instance, one possible explanation could be due to the so-called ground effect. The actual frequency of the ground effect dip, and its associated bandwidth and depth, will in practice depend on the actual ground conditions, and in particular the flow resistivity of the ground surface layer. However, based on a simple hard ground model, the path length difference between the direct and ground reflected propagation paths in this instance equates to a calculated ground effect dip at 300 Hz for the measurement at 300 m distance (P1): see Figure 3.3. In contrast, for the measurement at 600 m distance (P2), the ground effect dip is calculated to be approximately twice this frequency. Therefore, if the dominant modulation is occurring around 300 Hz, this could well explain the reduced modulation depth seen at 300 m when compared to that seen at 600 m, as the modulation peaks may then be attenuated.

Figure 3.3 – Calculated typical propagation attenuation function, as a function of frequency based on a 1.2m receiver 300 m away from an elevated source, illustrating a “dip” in the 300 Hz region
Another interesting feature of the results shown in Figure 3.4 is the appearance of closely spaced ‘double peaks’ being quite evident in the 300 m and 600 m distance traces. It can be seen that, in some instances, these double peaks appear to drift apart with time and then drift back together to form a single peak. The presumption here is that these double peaks represent the amplitude modulated noise from two separate turbines, each having a slightly different rotational rate. In order to check this presumption, it is useful here to focus on the final 10 seconds of Figure 3.4 and on the measurement location P1. This data shows one of the double peaks being higher than the other. It is the higher peak that becomes increasingly delayed when compared with the occurrence of the lower peak. A check on the measured rotational rate of turbines T1 and T2 over this period reveals that it is T2 (i.e. the turbine more distant from the measurement location) that was rotating at the slightly slower rate. It therefore appears that the more distant turbine (located approximately 600 m from the measurement location) is resulting in higher levels of amplitude modulated noise than the turbine located approximately 300 m from the measurement location.

As the measurements made at ground levels on the board at B3 minimise the influence of ground reflections effects, they are considered further below.

Figure 3.4 - Time history at locations P1, P2 and B3 for a 1-min period in period 1 (measured $L_{Aeq,100ms}$ and corresponding AM ratings for locations P1 and P2)
WIND TURBINE AMPLITUDE MODULATION: RESEARCH TO IMPROVE UNDERSTANDING AS TO ITS CAUSE & EFFECT
WPD - MEASUREMENT AND ANALYSIS OF NEW ACOUSTIC RECORDINGS

Figure 3.5 - A-weighted spectrogram of the audio recording corresponding to the 1min period shown in the above Figure 3.4: location B3 (~90m downwind) (arbitrary scale).

Figure 3.6 - A-weighted spectrogram of the audio recording corresponding to the 1min period shown in the above Figure 3.4: location P1 (~300m downwind) (arbitrary scale)

Figure 3.7 - A-weighted spectrogram of the audio recording corresponding to the 1min period shown in the above Figure 3.4: location P2 (~600m downwind) (arbitrary scale)
3.5.7 Earlier in the same evening, short-term phased shutdowns of the turbines were undertaken during which each of the three turbines studied was operated in isolation for periods of 5 minutes each with the 2 adjacent turbines switched off. This was done primarily to study if the interaction of the flow between the different turbines could be a potential factor in the modulation observed (although, for example, in the above conditions T1 was not directly downwind of T2 or T3). The shut downs additionally allowed for further analyses to be undertaken on the potential propagation effects between turbines and measurement locations at varying separation distances to be undertaken to supplement the observations already made in connection with the results shown in Figure 3.4.

3.5.8 Figure 3.8 below shows the calculated AM rating levels at both P1 and P2 locations, as well as those from the ground-board at B3 (cross-wind of T1 but down-wind of T2, see Figure 3.1). During this period, each of the three turbines studied was operated in turn for a period of 5 minutes, with the 2 adjacent turbines switched off. A period with T3 operating in isolation first occurs between 21:00 and 21:05 (this is known although no power output data was available to be shown on Figure 3.8), then T1 and T2 respectively, and this can clearly be seen in the latter case from the measured short-term operational data (generating power as a % of rated power).

![Figure 3.8](image)

**Figure 3.8** – Time history of AM ratings for locations P1 and P2 during a period of phased shutdown resulting in the isolated operation of Turbines T3, T1 then T2. Periods in which the modulation frequency returned from the FFT analysis method did not match the corresponding BPF were excluded. AM ratings for the ground-board location B3 (cross-wind of T1) are shown.

3.5.9 The following observations can be made:

- modulation rated at more than 3dB (similar to that of Figure 3.4) can occur with each turbine operating in isolation;
- the modulation experienced at P2 with T1 operating is comparable to that at P1 with T2: in both cases, the separation distance is similar (around 600m);
- the modulation was higher in the far-field than the near-field, and then reduced further with increasing distance: for example P2 is approximately 900m from T2 and modulation ratings were reduced from those at 600m (P1).
- For the period with T2 only operating, location B3 then represents ground-board measurements at a distance of 300m away, which can be compared to those obtained at P1 with T1 operating: marginally higher AM values are observed, although still comparably
lower than those observed at 1.2 m height at distances of 600 m in the other periods. Although the period is limited, this suggests the attenuation of the 300 Hz frequency region due to ground interference effects may not fully explain the lower levels of modulation observed in the mid-field.

3.5.10 The time histories of measured noise levels during the period of operation then the shutdown of turbine 1 is shown in Figure 3.9 in more detail. These results suggest a clearly dominant influence of separation distance on the amount of modulation experienced. Also, interaction of the flow between the turbines does not appear to be a dominant causal factor, as negligible flow interaction is expected with the adjacent turbines stopped. As above, increased levels of modulation are experienced with increasing distance from the turbine, with a peak in this instance at approximately 10 RD followed by a decrease thereafter. It is stressed, however, that based on this analysis it is not possible to confirm whether this is a general feature of this type of noise or a situation specific effect.

3.5.11 Similar results were obtained for a second shutdown period, although they are less clear as lower wind speeds led to reduced modulation levels.

Figure 3.9 – Time history of $L_{Aeq,100ms}$ for locations P1 and P2 for a period of shutdown of T1 operating in isolation (illustrated by active power time history).
3.6 Wind direction 1 (WD1) – period 2 (evening)

3.6.1 A longer period of variable modulation experienced downwind at the far-field at location P2 can be studied in further detail. On this day, a systematic analysis was undertaken in the evening between 19:00 and 23:00. The evolution of the modulation spectrum for the entire period is shown in Figure 3.10 for each of the 10s blocks of the analysis. This illustrates the varying presence of modulation at an evolving rate (close to 0.8Hz) and harmonics at multiples of this frequency. Some spurious periods are identified through the presence of peaks at lower frequencies but this does not appear to excessively affect the results.

Figure 3.10 – Time history of the modulation spectrum amplitude determined for location P2 from the automated procedure for period 2 (vertical axis represent the 10s blocks analysed).

3.6.2 Figure 3.11 illustrates the result of the subsequent filtering process. This process has retained the determined modulation rating from the automated metric analysis only when the resulting rate corresponds to the known actual rate, as determined from the rotational speed of the nearest turbine (T1) on a 10 second by 10 second basis with a permitted tolerance of 0.05 Hz prior to rejection of the sample. It can be seen that the resulting modulation frequency is consistently accurate within the resolution of the analysis undertaken which was 0.04Hz, which represents an impressive performance for the procedure.

3.6.3 The modulation frequency determined from the average turbine rotational rate from the 10 minute data is seen to capture the correct data trend, but does not capture short-term variations occurring within individual minutes, and a coarser tolerance would be required when considering such data. In this case, the minimum and maximum rate within each 10 minute period was provided by the SCADA system, which allows a finer analysis. However, a slight time offset is visible and this highlights the crucial importance of time synchronisation for such measurements.
3.6.4 Finally Figure 3.12 shows the excluded frequency values, as well as the resulting modulation rates, both with and without filtering. It can be seen that the excluded values overwhelmingly corresponded to period of low or spurious modulation, whereas for high modulation the correct frequency was generally accurately determined from the clearer signal. It was verified that the resulting periods of highest modulation indicated did correspond to period of clear AM.

Figure 3.11 – Time history of the modulation frequency determined for location P2 for period 2, using the automated procedure after filtering.

Figure 3.12 – Time history of the modulation frequency and amplitude for location P2, also showing the filtered values (F) which were excluded as their frequency was erroneous.
3.6.5 The variation in the determined AM rating parameter over this period (after filtering) can be examined in relation with different meteorological and operational parameter to assess the likely significance and relation with the varying levels of modulation experienced in the far-field.

3.6.6 First of all, the evolution of wind shear across this period can be visualised either through the wind speed profile at different heights or the corresponding shear exponents\(^1\). The heights refer to those defined in Figure 3.2. It is striking from Figure 3.13 that the period of elevated modulation is associated with a period of reduced wind shear.

\[
m = \log \left( \frac{H_{UU}}{H_{ref}} \right)
\]

Figure 3.13 – Time history of the AM rating for location P2, in parallel with either: a) wind profile evolution at different heights and b) associated shear exponent coefficient.

\(^1\) The shear exponent m represents a measure of the wind shear using this model: \(U = U_{ref} \left( \frac{H}{H_{ref}} \right)^m\)
3.6.7 Similarly, Figure 3.14 shows the variation in wind veer across the rotor with time. In this instance the wind veer is defined as the measured difference between the wind direction at different heights compared to the wind direction at the hub height.

3.6.8 Figure 3.15 then shows how turbulence levels, defined as the ratio (%) of the 10-minute standard deviation and mean wind speed, vary with height across the turbine rotor.

3.6.9 Figure 3.16 is more instructive as it shows the variation in the turbine generating capacity, and it can be seen that the turbine T1’s power generating output (as measured in short timescales) broadly correlates with the amount of modulation experienced in the far-field: at the beginning of the period, although wind shear, veer and the gradient of turbulence are relatively high, there is little modulation. As the wind speed (Figure 3.17) increases, the amount of turbulence, wind shear and wind veer decrease, but the power output increases and so does the amount of modulation in turn.
When examining the time history in further detail, it can be seen that the short period of relatively highest modulation rating values visible in these graphs, at around 21:30, is not directly associated with the high wind speeds or generating power, as it is immediately followed by similar conditions but without the same AM in the far-field.

As the turbines at Site B are variable-speed, pitch-regulated machines, the interaction of rotational speed, incident wind speed and power regulation is complex and determined by the turbine’s control system. As discussed in the Annex to this report, for evaluation purposes, it can be interesting to estimate the potential changes in the angle of attack of the flow on the blades corresponding to different conditions. Determining this precisely would require a full knowledge of the blade geometry, flow conditions, etc., or it can be measured using dedicated...
on-blade sensors, as reported in some experiments by others [7], but this was not possible within the scope of the current measurements.

3.6.12 A “relative” angle of attack (“alpha”) can be estimated based on the rotational speed, incident wind speed and pitch adjustment for each 10 s period, to represent a reasonable estimate of the likely variation of the incident flow character with time. This is shown here in Figure 3.18. This suggests that the period of elevated modulation coincides with a rapid increase in the effective angle of attack on the blades, during a period when the turbine is generating significant power (>15% of its total rated power).

![Figure 3.18](image)

**Figure 3.18** – Time history of the modulation amplitude for location P2, in parallel with the variation in T1 relative angle of attack (10s resolution).

3.6.13 The difference between the $L_{A_{eq,10min}}$ and the $L_{A_{90,10min}}$ for the period of relatively elevated modulation (around 21:30) was approximately between 2 and 3 dB.

3.6.14 Finally, whilst the above analysis focused on the far-field location (P2), it can be useful to compare the relative level of modulation experienced at the other locations. Figure 3.19 shows a comparative plot of the filtered AM amplitudes between the different locations. This first confirms that, in the downwind direction, the modulation in the far-field (P2) is higher than in the mid-field (P1). This also shows that mid-field modulation is comparable between P1 (downwind) and P3a (cross-wind), but that the latter tends to be lower.

![Figure 3.19](image)

**Figure 3.19** – Comparison of the filtered modulation amplitudes measured at locations P1, P2 and P3a for period 2 (20:00-22:00).
3.7 Wind direction 1 (WD1) – period 3 (evening and following morning)

3.7.1 A longer period of variable modulation experienced downwind in the far-field at location P2 can be studied in further detail. On this day, a systematic analysis was undertaken in the evening between 21:00 and 01:00 and 04:00 to 07:00 the next morning. The evolution of the modulation spectrum for the entire period is shown in Figure 3.20 for each of the 10s blocks of the analysis. The entire analysis took less than 10 minutes using a PC with a 64-bits 2.7GHz processor with the MATLAB software, which means that a systematic data analysis is feasible in practice.

3.7.2 A clear pattern of modulation at a varying frequency close to 0.8 Hz, as well as several harmonics, is visible for most of the periods. Narrow, horizontal lines represent artificially high values across the entire modulation spectrum which are caused by short-term spurious sources, for example early morning bird call noise towards the end of the period. As these occur across the modulation spectrum, they may not be eliminated by the filtering procedure above, but it is a straightforward procedure to exclude them manually.

3.7.3 In this case as well, the metric analysis can be filtered using the known rotational speed of the turbines at any one time. The resulting evolution of modulation frequency is shown Figure 3.21 and a very good performance is again achieved, consistently, with the pattern of Figure 3.20. As previously, the differences between the $L_{Aeq,10min}$ and $L_{A90,10min}$ did not deviate significantly from typical values of 1.5 to 2.5 dB.

3.7.4 The variation in the AM metric is then shown alongside a range of parameters as previously: Figure 3.22 and Figure 3.23. Values of wind shear/veer are generally more elevated than for period 2 considered above, but again no clear association is evident from these graphs, which in fact again suggest that AM increases occur following reductions in wind shear.

3.7.5 The turbulence data is similar to that of Figure 3.15, with a relatively uniform distribution across the rotor, and values of less than 10%, for the periods of more significant modulation. This can be compared to theoretical considerations (WPA2) which suggest that a 10-fold increase in turbulence amplitude would be required to correspond to the variations in source levels of the right order of magnitude.

3.7.6 Figure 3.25 shows the evolution of the relative angle of attack “alpha”. These results are not conclusive but suggest that the turbine generating output and an increased angle of attack represent key associated factors for the associated AM in this case.

3.7.7 Finally, Figure 3.26 shows the measured wind profile at different representative times (see time history in Figure 3.22) which illustrates the actual wind shear across the rotor. The measured wind speed above the rotor tip height is compared with that extrapolated using an exponent shear profile across the rotor. This was done following the suggestion of McLaughlin [8] that low-level jets may be present and affect source levels or propagation. However, the observed wind shear profiles did not highlight the presence of such a jet.
Figure 3.20 – Time history of the modulation spectrum amplitude determined for location P2 from the automated procedure for period 3 (vertical axis represent the 10s blocks analysed).

Figure 3.21 – Time history of the modulation frequency determined for period 3, location P2 from the automated procedure, after filtering. The residual variations observed are similar to the frequency resolution of 0.4 Hz in the analysis.
Figure 3.22 – Time history of the modulation amplitude for location P2, in parallel with the associated shear exponent coefficient at different heights, for period 3.

Figure 3.23 – Time history of the modulation amplitude for location P2, in parallel with the variation in wind veer at different heights, for period 3.

Figure 3.24 – Time history of the modulation amplitude for location P2, in parallel with the variation in T1 generating power (as a percentage of rated power, 10s resolution), period 3.

Figure 3.25 – Time history of the modulation amplitude for location P2, in parallel with the variation in T1 relative angle of attack (10s resolution), period 3.
3.8 Wind direction 2 (WD2) – period 4 (morning)

3.8.1 In the last phase of the survey at site B, the system at location P3a (mid-field) was moved further away from the turbines to location P3b. This allowed a study of the propagation of the modulation noise in a second wind direction (WD2) for comparative purposes: see Figure 3.1. This also allowed a direct comparison between two far-field locations: P3b (downwind) and P2 (crosswind in this case).

3.8.2 By the time of this phase of the measurements, the LiDAR sensor had been decommissioned and so reference was made to the remaining, less detailed meteorological information from the wind farm’s SCADA system.

3.8.3 The first of the two periods of suitable weather conditions identified was an early morning period in which variable levels of modulation were experienced. The resulting modulation spectra evolution for the period is shown Figure 3.27. It can be seen that similar modulation features can be observed in this wind direction in the far-field as that observed at comparable distances at location P2, which was downwind for the periods experiencing WD1. The modulation frequency is relatively constant across this period which is consistent with the measured rotational rate, with a similar filtering as above having been applied.

3.8.4 For this period, P2 is located cross-wind and the modulation magnitude experienced at both far-field locations is compared in Figure 3.28. It is clear from this analysis that the far-field (~10RD) cross-wind location experienced significantly less modulation than the downwind one.

3.8.5 The wind shear across the bottom half of the rotor was available for this period and is shown in Figure 3.29 along with the filtered AM magnitude. This suggests again a weak negative correlation of AM rating with the amount of wind shear.

3.8.6 In Figure 3.30 and Figure 3.31 the change in generating power and relative angle of attack is displayed. T2 is then used as a reference because of its relative proximity. It can be seen that the AM generally varies broadly in line with the power output of the turbine, and that elevated AM rating values can be associated with periods of variation in the angle of incidence.
Figure 3.27 – Time history of the modulation spectrum amplitude determined for location P3b from the automated procedure for period 4 (vertical axis represent the 10s blocks analysed).

Figure 3.28 - Comparison of the filtered modulation amplitudes measured at P3a (downwind) with that measured for the same period at location P2 (cross-wind).
Figure 3.29 – Time history of the modulation amplitude for location P3b, in parallel with the associated shear exponent coefficient, for period 4.

Figure 3.30 – Time history of the modulation amplitude for location P3b, in parallel with the variation in T2 generating power (as a percentage of rated power, 10s resolution), period 4.
3.9 Wind direction 2 (WD2) – period 5 (morning)

3.9.1 Period 5 comprises another early morning period (04:30 to 07:30) which experienced similar wind directions (WD2) as period 4. A similar modulation pattern is observed, with some 10 second periods rated between 4 dB and 5 dB using the metric implementation for the data of P3b.

3.9.2 Figure 3.32 and Figure 3.33 illustrate that the algorithm performs well, even with a change in BPF of 0.6 to 0.8 Hz across the period, and that the subsequent filtering mostly eliminates some relatively low periods of modulation.

3.9.3 The measured shear exponent (over the bottom half of rotor) during this period slowly decreased from 0.5 to 0.3 across the measurement period, with little observable effect on the rate of far-field modulation.

3.9.4 Figure 3.34 and Figure 3.35 present similar data as for period 4, and similar observations can be made as for period 4 in terms of the relationships of AM rating with operational parameters.

3.9.5 Finally Figure 3.36 and Figure 3.37 present the time history for two periods of clear modulation observed in the far-field (location P3b), and compare the variations in $L_{Aeq,10ms}$ at this location with those obtained at a similar distance cross-wind (P2), showing reduced levels of modulation. Near-field measurements made on ground-boards closer to turbine T2 are shown: B1 and B2, representing both the down-wind and cross-wind directions. The latter experiences deeper modulation than the former, but in both cases the magnitude of modulation is higher in the far-field. Corresponding spectrograms are shown in Figure 3.38 Figure 3.39 respectively.
WIND TURBINE AMPLITUDE MODULATION: RESEARCH TO IMPROVE UNDERSTANDING AS TO ITS CAUSE & EFFECT
WPD - MEASUREMENT AND ANALYSIS OF NEW ACOUSTIC RECORDINGS

Figure 3.32 – Time history of the modulation frequency and amplitude for location P3b, also showing the filtered values (F) which were excluded as their frequency was erroneous.

Figure 3.33 – Time history of the modulation frequency determined for location P2 for period 2, using the automated procedure after filtering.
Figure 3.34 – Time history of the modulation amplitude for location P3b, in parallel with the variation in T2 generating power (as a percentage of rated power, 10s resolution), period 5.

Figure 3.35 – Time history of the modulation amplitude for location P3b, in parallel with the variation in T2 relative angle of attack (10s resolution), period 5.
Figure 3.36 – Time history of measured $L_{Aeq,100ms}$ levels for a sample period showing: two far-field locations (P3b downwind and P2 cross-wind) and two near-field locations (cross- and down-wind).

Figure 3.37 – Time history of measured $L_{Aeq,100ms}$ levels for a sample period showing: two far-field locations (P3b downwind and P2 cross-wind) and two near-field locations (cross- and down-wind). The elevated levels at P2 towards the end of the period correspond to bird noise, as can be seen on Figure 3.39.
Figure 3.38 – A-weighted spectrograms for the modulation period shown in Figure 3.36: showing locations P2, P3b and B1 respectively (arbitrary scale).
Figure 3.39 – A-weighted spectrograms for the modulation period shown in Figure 3.36: showing locations P2, P3b and B1 respectively (arbitrary scale).
3.10 Site B - conclusions

3.10.1 The measurement campaign undertaken at site B allowed a detailed study of the directivity and characteristics of 'other AM' noise. In the far-field, instances of clear AM were associated with propagation in the downwind direction and were reduced cross-wind. The effects in the near-field were more difficult to discern. Furthermore the AM levels in the far-field were strongly variable and did not seem to be simply associated with most of the operational or meteorological parameters considered. This suggests a strong influence of propagation effects. The AM increased downwind between the mid-field and far-field region, with a slight decrease further away (although the latter may be due to reduce signal strength). This is consistent with observations made by Di Napoli [9].

3.10.2 In addition to wind direction, the turbine generating output seemed the main associated variable related to the observed AM magnitude, in the sense that little modulation observed when the turbine was generating little (as could have been expected). In conditions of sufficiently elevated generation, rapid changes in the estimated relative angle of attack of flow on the blade did also appear to sometimes be a factor in enhanced AM depth, although the behaviour appeared complex.

3.10.3 These observations are not consistent with the "standard" modulation model, hence the use of the description "other AM". However, several of the observed features are consistent with some of the predicted outcomes of the detached flow theoretical model of WPA1. These are most notably that there is significant modulation in the far-field downwind (see WPA1 figures 19/21), the presence in some cases of a spectrum bias towards 200Hz and spectral differences between peaks and troughs. Although reduced modulation was observed in the mid-field, this may be attributed in part to ground reflection effects.

3.10.4 The observed far-field modulation was of a higher depth (more than 5dB(A) at times) than predicted in the standard model of WPA1, but it was noted that this prediction is highly dependent on the features of the detached flow source model (WPA1 figure 29) which was largely uncertain. The large modulation predicted in one cross-wind direction in the near-field (WPA1 figure 29), was also not observed (see Figure 3.4 for example), and this may again be a very specific feature of the particular model employed (turbine geometry etc.). Finally as noted in WPF, the model employed does not incorporate propagation effects and, because of the strong influence of such effects, it may be interesting to extend this model to include them, as in the work of Boorsma and Schepers [10]. Ground effects in particular may cause significant variations in response at varying source heights, receiver heights, separation distances and different ground types.

3.10.5 Because of the lack of detailed frequency measurements, the analysis was limited to evening and night-time periods, in which levels of human or bird-related activity decreased significantly, but these periods will also be those in which increased wind shear due to atmospheric effect will tend to be greater at this site, because of atmospheric stability effects. This was, however, clearly not a necessary condition as some periods of elevated modulation were observed as the wind increased and the wind shear decreased.

3.10.6 Thus other source mechanisms may be at play. It is also conceivable that particular blade designs could experience partial blade stall in certain conditions without the influence of non-uniform inflow conditions, as was assumed to trigger it in WPA1. For example, aero-elasticity effects may vary the blade geometry in such a way it departs significantly from its design conditions. There is, however, very limited information available to study this in the current state of knowledge.

3.10.7 It should be borne in mind that, on some sites, the impact of wind shear on effective modulation may be more important at (non-sheltered) residential location surrounded by vegetation. This is because increased wind shear will correspond to relatively reduced wind near the ground, and this will have an effect on the level of masking background noise which may otherwise reduce...
the effective modulation depth. The chosen monitoring locations were surrounded by negligible vegetation and therefore this effect was minimised in these measurements, but it likely represents a complicating factor in many other situations. This is because a lower signal-to-noise ratio will rapidly reduce the effective modulation measured.

3.10.8 As the effect of partial stall is posited and the effect of angle of attack of the flow appear significant for the study of “other AM”, the next section describes further tests which were undertaken at a site in which turbine pitch was directly varied and the effects measured.
4 SITE C – DEDICATED TRIAL MEASUREMENTS

4.1.1 This aspect of the project involved targeted measurements on a wind farm site using novel techniques to investigate the influence of turbine operation on the character of the AM noise produced, as informed by the results of the other work packages in this project.

4.1.2 In particular, the hypothesis raised in WPA1 that partial blade stall may lead to increased levels of modulation at large distance downwind warranted particular investigation. Considering this, along with the linked discussions in WPA2 and WPF, the influence of the turbine’s pitch regulation system was considered crucial. In certain conditions the angle of attack of the flow on the blade may be such that stall occurs for part of the blade rotation. Although complex, this effect would be most sensitive to changes in the blade pitch, which would either increase or decrease the angle of attack and therefore affect the likelihood of stall.

4.1.3 Designing a measurement campaign capable of addressing the foregoing issues required detailed cooperation with turbine manufacturers. With this in mind, a meeting was organised in April 2011 with representatives of most of the major wind turbine manufacturers in Europe to present the preliminary results of the research undertaken to date. This was considered necessary in order to better understand and/or evaluate the functioning of the power-control and regulation mechanisms in modern wind turbines. It was also considered valuable to investigate in more detail the impact of modifications in the turbine operation on the character of the noise. A detailed knowledge of the blade geometry and operating condition is generally not available publicly because of commercial confidentiality considerations.

4.1.4 It was proposed to undertake tests in which the pitch of the turbine was controlled directly in order to attempt to trigger detached flow on the blade, and to assess the relative impact on far-field modulation. Similar manual pitch changes were undertaken in previous investigations [11], but these focused on overall sound power levels rather than modulation. The project team is not aware of such investigations having been undertaken previously.

4.2 Measurement description

4.2.1 The test site comprised a dozen pitch-regulated, variable speed turbines, located on a treeless moorland hill, amongst generally hilly terrain and valleys. The site was relatively isolated from any habitations, roads or settlements, and therefore exposed to relatively low levels of noise from human activity.

4.2.2 A single turbine was selected as a test turbine. It was selected as being relatively isolated from the rest of the wind farm, and at a location from which measurements could be undertaken at increasing distance downwind (under prevailing wind directions) whilst moving away from most of the wind farm site, thus minimising the need for extensive turbine shutdowns, which would have been more difficult to justify and secure.

4.2.3 Noise monitoring equipment was installed at seven locations surrounding the test turbine for the duration of the testing, focusing on the downwind direction, at distances of up to 1km from the test turbine. These locations are represented on Figure 4.1 and listed in Table 4.1.

4.2.4 01dB Duo integrating sound level meters with audio recording were used at six of the measurement locations (L2-L7). Two of these systems were installed at crosswind positions either side of the test turbine at a distance of approximately 1 RD (L6 and L7). Three more systems were installed at positions downwind of the test turbine at various distances of up to 1km (L2-L5). As shown in Figure 4.2, the most distant downwind location (L4) was located across a valley; it experienced the influence of noise from a water-course at the bottom of this valley. The remaining system (L5) was installed at a cross-wind location which was in a relatively sheltered location, which experienced partial terrain shielding from the test turbine.
4.2.5 The Duo systems were mounted on tripods with the microphone height at approximately 1m from the ground. The microphones were fitted with primary and secondary wind shields. Each system was connected to a 12V external battery which was also used to weight down the tripod to avoid toppling in high winds. However due to a manipulation error, the system at location L7 did not record any data for the measurement period.
4.2.6 A final measurement system was installed downwind at location L1, approximately 1RD from the test turbine. This comprised a single 01dB Blue Solo sound level meter, configured in conjunction with a low power computer running the 01dB “dBTrig” measurement software and housed in an environmental enclosure. This location was used to conduct measurements of the effective turbine sound power levels, with reference to the guidance in the IEC 61400-11:2003 standard, although the latter was not strictly complied with. This system was configured with the microphone mounted on a circular ground board and was fitted with primary and secondary windshields. All sound level meter systems meet the requirements of a Type 1 sound level meter. Each system was set up to undertake simultaneous and synchronised noise level recordings, including $L_{Aeq}$, $L_{AF}$ and third-octave band frequency data between 6.3Hz and 20kHz, every tenth of a second, as well as near-continuous audio recording with an audio sampling rate of 12.8 kHz.

4.2.7 In addition to the noise monitoring equipment, a dedicated data logger was prepared by HLA, in consultation with the turbine manufacturer, in order to capture turbine operational data with a resolution of 1s. It was therefore possible to obtain data on the respective generating power, rotor blade pitch, yaw (turbine orientation) and wind speeds (measured at hub height) with a 1s resolution. Unfortunately data on the turbine rotational speed was not captured in this instance.

4.2.8 All HLA noise and SCADA measurements systems were set to the same time reference by their synchronisation with Greenwich Mean Time (GMT). This was achieved through the use of a global positioning system (GPS) receiver or the internal GPS receiver of the Duo systems. All equipment was set to run continuously so that tests could be conducted without delay once the required wind conditions occurred.

4.3 Test procedure

4.3.1 During testing, turbine engineers could use specifically-developed turbine operational modes to vary the pitch of the turbine blade at a range of integer pitch angles three degrees either side of the default standard pitch setting for the turbine. Note that, in the convention used in this case:

- the standard pitch setting during conditions present for most of the test was -1 degrees;
- decreasing the pitch (down to a minimum of -4 degrees) would mean increasing the relative angle of attack and therefore the likelihood of blade stall;
- increasing the pitch would tend to reduce the angle of attack, which is what is done at high wind speeds to regulate the power generation of the turbine.

4.3.2 It was expected by the manufacturer that the lowest setting would correspond to blade stall conditions. Due to the operating restrictions of the turbines and safety consideration, such tests could only be conducted during particular weather conditions. The main requirement was of not exceeding a certain wind speed threshold, above which the power regulation requirements would automatically over-ride any manual pitch settings entered in the control system. Of course completely calm conditions would not have been suitable either. It was also necessary to experience certain wind directions because of the practical constraints and measurement layout outlined above. The SCADA data analysis described in the Annex to this report suggested that this range of wind speed would be suitable to the pitch investigations as relatively high angle of attacks were calculated.

4.3.3 As a consequence of these requirements, the window of opportunity for conducting the tests was limited, with several abortive attempts to measure being made. This section of the report describes a test which was undertaken several months later, over a period in which conditions were anticipated to be more favourable. Strong winds were still dominant for most of the three days when the testing equipment was installed. It was nonetheless possible to undertake two measurement test sequences on the second day of the measurements. Although further testing may have provided useful supplementary data, this was not undertaken as this would have
delayed the current project still further, the project already having been delayed to accommodate the tests reported herein that were undertaken on Site C.

4.3.4 Each test sequence consisted of successive periods of approximately 5 minutes in which the pitch angle was varied in steps of one degree. This was so that the full range of pitch angles could be tested before wind conditions changed significantly. During each test, the nearest two turbines to the one tested (located approximately 400m upwind) were switched off. This was done to minimise the influence of the rest of the wind farm at most locations, but at the most distant locations, such as L4 or L5, the separation distance from the test turbine was more comparable to that of other, operating turbines and a residual influence of these other turbines could not be excluded. For example, one turbine was operating at approximately 1.5km from location L4, compared to the distance of 1km from the test turbine.

4.4 General considerations

4.4.1 Due to the hilly nature of the terrain at the site, it was not considered likely to experience strong levels of wind shear. An analysis of the 10 minute wind speed data collected at two heights over a period of several months at the site’s permanent meteorological mast showed that, even if excluding periods of negative shear, the shear exponent coefficients (defined in 3.6.6 and WPA2) averaged over different hours of the day did not typically exceed 0.2 (as compared with site B where values of up to 0.4 to 0.5 were experienced at times, see Figure 3.22).

4.4.2 The nature of the site means that it will tend to experience complex flow in certain conditions, although detailed turbulence data was not available. The test turbine was situated downwind of a hill as the ground climbed up to about 100 m more in the up-wind direction. Based on the analysis of WPA2, it was thought that these complex flow conditions may trigger blade stall at times, even in the absence of high wind shear conditions, particularly when the pitch of the turbine was decreased. Whilst undertaking measurements on site, sporadic ‘thumps’ were audible from some of the turbines at times, although these were quite rare: these observations may consistent with the occurrence of complex flow, or large-scale turbulence triggering blade stall.

4.4.3 As in previous sections, a systematic analysis of the modulation level measured at the different locations was undertaken using the same AM metric routine described above, with the MATLAB software. This was based on the recorded short-term history of measured noise levels at each of the noise monitoring locations. This systematic analysis was verified using a review of recorded levels and audio samples. The analysis was first done on the basis of the A-weighted levels $L_{Aeq,100ms}$, but excessive contamination from spurious sources was encountered, in particular at the most distant location (L4) which was affected by water-course noise. The recorded time-history of 315 Hz levels provided by the sound level meters was then used instead, as it was established that this provided a more accurate measure of the amount of modulation experienced at the different locations.

4.5 Test sequences

4.5.1 On the main day of testing, wind speeds at the site reduced sufficiently at times so that meaningful tests could be undertaken. A first test sequence was undertaken shortly after 15:00: with the pitch increased from -4 to +2 degrees in 1 degree steps. The recorded history of 1 second pitch values recorded by the data logger is shown in Figure 4.3. It can be seen that deviations from the proposed setting were experienced at times: this was due to gusts of wind increasing above the threshold meaning the turbine control system needed to override the settings.
This test was aborted when the wind increased again. Even when rejecting the short excursions periods, it was difficult to exclude their potential effect in the analysis, particularly given the test duration. This meant that the results of this first test were not considered conclusive and they are therefore not considered further here.

A second test sequence was initiated remotely later this day; see Figure 4.4. The range of pitch values in this sequence was wider and more comprehensive, and the analysis will therefore focus on this period. Short deviations from the desired pitch setting and any disturbance in the measurement were excluded from the subsequent analysis.

For the measurements undertaken on the ground-board mounted microphone at location L1, an apparent sound power was calculated from the measured $L_{Aeq}$ levels by subtracting 6dB and
correcting for the slant distance to the turbine. Although this was clearly done with reference to the IEC 61400-11 standard, the aim was to assess relative changes in the overall sound power of the turbine in different conditions, and not to undertake an assessment of the absolute sound power level of the turbine. Some effective deviations from the standard requirements were made, such as the distance from the turbine and the windshield system used, because of practical considerations.

4.6.2 The evolution of the apparent A-weighted sound power level ($L_{WA}$) with time is shown in Figure 4.5 below, both on a 1 second basis and for 1 minute averages (as suggested in IEC 61400-11). The corresponding evolution of the pitch setting is also shown, and this graph suggests that the lowest pitch setting tend to correspond to elevated values of $L_{WA}$. Significant variability is however visible, which can be explained by short-term variations in the hub height wind speed. This was established by calculating the wind speed from the generating power of the turbine using its power curve (in accordance with the IEC 61400-11 standard). If $L_{WA}$ is plotted as a function of the 1 minute wind speed at hub height, standardised at 10 m height in accordance with the 61400-11:2003 standard, the relationship becomes clearer: see Figure 4.6.

4.6.3 This shows that elevated levels of overall noise were produced by the test turbine for the lowest pitch setting (-4 to -3 degrees in particular), which represents an indicator of the extensive presence of stall on the blades, as expected. This was also consistent with subjective impressions on site in a "roaring" type of noise when these settings were in place. It would therefore follow that increasing the level of pitch further may be conducive to partial blade stall, which (according to the model of WPA1) would correspond to elevated levels of "other AM". For all pitch values of -1 and above, similar overall sound power levels are observed.

Figure 4.5 – Evolution of the pitch and apparent sound power level (in 1 second or 1 minute averages) during the main test sequence, with averages shown for each pitch step.
4.7 Modulation analysis

4.7.1 Figure 4.7 presents a comparative example of the analysis of AM for a three-hour period (which included the test period) at the most distant location (L4) based on either the A-weighted data ($L_{Aeq,100ms}$) or the 315 Hz 1/3 octave band levels (in 10s periods). The technique used is the same as above and described in section 2.6. This illustrates the effectiveness of the filtering in eliminating spurious sources from the analysis, most of which appear as horizontal lines in this plot, when all “modulation frequencies” are affected; sometimes the effect of spurious sources results in a more general masking effect which is more difficult to detect.

4.7.2 In this case, short-term turbine rotational speed data was not available to verify if the modulation frequency obtained was correct (as was done for site B), but the turbine’s rotational speed was relatively constant during the test period, as can be seen on Figure 4.7. Furthermore, given the limited duration of the test, a manual review of the AM peaks identified could be undertaken to limit the amount of potential negatives.

4.7.3 The evolution of the values of AM ratings (for each 10s analysis period) are shown for the main test sequence, along with a graph showing the evolution of the pitch values during the test, in Figure 4.8 to Figure 4.12 for all measurement locations. An average was calculated of the AM rating values (dB) obtained for each of the 5-minute pitch stepping periods. To represent the incidence of the highest AM values, as obtained within each 5 minute step, the 90th percentile (top 10%) of the AM values are considered separately (in purple) and a separate average made.

4.7.4 Although some sporadic periods of high AM are recorded throughout, the prevalence of these events appears to increase significantly as the pitch decreases, particularly for “intermediate” values (-2 or -3 degrees). It can be noted that, for example in Figure 4.10, the trend appears broadly symmetric relative to the evolution of the pitch setting, which suggests a systematic effect. This would be consistent with an enhanced likelihood of partial blade stall caused by a
progressive increase in the effective angle of attack of the flow, and triggered by complex flow events such as wind gusts or large turbulent structures.

4.7.5 The incidence of modulation did not appear to decrease significantly when the pitch angle increased further beyond 0 degrees. The picture is made more complex overall by the presence of sporadic AM at times, which may be caused by isolated events of non-uniform flow, caused by the complex flow present at the site. The influence of other turbines, situated further away, could also not be completely excluded and was observed at times whilst on site during the first test. The effect in the near-field (location L6, Figure 4.8) was more limited, as is predicted in WPA1, although a marked change was observed at the lowest pitch setting.

Figure 4.7 – AM Analysis for the data at location L4 (1km) for the period 18:00-21:00, based on the analysis of $L_{Aeq,100ms}$ levels (left) and 315 Hz 1/3 octave band levels (right)

Figure 4.8 – Evolution of the AM rating (including top 10%) for each pitch step period – L6
WIND TURBINE AMPLITUDE MODULATION: RESEARCH TO IMPROVE UNDERSTANDING AS TO ITS CAUSE & EFFECT WPD - MEASUREMENT AND ANALYSIS OF NEW ACOUSTIC RECORDINGS

Figure 4.9 – Evolution of the AM rating (including top 10%) for each pitch step period – L2

Figure 4.10 – Evolution of the AM rating (including top 10%) for each pitch step period – L3
WIND TURBINE AMPLITUDE MODULATION: RESEARCH TO IMPROVE UNDERSTANDING AS TO ITS CAUSE & EFFECT
WPD - MEASUREMENT AND ANALYSIS OF NEW ACOUSTIC RECORDINGS

Figure 4.11 – Evolution of the AM rating (including top 10%) for each pitch step period – L4

Figure 4.12 – Evolution of the AM rating (including top 10%) for each pitch step period – L5
4.8 Site C - conclusions

4.8.1 The measurements on Site C were undertaken in a highly targeted manner in an attempt to elicit information that could not be gained from the types of measurements undertaken at Sites A and B. The additional factor which was within the control of the project team (via the wind turbine manufacturers) at Site C compared with Sites A and B was the ability to control the pitch of the turbines away from their standard design settings. In this manner the effect of angle of attack of the turbine blades on radiated noise could be studied.

4.8.2 The primary aim at Site C was to confirm the hypothesis that separated flow (i.e. stall) would consistently result from too high an angle of attack. Further, it was desired to test the suggestion that, around the angle of attack where the transition between fully separated and attached flow occurs, there exists an increased likelihood of localised flow separation (transient stall) giving rise to an increased likelihood of other AM.

4.8.3 In order to positively test for the occurrence of stall, either in the form of totally detached flow or in the form of localised (transient) stall, ideally what is required would be pressure measurements or stall flags on the surface of the blades themselves. However, this was not possible within the scope of the project, so reliance had to be placed on the noise data in order to establish any changes to the radiated noise that may indicate stall. In order to achieve the foregoing aims, a test turbine was selected and installed with a high resolution data acquisition system which was set up to record the key turbine operational parameters at 1 second intervals. Audio recording and logging noise measurement systems were located at a total of 7 noise monitoring locations around the test turbine, at various distances ranging from approximately 80 m to 1000 m in both downwind and cross-wind positions relative to the test turbine.

4.8.4 Ideally the measurements would have been undertaken over extended periods such that more data could be obtained to enable a more complete statistical analysis to be undertaken on the measurement data. In this manner the significance of the relationship between potential causes and effects could have been better established. However, due to the need to avoid controlled blade pitching during conditions of higher wind speeds, it was only possible to undertake two runs of these tests during which the pitch of the blades was altered from +2 degrees to -4 degrees, as compared to the ideal design pitch for the test conditions which was approximately -1 degree.

4.8.5 Notwithstanding the practical limitations just described, the limited extent of the acquired data still allows a useful analysis of the effect of changing blade pitch. In terms of overall radiated noise levels, a systematic change in noise levels was measured as a result of re-pitching the blades away from their optimum design pitch. Negative blade pitching moved the blades closer to stall, and by the point at which the blades were pitched to -4 degrees the ‘roar’ of stall noise became subjectively quite apparent. This was reflected in the increased level of sound power which was measured under these same conditions when compared with optimally pitched or positively pitched blades. Around the ‘transition’ pitch angle of -2 to -3 degrees, the likelihood of the existence of intermittent AM noise (as opposed to the more continuous roar of stall noise) became subjectively more apparent. The increased prevalence of such AM noise under these same conditions was also confirmed by measurements. However, there was no single pitch setting in which a total absence of AM occurred. This may be due to the complexity of the site or, more likely, from AM arising from other operational turbines (other than the test turbine) which remained operational throughout the measurement period.

4.8.6 As a final conclusion and recommendation, the tests at Site C have confirmed the effect of blade pitch on the potential for inducing or reducing the chances of AM occurring. However, more extensive test measurements would be required, under much more closely controlled conditions, and ideally also including blade surface measurements, in order to positively identify when stall occurs and therefore to enable firm conclusions as to the use of pitch variations to positively control AM.
CONCLUSIONS

5.1.1 The objective of work package D was to undertake additional measurements to supplement the data available as part of the other work packages, and in particular work package C. As a consequence of the output of other work packages, it was decided that the best approach would be to undertake a series of measurements across three sites, with a very different approach to the measurements being undertaken at each site:

- At Site A measurements were undertaken at residential dwellings where AM noise issues had been reported by the residents. Noise measurements were undertaken at two dwellings in the absence of any other operational data from the wind farm and the data obtained used to test the AM metric routine developed under work package B1;
- At Site B detailed measurements of noise at multiple locations around the test turbines, meteorological conditions and turbine operational data were undertaken on a wind farm site. The opportunity was provided for the switching on and off of various turbine combinations, but no control was provided for manually varying the operational parameters of the turbines.
- At Site C multiple noise measurements were undertaken around a test turbine (located within an operational wind farm) together with turbine operational data. The opportunity was provided to manually control the blade pitch settings of the test turbine away from its optimal design setting such that the effects on noise output of inducing full or partial stall could be established.

5.1.2 The results obtained at all sites have reaffirmed the point that the measurement of wind farm noise, particularly in the far field, is made difficult because of the relatively low acoustic power of the source and the dependence on wind conditions, both in terms of propagation effects and background noise effects, both of which can reduce the signal to noise ratio and thus the consequent utility of the measured data.

5.1.3 However, the test results have also confirmed that the incidence of "other AM" was most readily detectable in the far-field locations. This therefore represents a significant additional challenge for detailed measurements studies, which is probably one of the main factors which has limited the progress made in the subject to date. Compared to the assessment made in the near to mid-field (such as for sound power testing or previous modulation studies [12]), assessments in the far-field are complicated by the dominance of propagation effects and the masking of other sources.

5.1.4 Notwithstanding these measurement challenges, analysis of the results obtained at all sites have shown that the type of analysis techniques which have been described and developed as part of other work packages of this project can be realistically and meaningfully applied to both detect and rate the levels of modulation in the far-field noise from wind turbines, even in complex rural environments in which wind turbine noise can often be difficult to detect (let alone characterise in detail). In particular, the main AM metric routine described in WPF was systematically used at each of the different sites and proved effective in both detecting and rating the magnitude of the modulation.

5.1.5 In particular, the use of measured data in specific 1/3 octave band characteristic of the modulation has been successfully demonstrated to enable most spurious sources to be efficiently excluded from the analysis, without the excessive practical difficulties involved with continuous audio recordings. But even using these techniques for a carefully filtered and scrutinised analysis of a real measured dataset in a typical rural environment will produce values of the AM rating metric of up to 2 dB (with a limited amount of sporadically higher values) even in the absence of any significant modulation. This is mainly due to residual noise, uncertainties associated with digital processing and the integration process used, and should be borne in mind when applying such techniques. Perhaps counter-intuitively, the differences between the longer-term $L_{Aeq}$ and $L_{A90}$ did not deviate significantly from values of 1.5 to 2.5 dB
typical of general wind turbine noise, and this cannot therefore represent a good indication of the presence of OAM.

5.1.6 Based on the various measurement results, and particularly those at Site B, it has been concluded that the general characteristics of other AM noise are consistent with the characteristics identified by WPA1 which assume the directivity and spectral characteristics of stall noise, thus exhibiting a significantly increased effect in the downwind direction from the wind turbine.

5.1.7 In particular, the measurement campaign undertaken at site B allowed a detailed study of the directivity and characteristics of 'other AM' noise. In the far-field, instances of clear AM were associated with propagation in the downwind direction and were reduced cross-wind. The effects in the near-field were more difficult to discern, although the expected presence of normal AM was clearly characterised by higher modulation depths, of up to 5 dB, in the cross-wind direction compared to reduced levels downwind. Furthermore the AM levels in the far-field were strongly variable and did not seem to be simply associated with most of the operational or meteorological parameters considered. This suggests a strong influence of propagation effects. The measured AM increased downwind between the mid-field and far-field region, with a slight decrease further away (although the latter may be due to reduce signal strength). This is consistent with observations made by Di Napoli [9].

5.1.8 The reported test measurements have also enabled the testing of various other hypotheses that have variously been proposed as possible causal mechanisms for other AM. Whilst the results cannot generally rule out any of these as potential contributory factors, they can confirm the ability of other AM to exist in situations where the factors are known not to contribute. In summary, significant other AM has been measured under conditions of:

- low wind shear;
- low wind veer;
- uniform turbulence;
- single operational turbines (i.e. no interaction effects);
- on both flat and hilly sites;
- turbines with high tower to rotor diameter ratios (see WPC).

5.1.9 The only positively identified association between the occurrence of other AM is that of power generation and changes in angle of attack (as per Sites B and C).

5.1.10 The tests at Site C have confirmed the effect of blade pitch on the potential for inducing or reducing the chances of AM occurring. It is therefore recommended that more extensive test measurements are undertaken, under much more closely controlled conditions, and ideally also including blade surface measurements, in order to positively identify when stall occurs and therefore to enable firmer conclusions as to the potential use of pitch variations or other mitigation solutions to positively control AM.

5.1.11 Other source mechanisms may be at play. It is conceivable that particular blade designs could experience partial blade stall in certain conditions without the influence of non-uniform inflow conditions, as was assumed in WPA1, to trigger it. For example, aero-elasticity effects may vary the blade geometry in such a way it departs significantly from its design conditions. There is, however, very limited information available to study this in the current state of knowledge.

5.1.12 It should also be borne in mind that, on some sites, the impact of wind shear on effective modulation may be more important at (non-sheltered) residential location surrounded by vegetation. This is because increased wind shear will correspond to relatively reduced wind near the ground, and this will have an effect on the level of masking background noise which may otherwise reduce the effective modulation depth.
6 REFERENCES


[7] DAN-AERO MW project, see for example: H. A. Madsen and A. Fischer, Wind shear and turbulence characteristics from inflow measurements on the rotating blade of a wind turbine rotor, European Wind Energy Conference and Exhibition (EWEC), Marseille, France, March 2009.


ANNEX – SCADA DATA ANALYSIS

In most cases, detailed information on the operation and power regulation of particular turbines will be proprietary and subject to commercial confidentiality considerations. A full analysis would also require a very detailed knowledge of the turbine and blade geometry, internal working, etc. This becomes particularly complex for pitch-regulated turbines.

But a qualitative and outline analysis can be made, based on summary data typically available from the turbine Supervisory Control And Data Acquisition (SCADA) system. This may assist in evaluating the implications of different modes of operation of a turbine and assess the potential impact this could have on the effective angle of attack of the flow on the blade. This can be done in practice based on the 10-minute average data which is typically available from wind turbine SCADA system: this may highlight relevant trends, although this would of course miss short-term changes and be subject to additional variability.

As a simplification of the full assessment of inflow angle as detailed in WPA1 [2], we can consider a relative angle of attack of the flow on the blade, based on the ratio of the apparent rotational speed and the incident wind speed on the turbine rotor. Given the considerations in WPA1, it seems natural to consider evaluating this at a point on the blade rotation typical of where blade source noise emissions tend to be maximal and where any blade stall would be more likely to occur: at 75% of the rotor radius, at a distance of \( d_{75\%} = 0.75 \, R \), where \( R \) is the turbine Rotor diameter.

For each (10 minute) period \( i \), if the rotor rotational speed is \( RPM(i) \), the corresponding apparent wind speed \( V_{75\%}(i) \) due to the blade velocity at \( d_{75\%} \) is given by:

\[
V_{75\%}(i) = 2\pi d_{75\%} \frac{RPM(i)}{60}
\]

We can then consider this in relation to the incident wind speed, generally measured by the turbine at the hub height (HH): \( V_{HH}(i) \). In practice, because the wind is slowed down by the rotor, the effective incident wind speed will be reduced according to a certain induction factor. As discussed in WPA1, there are some complex considerations there to take into account, but as a reasonable starting the purpose of an approximate analysis, a factor of \( A = 0.2 \) (corresponding to 20%) is assumed. If, for period \( i \), the blade pitch \( \mu(i) \) (in degrees) is also known, this can be taken into account. The relative estimated angle of attack \( \alpha(i) \) would therefore be given by:

\[
\alpha(i) = \tan^{-1}\left( \frac{1 - A}{V_{HH}(i) V_{75\%}(i)} \right) \frac{180}{\pi} - \mu(i)
\]

Please note that the above assumes the convention that an increase in the pitch \( \mu \) corresponds to a decrease in the angle of attack, which might not be the case for all control systems.

This effectively assumes that the incident wind speed on the rotor is uniform. To take into account the actual effects of non-uniform flow due to wind shear may be more realistic in some cases. If the wind shear exponent \( m(i) \) is known by measurements or estimated based on long-term data, we can then consider, instead of \( V_{HH}(i) \), the actual wind speed at \( d_{75\%} \) when the blade is at top dead centre (TDC), as this will then be the worst case under this assumption. In the above equation, we would then replace \( V_{HH}(i) \) by:

\[
V_{75\%}(i) = V_{HH}(i) \left( \frac{HH + d_{75\%}}{HH} \right)^{m(i)}
\]

And therefore this results in a modified angle:

\[
\alpha'(i) = \tan^{-1}\left( \frac{1 - A}{V_{75\%}(i)} \right) \frac{180}{\pi} - \mu(i)
\]
It can be useful to then consider the variation of $\alpha$ or $\alpha'$ as a function of the hub height wind speed or, for a variable speed machine, the turbine rotational speed (after exclusion of spurious periods such as those when turbines were not operating). This may highlight particular operating conditions in which the angle of incidence of the flow, and therefore the potential for partial blade stall, increases significantly. It should be noted that this analysis should be considered quantitative and relative, and that the calculated $\alpha$ values not necessarily directly indicative of actual flow angles, as the effects of blade geometry and twist and actual flow induction are not considered.

This represents the basis of the analysis undertaken in this report. An example is shown below, with or without incorporating wind shear effects: Figure A.

Figure A – example of calculated relative angle of attack calculated as a function of wind speed, with and without the inclusion of wind shear effects. This highlights in this example an effective increase of angle of attack at lower wind speeds.
Work Package F
Collation of work packages reports and final reporting
Hoare Lea Acoustics
Wind Turbine Amplitude Modulation: Research to Improve Understanding as to its Cause & Effect

Work Package F (WPF) - Collation of Work Package Reports and Final Reporting
This report is provided for the stated purposes and for the sole use of the named Client. It will be confidential to the Client and the client’s professional advisers. Hoare Lea accepts responsibility to the Client alone that the report has been prepared with the skill, care and diligence of a competent engineer, but accepts no responsibility whatsoever to any parties other than the Client. Any such parties rely upon the report at their own risk. Neither the whole nor any part of the report nor reference to it may be included in any published document, circular or statement nor published in any way without Hoare Lea’s written approval of the form and content in which it may appear.
# Table of Contents

EXECUTIVE SUMMARY ................................................................. 4  
1.0 INTRODUCTION & PROJECT OVERVIEW .............................................. 10  
Acknowledgments .............................................................................. 14  
2.0 BACKGROUND TO AM ISSUES .......................................................... 15  
3.0 OUTLINE DESCRIPTION OF WORK PACKAGES ................................. 18  
4.0 SUMMARY OF FINDINGS ..................................................................... 25  
4.1 What is AM? ......................................................................................... 27  
4.2 What causes OAM? .............................................................................. 31  
4.3 Can AM be objectively measured and quantified? ................................. 36  
4.4 How does the theory for AM identification apply to real world data? ......... 41  
4.5 What is the subjective impact of AM? .................................................. 44  
4.6 What are the characteristics of OAM when measured? ....................... 47  
4.7 Can OAM be predicted? ..................................................................... 50  
4.8 Can OAM be suitably mitigated? ........................................................ 51  
5.0 CONCLUSIONS .................................................................................. 53  
GLOSSARY OF TERMINOLOGY ................................................................ 62  
REFERENCES ....................................................................................... 65  
Annex A - A Summary of the State of Technical Knowledge .................... 67  
Annex B – Evaluation of additional propagation effects on am model results ... 71  
Annex C – Application of an AM metric routine to a range of signals .......... 76
EXECUTIVE SUMMARY

Background

This report describes the results of theoretical and experimental investigations into the causes of amplitude modulation of noise from wind turbines, the subjective response to this phenomenon in terms of annoyance, and potential mitigation methods should it occur.

The work has been funded by RenewableUK and carried out by a consortium of UK companies and universities in partnership with the lead contractor, Hoare Lea Acoustics. Additional complementary research was commissioned from a specialist at the National Aerospace Laboratory in the Netherlands. The members of the research team were selected on the basis of their technical expertise and experience in the fields of aerodynamics and wind turbine acoustics. The research was overseen by a technical steering group and will be peer-reviewed by other specialists working in the field. The experience of the research team and steering group represent a balanced perspective both from those generally perceived to be involved with the wind energy industry and those who are likewise generally perceived to be wholly independent of the wind energy industry.

Amplitude Modulation – general

All wind turbines generate noise. The main noise source for modern turbines is ‘aerodynamic noise’ - the noise generated by the interaction of flow turbulence with the surfaces of the rotor blades. The noise is said to be amplitude modulated when its level (loudness) exhibits periodic fluctuations at a rate corresponding to the frequency at which a rotor blade passes a fixed point (the ‘blade-passing frequency’).

Amplitude modulation (AM) is always detected close to a rotating wind turbine, and is commonly described as ‘swish’. The principal source of noise from the blades is trailing-edge noise, caused by the interaction of turbulence in the boundary layer (the slower-moving air close to the blade surface) with the trailing edges (the rear, thinner edges) of the rotor blades. Because this noise source has particular directional characteristics, an observer close to the wind turbine will hear the noise from each blade separately, particularly in the crosswind direction from the rotor as the blade comes down. These trailing edge directivity effects will be present at locations near a turbine even in completely uniform flow. This characteristic swish has been explained theoretically and demonstrated by measurements carried out prior to the current research.

For the purpose of this research, AM resulting from this trailing edge noise directivity effect is termed ‘Normal AM’ (NAM). Based on theoretical models and experience to date, NAM would not be expected to be apparent (except at insignificant levels) downwind or upwind in the far-field of a wind turbine.

However, on some wind farm sites, AM has been detected in the far-field down-wind from wind turbines. In some cases, the magnitude of the variations in noise levels is higher than predicted and the noise is described as being more impulsive in character, better described as a ‘whoosh’ or ‘thump’ rather than a ‘swish’. These occurrences cannot be accounted for by the established trailing edge noise mechanism and it is therefore concluded that other source mechanisms or propagation effects must be responsible.

For the purposes of this report, AM phenomena with characteristics that fall outside those expected of NAM are termed ‘Other AM’ (OAM).

Reported incidences of OAM are relatively limited. However, wind turbine OAM is a recognised phenomenon and has been the subject of several publications and presentations at international

---

1 For a modern multi-megawatt 3-bladed wind turbine a typical upper rotational rate is 16 rotations per minute, for which the blade-passing frequency would be 0.8 Hz (slightly less than once a second).
conferences in recent years. Since the causal mechanisms have not been understood to date, no specific information has been available to guide operators towards the likelihood of occurrence of OAM or remedial actions which may be required. Furthermore, where OAM is known to occur, there has been no universally accepted means of measuring its magnitude or determining whether complaints from neighbours are justified.

**Scope of Research - Objectives**

This project was directed towards:

- identifying the causes of OAM and therefore also potential methods of controlling it should it occur;
- defining a robust methodology for measuring amplitude-modulated wind turbine noise and an associated metric that represents the degree of modulation;
- determining a dose-response relationship between AM, as rated using the adopted metric, and annoyance, in a way that takes account of the time-varying characteristics of amplitude-modulated noise in addition to its ‘average’ level;
- dissemination of results to the research community and all involved in wind farm planning and operation.

The discussions in the present work are directed principally towards variable-speed pitch-regulated wind turbines of upwind configuration, the most common type of large turbine, although many of the principles will apply to other turbine types.

**Organisation of Work Packages**

The work programme was divided into 8 work packages (WPs) as follows. Principal contributors to each WP are stated, although the WPs are essentially inter-linked and inter-dependent and all contributors were involved (to a greater or lesser extent) in all WPs through frequent communications and regular project meetings.

<table>
<thead>
<tr>
<th>WP</th>
<th>Description</th>
<th>LEAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>Source generation effects modelling</td>
<td>NLR</td>
</tr>
<tr>
<td>A2</td>
<td>Fundamental Research into Possible Causes of Amplitude Modulation</td>
<td>ISVR</td>
</tr>
<tr>
<td>B1</td>
<td>Development of an Objective AM Measurement Methodology</td>
<td>ISVR</td>
</tr>
<tr>
<td>B2</td>
<td>Development of an AM Dose-Response Relationship</td>
<td>ARC</td>
</tr>
<tr>
<td>C</td>
<td>Collation and Analysis of Existing Acoustic Recordings</td>
<td>HLA</td>
</tr>
<tr>
<td>D</td>
<td>Measurement and Analysis of New Acoustic Recordings</td>
<td>HLA</td>
</tr>
<tr>
<td>E</td>
<td>Wider Dissemination of Results</td>
<td>ALL</td>
</tr>
<tr>
<td>F</td>
<td>Collation of Work Package Reports and Final Reporting</td>
<td>HLA</td>
</tr>
</tbody>
</table>

WPs A-D have been completed and the outcomes presented in the individual WP Reports, and collated and summarised in the present overarching report which has been produced under WPF. WPE will be achieved through the publication and dissemination of the results.

Existing data was obtained from a number of sources, both in response to general requests at the Fourth International Meeting on Wind Turbine Noise, Rome, April 2011 and also through personal contacts with others working in this field. This data was provided at no cost and thanks are due to the donors. This was supplemented by WPD, which required detailed and innovative measurements to be carried out at three wind farm sites to study the characteristics of OAM in more detail. The measurements were related, wherever possible, to turbine operational parameters, such as wind speeds and directions at each turbine and other relevant meteorological variables.
Causes of OAM

Of the potential OAM ‘source’ effects, the prime candidate is transient separation of airflow from each blade (‘stall’). The turbine blades operate at an ‘angle of attack’ (determined by a combination of the incoming air velocity and the velocity from rotation). Above a given angle of attack (mainly determined by the air velocity and the blade profile), the air flow over the upper (suction) surface of the blade may detach, resulting in the generation of a region of turbulent air on a region of the blade surface (stall) and a loss of lift.

The noise generated by the interaction of the turbulent air in the stalled region with the blade surface will result in increased noise (compared with the un-stalled, attached-flow case). In consequence, stall occurring over a small area of each turbine blade in one part of the blade’s rotation only (for example as it passes over the top of its path) will result in cyclic increases in noise level (and therefore OAM). Stall noise also has a lower characteristic frequency than noise from an un-stalled blade and, importantly, it will also exhibit different directivity. Based on a model developed as part of this work, this change in directivity in particular is predicted to result in significant modulation levels and downwind directions, which is consistent with observations of OAM made in WPD. Downwind directions are those in which the highest overall levels of turbine noise are generally experienced in the far-field of the turbines. This results from a combination of source directivity and propagation effects and would explain the different characteristics and impact of OAM when compared to NAM. Although the same model predicts radiation of OAM in the upwind direction, it does not account for propagation effects which would generally significantly reduce far-field noise levels in this direction, consistently with observations made as part of WPD. It should be noted that, if stall occurs round the whole of the blades’ rotation, OAM would not occur, though the characteristics of the noise will change (with increased overall noise generation rather than modulation).

The effect of changing blade pitch to initiate blade stall was investigated on a test turbine (in WPD). On other sites, the observed directivity of the OAM in the far-field was found to be highest downwind and more limited cross-wind. In each case, the observations were consistent with the ‘transient stall’ model.

Non-uniform air flow into the rotor means that the angle of attack of a blade varies as the blade rotates even when the pitch remains the same. This means that the blade may stall over a small part of the rotation. A number of factors which could lead to non-uniform inlet flow are identified in WPA. These factors include non-uniform wind profiles, for example due to a vertical or lateral variation in wind speed, or a spatial variation of the angle of the wind onto the rotor, where high wind shear or local wind gusts could provide the conditions for this to happen.

However, some of these factors are almost always present, for example variations in wind speed with height above the ground (vertical wind shear). Theoretical analysis made as part of WPA suggests that the effect of vertical wind shear cannot, in itself, account for the observed characteristics of OAM, and that partial stall was required in addition. Furthermore, OAM has been observed (on one site studied in WPD) when wind shear has been low but absent when wind shear was high (for the same wind speed) indicating that high vertical wind shear is not an essential factor.

It is also conceivable that particular blade designs could experience partial blade stall in certain conditions without the influence of non-uniform inflow conditions to trigger it. Turbine blades are also subject to aero-elastic effects (they bend and twist under load) and the resulting changes in angle of attack may be a factor (although not assessed in this report) in the occurrence of transient stall and therefore OAM.

Non-uniform turbulence distribution entering the rotor disk, due to upwind obstructions or meteorological conditions, could in theory cause time-varying levels of inflow turbulence noise as a result of the blades passing into and then out of the regions of higher turbulence, although this is not strongly consistent with the evidence (as determined in WPD in particular).
Whether or not a wind turbine on a particular site will exhibit OAM is therefore dependent on a large number of complex factors, including the local atmospheric conditions (particularly variation in wind speed and direction over the area of the rotor disk), local topography (which may influence rotor inlet flows in different wind directions) the design of the turbine blades and the way they are controlled. Several of the potential causal factors which have been suggested in the past have been shown, through the review of WPC and measurements of WPD, to have little or no association with the occurrence of OAM. However some of them may represent potential contributory factors. It is not therefore possible to be prescriptive as to whether any particular site or wind farm design is more or less likely to give rise to OAM being generated. This is considered likely to be due to a combination of site and installation-specific factors, including meteorology.

Where a wind installation exhibits OAM, it is then natural to consider how it can be assessed in terms of annoyance, and, in the event that the assessment shows that OAM requires to be mitigated, how this can be achieved.

**Measurement of OAM**

To devise an assessment method for AM (NAM or OAM), it is essential first to define the magnitude of this modulation. The ‘modulation depth’ or difference between ‘peak’ and ‘trough’ noise levels has often been used to date. What is important here is that any such method should be representative of the subjective response to amplitude-modulated noise and should be able to be robustly and objectively applied to real measured data. This is not as straightforward as may first appear, as different analytical methods applied to the same signal can produce a wide range of values (metrics), each of which may be valid in rating the severity of AM in terms of subjective response.

WPB1 has considered the philosophy of devising metrics for rating AM. The key feature of OAM that assists in its detection and analysis is the fact that the noise has a periodic character. Using this, Fourier-transform-based signal analysis techniques were used to objectively identify the modulation frequency in a noise signal. The magnitude of the variation in level of the signal at that frequency can then be rated in an objective manner. This is often not possible from the manual review of measurement results in realistic conditions due primarily to the compounding effects of spurious, non-wind turbine related, noise such as bird song that may equally vary with time and affect the measured levels of individual peaks and troughs of the OAM noise.

In parallel with defining an appropriate metric, these methods were also shown to be effective for detecting wind turbine AM ‘automatically’ in a measured noise signal by post-analysis of continuous measurements. This is an essential tool since OAM, where it occurs, is infrequent and its onset cannot generally be predicted, although in some cases experience may indicate that it is more likely to occur in some ranges of wind speed and wind direction. Most sources of extraneous noise can be excluded by applying signal filtering prior to the Fourier analysis, therefore focusing the analysis on the audio frequency bands in which the modulation is most significant and thereby providing a more robust procedure.

The results of analysis of field recordings of OAM, undertaken in WPB1, WPC, WPD and WPF, show that such methods perform well, even in challenging conditions present in rural environments.

**How People Respond to Amplitude-Modulated Wind Turbine Noise**

An extensive series of listening tests was carried out as part of WPB2 in a specialist facility at the University of Salford. This was done to establish if and how noise with a modulating character can be more annoying than steady noise of the same measured level, in order to supplement existing published information on this subject.

Simulated recordings, based on an analysis of actual field recordings, and with a wide range of input parameters, were played back to a range of up to 20 subjects of different ages and sensitivity but of normal hearing.
The frequency spectra and levels of sounds were intended to represent the varying characteristics of wind turbine AM as it might be perceived in a rural garden. Subjects were asked to rate the noise in two ways: on an absolute annoyance rating, and with a rating relative to un-modulated noise (by the subject adjusting the levels of modulated and un-modulated noise to achieve the same annoyance rating), with the presence in some cases of background noise with a spectrum and character representative of a rural garden.

Responses were not significantly affected by the frequency content of the modulated noise (either dominated by medium or lower frequencies), the modulation waveform or the presence of limited amounts of wind-disturbed vegetation noise.

The annoyance ratings were, however, significantly related to the frequency (rate) of the modulation, the overall A-weighted level (or loudness) of the test sound and the modulation depth. It was noted that the term ‘modulation depth’ has no accepted definition and the exact value depends on the protocol adopted for analysing the modulated signal. This factor highlighted the central importance of relating any specific response to measured AM levels in a consistent way.

Annoyance ratings were correlated with mean noise level and a range of metrics defining the degree of modulation. This showed that annoyance increases slightly with modulation depth. However, the observed effect is continuous with there being no evidence of a clear onset of increased annoyance at a particular modulation depth, particularly when considering the large spread of ratings. In contrast, the mean overall noise levels were shown to dominate the annoyance rating.

The tests for which an un-modulated wind turbine noise was adjusted for comparable annoyance with the AM stimuli resulted in levels which were relatively constant from modulation depths of approximately 3 dB(A) upwards. The adjustments were on average 1.7 dB(A) for a 40 dB(A) stimulus and 3.5 dB(A) at 30 dB(A). The use of the L_{90} (the A-weighted noise level exceeded for 90% of the time over a certain period) as a measure of noise levels produced comparable results for moderate modulation depths.

The study necessarily relied on tests carried out under controlled laboratory conditions. Rating annoyance is subject to contextual and attitudinal issues and these factors are thought to be responsible for the wide error bands in the plotted data. However, the results of the WPB2 listening tests are generally consistent with those of existing research into subjective response to amplitude-modulated noise.

The effects of additional factors, such as the frequency of occurrence of OAM ‘events’ and their duration, were not addressed in the current research. The view of the steering group and the research team is that the significance of these factors would have to be assessed using professional judgment and experience and that it would not be practicable to assess them via further subjective testing.

**Can OAM be Effectively Mitigated?**

There is nothing at the planning stage that can presently be used to indicate a positive likelihood of OAM occurring at any given proposed wind farm site, based either on the site’s general characteristics or on the known characteristics of the wind turbines to be installed.

In the immediate term, the only guaranteed solution to mitigate OAM if it occurs in practice on a particular site is the cessation of operation of offending turbines during those conditions under which OAM is found to occur. The conditions leading to OAM, and the characteristics of that OAM when it occurs, appear to be very site-specific and would therefore need to be established specifically for each operational site considered.

Notwithstanding the above, it has also been concluded that, as the existence of OAM in the far-field requires some effect to have occurred at source, even though the effect may be exacerbated by propagation effects, the control of the source effect will remove the OAM experienced in the far field.
Given the characteristics of the partial stall mechanism identified, the effective mitigation of OAM in practice will require the future involvement and close cooperation of wind turbine manufacturers, and possibly involve detailed measurements that focus on better understanding the surface pressure distributions on the turbine blades themselves, particularly as the stall point is approached. Simple analysis methods have been developed to assist in identifying the most likely relevant conditions. It is believed that with such cooperation, methods will be capable of being developed for avoiding local stall conditions.

Such methods may involve software ‘fixes’ that seek to modify the logic of the control system algorithms, perhaps even through the application of more advanced cyclical pitch control. More fundamental, physical design changes may also prove worthwhile, such as innovative blade designs or the addition of blade vortex generators which may delay the onset of stall. Such methods would be likely to only have a limited or negligible impact on the generating capacity of the turbines.
1.0 INTRODUCTION & PROJECT OVERVIEW

This report presents the summary findings of a research project awarded by RenewableUK (ReUK) in March 2011. The research project is entitled ‘Wind Turbine Amplitude Modulation: Research to Improve Understanding as to its Cause & Effect’. The project comprises a total of six separate work packages, the outcome results of each of the work packages have separately resulted in their own dedicated final reports. This is the final report of the seventh work package (WPF) which consists in an overarching final report in which the key findings across the separate work packages have been collated and discussed.

Prior to embarking on any detailed discussion of the project, it is useful first to define what constitutes ‘Wind Turbine Amplitude Modulation’, as referred to in the project title, and also to clarify the definitions of some key terms that are subsequently used throughout the reporting of the project. This is considered important because the subject matter can, in parts, rely on quite detailed theoretical knowledge of several aspects of acoustics, including aero-acoustics, noise propagation, signal processing and subjective response to noise. In this respect, the reader is also referred to the glossary of terminology which is included at Appendix A to this report.

What is ‘Wind Turbine Amplitude Modulation’?

When considering noise, the term ‘amplitude modulation’ refers to any noise whose amplitude (perceived loudness) modulates (i.e. goes up and down) over time. Over short periods of time these amplitude modulations may repeat themselves with an almost constant period, thus resulting in what is termed ‘quasi-periodic’ noise. There are many common sources of noise whose amplitude modulates in a quasi-periodic manner over time, examples being emergency vehicle sirens, the passage of cars in a steady stream of traffic, the regular chirping of birds, etc. However, to this list can be added wind turbine noise, for the reasons set out below.

As the blades on a wind turbine pass through the air they produce aerodynamic noise. It will subsequently be discussed how this aerodynamic noise arises from a number of separate source generation mechanisms but, for the present, it is merely noted that the intrinsic nature of this aerodynamic noise, as it is generated at the blade surface, is generally a continuous type sound. However, this continuous ‘whoosh’ is not what is experienced by anyone standing on the ground close to a turbine. Due to the rotation of the rotor, any such listener will experience the tips of the blades successively moving towards them and then receding away from them. As the dominant source of aerodynamic noise is radiated from the trailing edge of the blades (the thin end of a cross section through a blade) in the region lying towards the blade tips, and as the noise level at any given receiver location varies as a function of distance from the source, the movement of the each blade tip towards and then away from the listener will result in the noise level experienced by that listener going up in level as a blade tip approaches them and then down as a blade tip recedes from them.

This up and down variation in noise level will repeat with the passage of every blade. As a consequence, the perceived noise will be amplitude modulated (i.e. it will go up and down) at a rate equal to what is termed the ‘blade passing frequency’ of the turbine, or BPF for short. For a modern, large scale wind turbine having three blades and an upper rotation rate of 20 revolutions per minute, the blade passing frequency (and hence also the modulation rate) typically equates to 3 blades x 20 revolutions per minute, which equals a modulation rate of around 60 per minute. This is more commonly expressed as a modulation rate of 1 per second, which is alternatively expressed as a modulation frequency of 1 Hz.

The fact that most modern, large scale wind turbines are now variable speed machines means that the frequency of this amplitude modulated aerodynamic noise may vary between anything from around 0.5 Hz to around 1 Hz, the actual frequency depending on the actual rotational speed, and hence blade passing frequency, of the turbine under consideration. Smaller turbines, such as were prevalent in the 1990s or still exist nowadays in the smaller end of the market, tend to rotate faster. The result of this faster rotational rate is that the time between each blade passage is reduced, with a consequent increased rate of modulation of typically double the values discussed above.

---

2 Modulation frequency should not be confused with audio frequencies, as discussed below. See also the Glossary at the end of this report.
3 Variable speed machines will adapt the speed at which their rotor turns depending on wind conditions.
Thus the ‘amplitude modulation’ of wind turbine noise, which is now commonly termed ‘AM’ for short, is nothing more than the quasi-periodic variation in the perceived level of aerodynamic noise as experienced by a listener standing relatively close to a turbine. This feature of wind turbine noise has long been accepted as a natural consequence of wind turbine operation, certainly ever since the introduction of the first commercial wind energy installations in the UK, which occurred some two decades ago now. The question must therefore reasonably be asked as to the need for the present project given that AM is such an accepted feature of wind turbine noise. The answer to this question lies in the specific character and incidence of the AM being considered. The project was commissioned on the basis that AM noise has received an increasing amount of attention more recently, mainly following the emergence of a number of reports of the existence of a certain type of AM whose character and/or incidence was not expected.

This is why it was felt necessary, at the introductory stage of the present project, to make clear the distinction between the long-accepted form of what is herein termed ‘normal’ AM (NAM), which is otherwise commonly referred to as ‘blade swish’, and any form of ‘other’ AM (OAM) which lies outside the range of what would be considered to be ‘normal’ AM.

It is the issue of OAM, as opposed to NAM, that the present project specifically seeks to address. This is because, as discussed in the relevant sections of this report, it is this OAM which has formed the focus of attention in recent years, with the presence of such OAM being cited in some cases as being a specific cause for complaint.

The ‘problem’ with the foregoing definitions of NAM and OAM is that the distinction between the two is not always so clear-cut as may be desired in the context of defining the scope of the present project. In this respect, two separate means of defining NAM and OAM may be considered: one in terms of source generation mechanisms and the other in terms of subjective character.

Defining NAM and OAM in terms of source generation mechanisms

Previous research into the issue of blade swish has resulted in a clear understanding of the fundamental source generation mechanisms involved in the generation of such noise and its resultant character and spatial distribution in the relative near-field of wind turbines (i.e. at distances of up to around 3 rotor diameters). Theory, backed up by detailed measurements, has concluded that blade swish noise results from noise generated at the trailing edge of the blades whose level and character varies quasi-periodically over time at any given listener location. This variation has been shown to be due to a combination of the specific directivity of the radiation of trailing edge noise relative to the blade geometry, coupled with the fact that the turbine blades are moving relative to the listener. This relative movement between source and listener results in variable amplitude effects due to a combination of the relative proximity of blade to the listener at any given moment in time and convective amplification, plus variable frequencies due to the Doppler effect.

Thus a potentially useful definition of NAM is that element of AM noise which can be fully explained by way of existing models of trailing edge noise that have been proven to be capable of successfully modelling ‘blade swish’ noise from wind turbines. The definition of OAM therefore becomes, by default, any form of AM noise whose physical characteristics (e.g. spectral content, amplitude, variability, directivity, etc.) and incidence (particularly at a distance from the turbines) cannot be explained by accepted source generation models for NAM. In making any such distinction between NAM and OAM on purely physical grounds it is important that no a priori assumptions are made concerning the relative subjective impact, or indeed acceptability, of the two different forms of AM.

Defining NAM and OAM in terms of perceived acoustic character

As an alternative to the foregoing distinction between NAM and OAM on the purely physical grounds of source generation mechanisms, the difference in the perceived acoustic character of the different forms of AM may also be considered. Such a distinction may be driven by noise complaints arising from specific characteristics of AM noise, whereby those affected have reported the noise to alter in character from the more usually encountered ‘swishing’ sound to that of a ‘thumping’ sound, with the latter sound being the cause for complaint. Some recent studies have also shown measurements, albeit limited, of the incidence of what could be characterised as OAM at a distance from some wind farms.

The Doppler effect relates to a change in perceived pitch due to the effect of the movement of the source towards or away from a receiver, for instance the effect which is commonly experienced as noise from an emergency vehicle siren changes in pitch as it comes towards, and then moves away from, an observer.

4 The Doppler effect relates to a change in perceived pitch due to the effect of the movement of the source towards or away from a receiver, for instance the effect which is commonly experienced as noise from an emergency vehicle siren changes in pitch as it comes towards, and then moves away from, an observer.
WIND TURBINE AMPLITUDE MODULATION: RESEARCH TO IMPROVE UNDERSTANDING AS TO ITS CAUSE & EFFECT

Collation of Work Package Reports and Final Reporting

Whilst any such difference in acoustic character may outwardly be an attractive means of differentiating NAM from OAM, the approach does raise its own issues. The main problem is that it relies on subjective judgement as to what constitutes NAM and what constitutes OAM. This subjective judgment can either be made by those involved in the research or on the basis of reported complaints. In the former scenario there must necessarily be some presumption on the part of those involved as to what may or may not be considered ‘normal’ (and possibly therefore also acceptable). In the latter case the successful discrimination between NAM and OAM relies on the reliable and consistent reporting of adverse noise effects by those living in the vicinity of wind farms. In this respect, any review is complicated by the difficulty in establishing the relevance of reported experiences and disturbances of wind farm neighbours from wind turbine noise, and in particular the relevance of the widely varying descriptions used by those reporting it and their potentially widely varying sensitivity to noise, especially when considered together with other potentially confounding, noise unrelated, issues. Even for some of the clearer reports (shown in different studies) of objective measurements of noise which could be characterised as OAM, the evidence was limited and often contradictory.

Choosing a definition of NAM and OAM for the present project

There is a further potential issue when considering either of the foregoing definitions as a means of differentiating between NAM and OAM. This issue relates to any change in character that may have occurred as a natural consequence of wind turbine development, and in particular the increase in physical size of turbines as they have increased in generating capacity from a norm of less than 500 kW two decades ago to typically greater than 2000 kW today. This general increase in physical size has included an increase in the diameter, chord and thickness of the rotor blades, coupled with the introduction of variable speed machines with lower rotational rates. The increased physical size of the blades would be consistent with a general reduction of the dominant frequencies radiated as a consequence of trailing edge noise generation mechanisms (as previously identified as being the main cause of NAM) from between around 500 Hz to 1000 Hz for earlier turbines to around 300 Hz to 800 Hz for modern, large scale turbines, although there is some conflicting data on this decrease. The reduction in the rotational rate of the blades has resulted in a reduction in the periodicity of the AM from a maximum of around 1.5 modulations per second (i.e. a modulation frequency of 1.5 Hz) for the earlier machines, to less than 1 modulation per second for current machines (i.e. a modulation frequency of less than 1 Hz, with the maximum typically being closer to 0.5 to 0.8 Hz). Taken together, these two factors result in NAM for current turbines occurring at approximately half the rate of earlier turbines, with a dominant audible frequency content also potentially approximately half that of the earlier turbines. This being the case then, defining NAM based on source generation mechanisms, it is the case that what constituted ‘normal’ AM for earlier turbines may be different to what constitutes ‘normal’ AM for current turbines. Whether or not this change is sufficient enough to result in a subjectively significant change in response (and possibly also acceptability) is a question that the project seeks to resolve.

Notwithstanding the complicating factors just discussed, the project requires some consistency of definitions if discussions are not to become confused. Therefore, the definitions of NAM and OAM adopted are those based on the physical source generation mechanisms involved, with NAM being defined as that capable of being fully described in terms of ‘standard’ models of trailing edge noise and OAM being any form of AM lying outside this definition of NAM. It is stressed here, however, that in line with the foregoing discussion concerning this definition, no a priori assumption is being made as to the relative acceptability or otherwise of NAM as opposed to OAM: it is for the project to deliver conclusions in this respect.

In specific situations, tonal noise emissions have been found to vary in time (i.e. modulate at the blade passing frequency) as the mechanical source producing this tone varies in time, this can be readily assessed using existing methods to evaluate (non-stationary) tones [3]. This was therefore excluded from the scope of the current project.

Modulation frequency and audible frequency

The foregoing discussion has highlighted a potential area of confusion when interpreting the outcome findings of the project, which is the difference between audible frequencies and modulation frequencies. Audible frequencies are those frequencies which are capable of detection and interpretation via the human hearing mechanism. These are the frequencies at which the air pressure actually fluctuates. Audible frequencies are typically stated to range from around 20 Hz to around 20 kHz. As an example,
within this range the dominant speech frequencies typically lie between around 400 Hz and 4 kHz, with hearing sensitivity peaking at around 1 kHz such that the peak in hearing sensitivity matches the general peak in speech frequency. Aerodynamic noise generation from wind turbine blades produces a ‘broad band’ of frequencies across the human audible frequency range. Whilst this noise is all aerodynamic in origin, it arises from a number of quite different interaction mechanisms between the blade and the air, with some source mechanisms (and therefore also their associated noise frequency ranges) becoming more prominent than others depending on operational conditions.

The various noises arising from the different aerodynamic source mechanisms combine to produce the overall audible aerodynamic noise that may be heard when standing relatively close to a wind turbine. However, as previously discussed, one of the features of wind turbine aerodynamic noise is that it may increase and decrease in level with time. These increases and decreases in level occur at a rate equal to the blade passing frequency of the blades which, for modern large scale turbines, has been identified to be around 1 Hz or less. These 1 Hz variations in level can be subjectively quite discernible when present. However, this is not because the listener is hearing very low frequency sound of 1 Hz. Rather, the listener is detecting the regular variation in level, about once every second, of aerodynamic noise which is itself in the audible frequency range. Thus modulation frequency relates to the rate of the subjectively discernible low frequency modulation of noise which lies within the normal audible frequency range: it does not relate to audible noise having a frequency of 1 Hz.

Bearing the above in mind, it is important when interpreting the outcome findings of the present project, that audible frequencies are not confused with modulation frequencies.

**Project specification overview**

The project specification was divided into a number of separate work packages. One of the key aims of project’s execution was that, whilst each work package should produce its own reported outcomes, the various work packages should be interlinked in terms of information flow such that the ongoing findings of each package could inform the development of the other. With this aim in mind, a key element of the project was regular and open communications between the teams undertaking the various work packages.

The various work packages that went to make up the totality of the project are listed in the following Table 1.1.

An overview of the specification for each work package is presented in the following section 3 of this report.

The detailed outcome results of each of the work packages is presented in separate final reports, with a dedicated final report for each of work packages A1, A2, B1, B2, C and D. In terms of work package E, the wider dissemination of results, this has to date been delivered through presentations at different conferences, as well as through the open publication and peer-review of all project outcome reports.

<table>
<thead>
<tr>
<th>WP</th>
<th>Description</th>
<th>LEAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>Source generation effects modeling</td>
<td>NLR</td>
</tr>
<tr>
<td>A2</td>
<td>Fundamental Research into Possible Causes of Amplitude Modulation</td>
<td>ISVR</td>
</tr>
<tr>
<td>B1</td>
<td>Development of an Objective AM Measurement Methodology</td>
<td>ISVR</td>
</tr>
<tr>
<td>B2</td>
<td>Development of an AM Dose-Response Relationship</td>
<td>ARC</td>
</tr>
<tr>
<td>C</td>
<td>Collation and Analysis of Existing Acoustic Recordings</td>
<td>HLA</td>
</tr>
<tr>
<td>D</td>
<td>Measurement and Analysis of New Acoustic Recordings</td>
<td>HLA</td>
</tr>
<tr>
<td>E</td>
<td>Wider Dissemination of Results</td>
<td>ALL</td>
</tr>
<tr>
<td>F</td>
<td>Collation of Work Package Reports and Final Reporting</td>
<td>HLA</td>
</tr>
</tbody>
</table>

Table 1.1 – Work packages included in the present ReUK research project

---

5 This included: Fourth International Meeting on Wind Turbine Noise, Rome, April 2011; Institute of Acoustics Conference, Cardiff, Jan 2012; Acoustics 2012, Nantes (France), April 2012;
The project commenced in March 2011, with an initially targeted duration of 8 months culminating in the issue of all associated final reports in November 2011. However, due to reasons largely associated with restricted access to the data necessary to undertake certain key areas of the work, the project programme slipped by 4 months, with a revised completion date for the major part of the project in March 2011.

**Aim of the present overview report**

The aim of the present report is to bring together the various outcome findings of the individual work packages, as set out in each of the final reports associated with each work package, into a single summary document. Clearly this document will be best read alongside the final reports from the different work packages. In particular those final reports provide much extended references and more detailed technical discussions. However, the present document has nevertheless been written to provide a stand alone summary of the project as a whole, as well as providing some additional considerations that may arise through the combination of outcome findings from the various separate work packages.

**Project team**

In order to best fulfil the project objectives, which are set subsequently in this report, the delivery of the project brought together a project team with strong combined expertise in both the aero-acoustic mechanisms of wind turbine noise and the environmental impact assessment and planning issues associated with wind farm noise. The experience of the project team was also selected to provide a balanced perspective both from those generally perceived to be involved with the wind energy industry and those who are likewise generally perceived to be wholly independent of the wind energy industry. The project team comprised members from the following organisations:

- **Hoare Lea Acoustics (HLA)** – Andrew Bullmore, Matthew Cand and others.
- **National Aerospace Laboratory (NLR)** - Stefan Oerlemans.
- **Institute of Sound and Vibration Research, University of Southampton (ISVR)** – Paul White, Malcolm Smith.
- **Acoustics Research Centre, University of Salford (ARC)** – Sabine Von Hünerbein.

with the technical monitoring of the Project being undertaken on behalf of ReUK by:

- Dr Jeremy Bass, RES
- Mr Dick Bowdler, Independent Consultant

The perceived benefit of the assembled project team was that it included both those having direct experience of current AM issues and, equally importantly, those without such direct experience of AM but with a long established track record in more general acoustics research, including aero-acoustics. It was considered that, through this combination, the research could at the same time focus on the immediate issues of AM facing the wind energy industry in the UK, whilst also remaining open to ideas and scrutiny from a wider acoustics perspective.

One of the project team members generally lead the technical input in each project area. Hoare Lea Acoustics (HLA) additionally acted in a general technical and project management role. The various work packages, and the lead project team organisation responsible for their delivery, have already been presented in the final column of the preceding table of work packages.

The reports for the different work packages will be referenced throughout as WPX, where X is taken from Table 1.1. For example, WPC corresponds to Work package C.

It should be noted that WPA1 was commissioned by ReUK to NLR on a separate basis and has therefore formed the subject of a separately issued final report. The results of the WPA1 package of work have, however, been extensively referenced to inform the work undertaken as part of the various work packages reported herein.

**Acknowledgments**

The financial support of RenewableUK for this research project, as well as the input from the wind turbine noise research community on the subject, are both gratefully acknowledged.
WIND TURBINE AMPLITUDE MODULATION: RESEARCH TO IMPROVE UNDERSTANDING AS TO ITS CAUSE & EFFECT
Collation of Work Package Reports and Final Reporting

2.0 BACKGROUND TO AM ISSUES

The issue of AM arising from the operation of wind turbines has recently been receiving an increasing focus of attention. Whilst the acceptability of audible noise from wind turbines continues to be the subject of considerable debate, the specific issue of AM has come to the fore following the publication of a number of studies claiming that the existence of such noise may result in an enhanced possibility of adverse impacts, in terms of increased annoyance.

The issue of AM is not a new one, having been the subject of a previous study undertaken by the University of Salford in 2007 [1]. That study was initiated following complaints of what was believed to be problematic levels of low frequency noise arising from a limited number of operational wind farms.

Following the publication of a number of press articles on the matter early in the 2000’s, one of the key wind farm noise issues that began to attract attention was that of infrasound. During this time, reports of the potentially adverse impact of ‘infrasound’ from wind turbines were discussed in the press. In order to investigate the magnitude of this infrasound ‘problem’, the DTI commissioned a study into the subject which included measurement campaigns at three UK wind farms where infrasound and/or low frequency noise had specifically been raised by wind farm neighbours as being a problem. However, when the output of the study was delivered [2], it concluded that infrasound from wind farms occurs at such low levels that it lies well below the thresholds of human perception. The overriding conclusion was, therefore, that infrasound poses no threat to health, nor could its presence at such low levels contribute to potential disturbance.

Notwithstanding the foregoing conclusion, the investigations did identify that the level of wind farm noise within the normal audible range was, at times, measured to increase above the threshold of audibility inside the premises at which noise measurements were undertaken. Where causal noise issues were positively identified, these tended to result not from low frequency noise itself, but rather from audible broad band aerodynamic noise that was being modulated in amplitude at a frequency related to the rotational rate of the wind turbine blades. An analysis of noise recordings made at the complainants’ properties identified that, during the affected periods, the degree of ‘swish’ arising from the rotation of the blades was higher than that normally encountered, and perhaps also higher than the level originally assumed when setting wind farm noise limits in accordance with the document entitled ‘The Assessment and Rating of Wind Farm Noise’, ETSU-R-97 [3]. This document, which has generally become referred to simply as ‘ETSU-R-97’, currently provides the commonly accepted best practice for the setting of noise limits for wind farms across the UK, and has done so since its original publication in 1996.

At roughly the same time as the DTI study into low frequency noise, claims were emerging from other researchers that, particularly under certain atmospheric conditions more prevalent at night, wind turbines were capable of generating noise having characteristics outside of that expected of them [4]. The characteristic being referred to was an enhanced level of amplitude modulated aerodynamic noise. This type of AM resulted in the blade swish becoming more impulsive in character, such that those exposed to it tended to describe it as more of a ‘whomp’ or a ‘thump’ than a ‘swish’. This was similar to the character of the noise identified in the DTI study [2]. Appendix A to the final report of WPC presents a more detailed review of such information.

As a consequence of the above, adverse effects from wind farm noise that had hitherto perhaps erroneously been blamed on low frequency sound or infrasound itself, tended to refocus on AM.

A note of caution is advised here in that residual confusion is still often encountered as to what aspect of wind farm noise is actually being complained of when reference is made to ‘low frequency sound’. This is because the term ‘low frequency sound’ is often erroneously used to refer to amplitude modulated aerodynamic sound. This is where the need for a very clear discrimination between low frequency sound itself, as opposed to the low frequency modulation of audible (higher frequency) aerodynamic sound, is required. With specific regard to low frequency sound, what is often meant in the context of wind farm noise is infrasonic sound in the generally sub-audible frequency range of less than 20 Hz. As far as such infrasound is concerned, repeated studies into noise and vibration from wind turbines, including the DTI study referred to above, have confirmed the lack of sufficient energy in these very low frequency bands to result in either direct adverse health effects or subjectively perceptible effects. In contrast, the same or similar studies confirmed the potential presence of audible wind turbine aerodynamic sound that is amplitude modulated at a low frequency of typically around 1 Hz.
WIND TURBINE AMPLITUDE MODULATION: RESEARCH TO IMPROVE UNDERSTANDING AS TO ITS CAUSE & EFFECT

Collation of Work Package Reports and Final Reporting

It was the confirmed presence of this type of AM that provided a possible causal link between a physically measurable and subjectively perceptible acoustic effect and reported adverse responses. A consequent resurgence in interest in AM has therefore arisen during the past five years or so. An issue that is of particular concern to potential neighbours to wind farms, and the wind energy industry alike, is the question as to how commonplace the occurrence of ‘problematic’ levels of AM is. In 2006, the DTI study [2] presented the results of noise measurements undertaken at 3 wind farms. This was 3 out of a total of 5 wind farms where disturbance due to ‘low frequency noise’ had at the time been formally reported. The alleged problem sites therefore represented less than 4% of the total number of operational wind farms in the UK at that time. At one of the tested sites the problem had already been alleviated by the introduction of a wind speed and sector noise management reduction system, which had to be switched off in order to acquire the data required for the report. At each of the other two sites, noise monitoring equipment had to be installed for a minimum of between 4 and 8 weeks for occurrences of the problem situations to be self-reported by the occupants of the dwellings concerned. Based on these facts alone it appeared, at least at that time, that the problem could not be regarded as commonplace across UK wind farms, either geographically or temporally.

The finding of the DTI study was further corroborated by the subsequent study undertaken by the University of Salford [1]. The evidence available at the time of the Salford Study concluded that the issue of AM was of limited extent across UK wind farms. Anecdotal evidence relating to wind farms in other countries reinforced this initial impression of limited impact. Nonetheless, AM was formally identified through the University of Salford study to occur at a limited number of wind farms.

Since the time of the Salford Study [1], there have been claims of increased occurrences of ‘problematic’ AM, with one suggestion being that the adoption of physically larger turbines invalidates the assumptions made in ETSU-R-97 concerning the ‘acceptable’ AM that may be expected to be produced through the normal operation of wind turbines. In this respect the ‘norm’ at the time of ETSU-R-97 being developed was based largely on turbines having typical hub heights and rotor diameters both of less than 40m. Current large scale wind turbines are now based around hub heights and rotor diameters of typically double this size at 80m or more. At the same time typical generating capacities have increased from less than around 500kW to 2,000kW or more.

Whilst recent research [5,6] undertaken prior to the present project has demonstrated that some degree of AM is inherent to the operation of all wind turbines, whether large or small in size, the features of the AM identified as a result of that research cannot explain the characteristics that have been reported at some sites (see, for example, the final report for WPC). Such characteristics include situations in which AM is distinctly audible in the far-field of turbines, predominantly in the downwind direction, is more impulsive in nature, and is observed to occur intermittently.

Whatever the root cause of this ‘other’ form of AM, the consequence of its occurrence on some wind farms has resulted in concerns increasingly being raised both by local authorities and the public alike as to the likelihood of it occurring around newly proposed wind farms. The argument has increasingly been presented that, if the current state of knowledge precludes the accurate prediction as to the form with which AM will occur at a proposed wind farm, then a precautionary condition should be set in place. The problem with imposing an AM based planning condition on such a precautionary basis is that the robustness and effectiveness of any such conditions would, within the current state of knowledge, be totally untried and untested. It would also necessarily be based on an incomplete knowledge of how any objective measure of the AM may relate to subjective response.

It is with the foregoing issues in mind that ReUK, on behalf of the UK onshore wind energy industry, commissioned the present research project. The main aims of the project are to address two key issues:

- First, the causal mechanisms for any AM that falls outside that which is known to result from a wind turbine’s normal operation need to be better understood. Only in this manner can its occurrence be predicted (and therefore precluded) at the design stage of a wind farm development. Achieving this goal of understanding the causal mechanisms would mean that certainty could be placed on proposed wind farm developments with regard to the occurrence of AM issues. This being the case, then the imposition of a condition against such an occurrence would become unnecessary.

---

7 It is noted that, even before this, the possible existence of ‘enhanced’ or ‘excess’ levels of AM (what constitutes ‘normal’ and ‘enhanced’ or ‘excess’ levels of AM remains the subject of some debate, and is an issue that the present project considers in some detail), the issue of AM had not been ignored. Indeed, even in the very early days of wind turbine development, the adoption of downwind configuration horizontal axis wind turbines, particularly in the USA, had resulted in reports of high levels of ‘blade thump’ noise even at large distances from the turbines.
Second, for those situations where it cannot be guaranteed that AM issues won’t occur (or in the event that the outcome of the foregoing investigation concludes that such an assurance is simply not possible), then a robust objective metric for the rating of AM effects is required to be developed for inclusion in any AM based condition. This metric should necessarily relate directly to the subjective impact of AM where it occurs, such that any AM condition based around the metric protects those exposed to it, whilst equally being wholly objective and repeatable in its derivation such that it provides certainty from the perspective of the wind farm operator.
3.0 OUTLINE DESCRIPTION OF WORK PACKAGES

The following descriptions of the various key work packages are based on the scope of coverage of each. In the main, these descriptions reflect the proposed content of the separate work packages at the contract definition stage. However, in some cases the detail of the approaches has varied from that originally envisaged as a consequence of the findings of one work package informing the others as the project progressed.

It is acknowledged that there may be some repetition of basic considerations in this section, as some of these have necessarily already been covered by way of general introduction in the preceding sections. However, it is felt useful to also incorporate those considerations herein in order to aid the understanding of the key issues facing the teams undertaking each work package.

Work Package A – Fundamental Research into the Causes of OAM

At the time of project definition, it was speculated that the primary cause of OAM at blade-passing frequency was non-uniform air flow into the rotor plane resulting in cyclic changes in blade-loading and resulting in variable noise generation. The non-uniformity may result from wind shear, inflow turbulence (from topographic forcing or the wake flow from other turbines), or yaw error (since the turbine control system can only control the rotor orientation by reference to the mean hub-height wind direction). AM may also be enhanced in propagation as a result of wind and temperature gradients. The relative importance of these contributory factors would then vary between sites and (probably) between turbine designs.

It was also recognised that there exists a large body of knowledge on aerodynamic noise from of all types of rotors, including wind turbines, helicopter blades, turbo-machinery in aero-engines, etc, and the catalogue of noise sources mechanisms are well known from the classical literature (see WPA2), including noise due to flow past the trailing edge of the aerofoil, the tip vortex, flow separations and inflow turbulence. Each source has particular frequency and spatial characteristics. Most relevant current research is led by the needs of the aircraft industry, involving work on high-speed fans and turbines and, increasingly, on noise generated by airframes (appendages such as flaps and undercarriages), which is now a significant noise source for commercial aircraft on approach.

The key to delivering an improved level of understanding of the key drivers for OAM was identified as being the ability to establish a clear correlation between the characteristics of noise (i.e. spectral, temporal and spatial features) on a few typical installations compared with the expected characteristics of the potential mechanisms. Oerlemans [5,6] has shown that some degree of NAM is inevitable, even under ideal environmental conditions, because of the inherent directivity of noise sources on a moving aerofoil. However, this does not explain the range of the feature reported in practice.

Therefore, in a first instance, the previously developed model of NAM [5,6] was developed and extended to cover more general inflow conditions and source generation mechanisms, in an attempt to replicate the observations of OAM: this was done by S. Oerlemans in WPA1.

WPA2 then continued this theoretical work from a more general point of view. Initially the research under WPA2 was based on an analysis of the existing data which is available immediately under WPC, thus limiting lead times for this element of the work. However, an important output from WPA2 was to inform the gathering of additional corroborative data of a specific and targeted nature to be carried out under WPD.

The scope of Work Package A2 comprised:

1. carry out a review of published literature relating to AM aerodynamic noise effects in rotating machinery;
2. examine existing wind turbine noise measurement data available from WPC;
3. produce a number of hypotheses for the origins of AM derived from the literature and current measurement data review and from ‘brain-storming’ meetings involving key staff from the project
team and representatives from ReUK, as well as contributions from other researchers in the field and from wind turbine manufacturers;

4. determine what the likely spectral, temporal and spatial features of each of the candidate mechanisms are likely to be, and compare this with existing data and use it to inform the data gathering undertaken as part of WPD;

5. use all available data to identify the key drivers for AM and hence establish potential causal mechanisms;

6. based on the identification of the key AM drivers, produce a list of AM ‘risk factors’ to assist developers in predicting the likelihood of varying AM occurring at any particular site with a particular turbine type and configuration (due to the necessarily limited scope of WPA2 it was recognised at the project outset stage that this list was highly unlikely to provide a means of calculating AM risk with any degree of precision, rather it should provide significantly better informed guidance than is currently available).

Work Package B – Development of Objective Amplitude Modulation Measurement Methodology & Development of a Dose-Response Investigation

There are three interlinked issues that this element of the project was required to address:

- the desire to develop an objective methodology which would allow the automated discrimination of wind farm amplitude modulated noise, in much the same way as there is an accepted methodology for the automated discrimination of tonal noise;
- the desire to enable the discrimination method to produce an objective rating of the identified amplitude modulation which could be related to a subjective ‘dose response’ relationship;
- the need to establish a ‘dose response’ relationship based on subjective testing.

It was clear that there would need to be some cross-fertilisation of ideas between the various elements of the work package, as each of the three foregoing issues relies to some degree on the other two.

Fundamental to developing a dose response relationship is the requirement to develop an objective metric which represents the characteristics of the stimulus (the amplitude-modulated noise) and weights these characteristics to generate (ideally) a single number value that can be shown to correlate with subjective response. However, the potential complexity of achieving the foregoing aim was recognised from the outset. For instance, signal-to-noise ratio was acknowledged to be a potential factor. In the presence of background noise levels that lie close to the mean level of a modulated superimposed sound, the superimposed sound can be partially masked and the modulation depth (peak-trough) reduced, depending on the frequency content of both components. Additionally the acoustic parameters will be different indoors and outdoors and whether windows are open or closed. In each case the background noise and spectrum will be different, with mid frequencies potentially being relatively more important outside and low frequencies being more important inside a double-glazed house, for example.

Another potentially complicating factor is that annoyance is also affected by non-acoustic factors. Such factors include an individual’s attitude to wind turbines in particular or to renewable energy in general. Annoyance will also be related to disturbance of concentration if an individual is undertaking various tasks, such as working at home, reading, listening to music or radio or television, trying to rest or sleep, working in the garden, or relaxing on a patio. Once a task has been disrupted, annoyance may increase rapidly. As such there is likely to be a relatively sharp threshold level between not annoying and very annoying. This threshold will vary from individual to individual, and from occasion to occasion for each individual according to the tasks being undertaken degree of concentration, number of times the noise is noticed, etc. The threshold may also depend on previous experience, as some individuals may become sensitised to a particular noise once they notice and recognise it, whereas others may become habituated. Thus, in designing the experiment, the questions posed to the subjects needed to be carefully considered, and the limitations and value of tests undertaken in a laboratory environment needed to be recognised.

In practice, the work undertaken under work package B was perhaps the element of the project which deviated most from the initially planned approach. In particular, the development of objective discrimination tools and the validation of the use of these various methods proved to be significantly more...
involved than had originally been envisaged. This was not least due to the fundamental issue of defining what actually constitutes a reasonable measure of the degree of modulation present in a signal, the variable ranges of objectively quantified values that can result from seemingly small changes in assumptions concerning the underlying models, and how these values may then be related to subjective response. In order to deliver the above, the work package was divided into two separate components: B1 considered the development of an automated AM identification and rating tool based on signal processing techniques, whilst B2 considered the subjective response to AM.

**B1 - Development of an AM Descriptor ('metric')**

The requirement was essentially to develop a signal processing method capable of robustly identifying and quantifying the presence of the modulation of the sound envelope of the noise signal. The basic starting premise for identifying potential identification methods was that modulation occurs in a generally periodic manner at regular intervals related to the blade passing frequency of the turbine. However, it was recognised that, in practice, the signals would be 'quasi-periodic' (i.e. the modulation would not be truly regularly spaced in time) due to the variable speed nature of turbines. Multiple modulation rates may also feature in any noise signal due to turbines across a wind farm site having different rotational speeds at any given moment in time. Extraneous sources could also cause the sound to also vary in level, quite independent from the presence of any wind turbine noise. Quite apart from these physical considerations, it was also recognised that any objective measurement methodology derived from the study may need to be modified to take account of the findings of the subjective testing being undertaken as part of WPB2, whose aim was to determine what parameters are important in controlling the dose-response relationship. However, in the first instance, the metric was expected to take account of such factors as:

- level and frequency content of the modulated sound;
- depth of modulation;
- waveform of modulation (modulation rate, sinusoidal, strongly impulsive etc);
- temporal variation in depth and waveform of modulation.

Notwithstanding the above, the final form of metric could not be developed in isolation: a key criterion for the appropriate metric was that it must produce repeatable results and show good correlation with subjective response. The necessary approach was therefore required to:

- develop a candidate metric (or metrics) which would ideally account for all variables that are likely to be subjectively detectable;
- design subjective tests in such a way that the range of stimuli presented to subjects represents all variables included in the metric(s), and the range of stimuli presented should correspond with the range observed on wind farm sites (based on supporting input from WPC and WPD);
- refine and develop the metric if needed to optimise correlation with subjective response.

It was also considered important to evaluate how these metrics could be applied to realistic field signals.

**B2 - Listening Tests**

It is known that level alone is only one piece of the equation that goes to make up an individual’s total annoyance response to noise. Other factors (some non-acoustic) often lead to the exposed individual becoming increasingly sensitised to the noise. Alternatively, through prolonged exposure, individuals may become habituated to a given noise, or they may develop coping strategies (either consciously or subconsciously) which result in a lessening of the impact. Two of the key factors other than level that affect an individual’s response to noise include spectral content and frequency of occurrence (when, how often, and for how long). It was therefore clear that laboratory based tests under controlled conditions could result only in relative judgements as to the perceived differences between different noises. Such short term tests could not produce an absolute measure of annoyance. The latter could only be established via a large scale social survey of individuals in their home environments, but then with the associated uncertainties concerning the actual exposure of the test subjects to the specific noise of interest.
It is plausible that OAM noise may be more disturbing than both steady and NAM wind farm noise. This possibility is driving an ongoing debate as to whether current guidelines for the assessment of wind turbine noise, such as ETSU-R-97, are sufficiently taking into account the possible occurrence of OAM. As a consequence, wind farm developers, planners and policy makers are interested in finding out how OAM noise is generally perceived and how listeners respond to it.

Unfortunately, not much is known about the occurrence of and response to OAM. The work undertaken under this work package was aimed at developing a scientifically based procedure for the rating of OAM effects. Previous work has suggested that the following general behaviour might be observed:

- a threshold of onset of annoyance will occur when the fluctuations become sufficiently pronounced that the modulating sound becomes more annoying than the steady sound of the same sound pressure level;

- for AM values above the threshold, there will exist a fixed relation between AM characteristic parameters and a mean annoyance score, with previous research suggesting that annoyance might be observed to systematically increase with the increased prevalence of certain characteristic parameters.

It was therefore recognised that, if one or both of the above hypotheses could be validated for OAM noise, then their quantification could aid the development of guidance for any OAM based planning condition. For example, a relation between mean annoyance scores and fluctuation strength (as defined in [7]) could potentially be used to define an assessment scheme for OAM by matching the mean annoyance scores of OAM noise with continuous noise. This would provide the basis for rating the OAM characteristic of wind turbine noise, if considered necessary.

The main objectives of the listening tests were therefore two-fold:

1. to validate different AM metrics as a measure of AM which correlates with subjective response;

2. to investigate the relationship between AM value and mean annoyance score, with the following aims:
   - to establish (in terms of AM ‘value’) the threshold of onset of annoyance (i.e. when modulated sound becomes more annoying than steady sound of the same mean level);
   - to establish the relationship between AM value and mean annoyance score at AM values above the threshold by matching the mean annoyance scores of AM noise with continuous noise.

The key stages of the development and implementation of the listening tests were as set out below.

1. key decisions had to be made as to the scenarios to be tested (for example indoors or outdoors, fixed AM or variable AM, range of AM depths, range of overall levels, key variable parameters, etc.);

2. test signals were generated using simulated data to represent the range of characteristics of AM noise generated by wind turbines based on input from WPC and WPD (the use of simulated data as opposed to recorded wind turbine noise was required to permit the necessary control over the various parameters whose effects were required to be tested);

3. test signals (including both background and wind turbine sounds) were selected to be representative of those experienced at typical nearest residential neighbours to wind farms in rural situations outdoors (i.e. below 45 dB(A));

4. pilot tests were carried out to validate and develop the experimental method (this involved presenting test sounds in a quiet listening room and asking subjects to record an annoyance score on the basis that they were relaxing outside their home, plus the alternative approach of requesting subjects to adjust the levels of the test samples on the basis of establishing ‘equal annoyance’ with certain standard signals);

5. samples were presented for durations of about 20-30 seconds in a random sequence to include background noise and to test ‘wind turbine’ noise at different levels and with varying AM characteristics, as achieved through varying the test parameters;

6. the pilot tests were undertaken involving a limited number of subjects, the results of which were to narrow down the range of parameters to be varied and tested for the final listening tests;
WIND TURBINE AMPLITUDE MODULATION: RESEARCH TO IMPROVE UNDERSTANDING AS TO ITS CAUSE & EFFECT

Collation of Work Package Reports and Final Reporting

7. final listening tests were carried out with an increased number of subjects in more controlled conditions;

8. the results of the final listening tests were analysed using the various objective metrics developed under WPB(1) to establish a dose response relationship.

Work Package C – Collation and Analysis of Existing Acoustic Recordings

Third party sources that may hold relevant acoustic data relating to AM were identified. These parties were then formally approached and access to their data requested on the basis of its confidential use. All parties thus identified and approached were added to a database developed as part of this Work Package C. Where available, stored data included relevant supporting information including, amongst other factors, site topography, turbine details (including operational data where available), reports of AM at the site, details of the noise measurements, etc.

It was highlighted as a potential risk to the project that the exercise of seeking data from third parties could result in no (or very limited) positive data returns, and that this would throw into some doubt the ability of WPC to deliver even a ‘broad’ estimate of the frequency and severity of the AM problem across UK wind farms. In an attempt to circumvent the foregoing issue, it was also requested that the identified data owners could alternatively release summary details of their own analysis of the audio data they hold, even if they are not prepared to release the audio data itself, on a site anonymous basis. It was also identified that confidentiality issues may also limit the returns available from even this reduced request. In reality, requests made under WPC were more successful than had originally been anticipated at the project tender stage, although requests were understandably received from a number of wind farm operators to keep the information confidential. This requirement of anonymity has not, however, taken away from the utility of the data in informing the project team and in contributing to the final outcomes of the project as a whole.

One of the complicating factors of the present study is that wind turbine noise generally only becomes an issue where it adversely affects residential neighbours to wind farms. The issue as to whether or not the operation of a particular wind farm may cause problematic noise therefore generally relies on the reliable and consistent reporting of its effects by those living in the vicinity of the wind farm. The review and interpretation of available information is complicated by the difficulty in establishing the relevance of reported experiences of wind farm neighbours, and in particular the relevance of the widely varying descriptions used by those reporting being affected by wind farm noise. The potential issue of relating subjective descriptions to actual effects applies particularly to the specific subject of Amplitude Modulation noise from wind farms, especially when it is appreciated that this potential feature of the noise may vary and/or take different forms, each of which may be self reported using different descriptors across different subjects. All the foregoing factors were recognised in terms of risk to the outcome conclusions resulting from this work package which relied on existing data allied with reports of AM.

In terms of formal deliverables for Work Package C, these comprised a compilation of audio recordings suitable for the testing of candidate AM assessment methodologies under WPB. It was also initially planned that this would allow an informed estimate (based on the data returns) of the extent of the AM problem across UK wind farms, at least as far as is practicable within the available budget, timescale and confidentiality constraints of the available information, but this did not in fact materialise in practice. In producing the foregoing outcome results from the available data, possible factors positively contributing to the occurrence of increased levels of AM were also to be considered.

Work Package D – Measurement and Analysis of New Acoustic Recordings

At the project outset it was initially conceived that additional measurements would be undertaken as part of Work Package D at up to seven separate sites, the original aim being to collect additional recordings to those of work package C, but using an essentially similar approach which would focus on recordings at the locations of neighbouring dwellings, or proxies thereof. On this basis, the proposed work programme for Work Package D comprised the following stages.

1. Based largely on the outcome of Work Package C, sites were to be identified at which AM is known or is alleged to occur to such a degree that it gives rise to adverse comments or formal complaints.
WIND TURBINE AMPLITUDE MODULATION: RESEARCH TO IMPROVE UNDERSTANDING AS TO ITS CAUSE & EFFECT

Collation of Work Package Reports and Final Reporting

2. A project programme was to be prepared for undertaking the proposed noise measurements, along with details as to how supporting meteorological and operational data would be acquired. This programme would contain details of the proposed sites at which measurements would be undertaken, the locations at which it was proposed to undertake the measurements and the measurement results against potential controlling factors.

3. Measurement sites were to be secured and noise monitoring / met monitoring systems were to be deployed at these locations.

4. The operator’s of the selected wind farm sites were to be approached in order to acquire relevant wind farm operational data for the duration of the noise monitoring exercise. A running analysis of any data acquired during the course of the measurement exercise at each site was to be maintained in order to inform the utility of further measurements and to amend the data acquisition programme, where deemed necessary, to maximise the chances of a successful project outcome.

5. A detailed objective AM analysis of the data acquired under Work Package D, where possible using the analysis tools developed under WPB1, was to be undertaken in order to correlate the measurement results against potential controlling factors.

6. The outcome results of the preceding analysis were to be used to refine, where found necessary, the analysis techniques used for the objective assessment of AM and to feed the results into WPB1 and WPB2, and also to provide recommendations as to the preferred measurement technique for the identification of AM effects.

7. The database developed under Work Package C was to be supplemented with all relevant information and audio records resulting from Work Package D.

Prior to implementing the initially envisaged measurement campaign under WPD, a review of the current knowledge and experience of AM was undertaken to provide a starting point for the investigation. The review sought to include relevant reports and potential data sources from projects from both within and outside the UK. Based on the information gathered, coupled with the experience of the project team, it was recognised that, even at those wind farm sites where AM has been reported to be an issue, its occurrence may be relatively infrequent. Also, for the reasons set out above under work package C, reliance on reports of AM could be open to interpretation.

It was therefore acknowledged that the capture of time periods when subjectively significant AM occurs may involve elapsed periods of several weeks or even months, even at those sites where it was accurately reported as occurring. As a consequence, the scope and methodology of WPD evolved significantly with time. It was determined that, rather than simply acquire more examples of AM audio recordings in the far-field, more detailed supporting information, such as better defined meteorological information and turbine operational information was crucial to obtaining an improved understanding of the potential causes of OAM. The approach adopted was therefore to focus on a more limited number of sites but to undertake more extensive and detailed measurements than originally envisaged at each of these sites using a variety of strategies, the requirements for data capture being guided by the findings of other work packages.

One of the benefits of the originally envisaged approach to the measurements to be undertaken under WPD was that recordings could be taken at any accessible location without necessarily the need for approval from any involved parties. However, the downside to this approach was quickly recognised to be the subsequent inability to access relevant supporting information from wind farm operators who were understandably cautious about allowing their wind farms to be used as part of the project.

The revised approach therefore required the direct involvement of wind farm operators if the necessary supporting information was to be made available. The benefits of the revised approach were determined to far outweigh any drawbacks, although it had to be accepted that one of the drawbacks was the significantly extended time required to arrange site access and to adequately address confidentiality considerations. Also, many logistical and technical challenges were associated with the more detailed and innovative nature of some of the measurements proposed, some of which required working in close collaboration with wind turbine manufacturers in addition to the wind farm operators. This led to some
delays to the overall project programme, but the value of the additional measurements which were undertaken were deemed to outweigh any issues associated with these delays.

It was also therefore not expected that the measurements undertaken as part of this work package would offer more evidence into the frequency of occurrence across the country of the phenomenon, but it was considered preferable to focus on acquiring further insight on the characteristics of 'other AM' and its potential causes.

Ultimately, a staged approach was taken in which different approaches were employed at three different sites in order to achieve separate aims, as summarised below.

**Site A** involved measurements that were most similar to wind turbine noise immission (far-field) measurements, as generally undertaken following the guidance of ETSU-R-97. However, in accordance with the expected requirements for the measurement of any modulation, high-resolution data including audio recordings were also collected as part of these works. Recordings were made at two residential properties neighbouring a wind farm site for which residents at the measured properties had been complaining about the noise from the wind farm, with investigations currently underway (by others) to assess the complaints further. Access was granted to the two properties which enabled detailed measurements to be made at suitable external locations over a period of several weeks.

**Site B** comprised a location where the existence of OAM had been positively identified. Efforts were therefore focused on undertaking a detailed series of measurements, allowing a study of conditions in which varying levels of AM were experienced and at different locations relative to the turbines. This also involved capturing detailed anemometry measurements and turbine operational data at a high resolution. The schedule and requirements of the measurement campaign were based on the theoretical considerations and requirements outlined in the WPA2 report, in as much as practical and budgetary conditions reasonably allowed. These measurements were significantly more detailed than those generally undertaken for immission measurements of wind turbine noise but were nevertheless still limited to some degree through practical constraints.

**Site C** involved targeted measurements on an operational wind farm site using novel techniques to investigate the influence of turbine operational parameters on the character of the AM noise produced, as informed by the results of the other work packages in this project. In particular, the hypothesis raised in WPA1 and WPA2 that partial blade stall may lead to increased levels of modulation at large distance downwind warranted particular investigation. Considering this, the influence of a turbine's pitch regulation system was considered a crucial element to be tested. Designing a measurement campaign capable of addressing the foregoing issues required detailed cooperation with turbine manufacturers, especially as a detailed knowledge of the blade geometry and control system operation of commercial wind turbines is generally not freely available due to confidentiality considerations. It was agreed with the turbine manufacturer to undertake tests in which the pitch of the turbine was controlled directly in order to attempt to trigger detached (stalled) flow on the blade, and to assess the relative impact on far-field noise, and in particular the potential for varying pitch angles to induce or control amplitude modulation. The project team is not aware of such investigations having been undertaken previously.
4.0 SUMMARY OF FINDINGS

As a consequence of how knowledge concerning AM has developed since the present project was conceived, it is useful to review what the important outstanding issues were then, and are now. To this end a summary comparison of the issues, and how they have developed since the start of the present project, is presented in Appendix A.

The present section seeks to summarise answers to the key questions concerning AM out of the findings of the various work packages. In doing so the aim is to highlight those areas where firm conclusions may be drawn, and those areas where information is still lacking. In this respect, whilst the outcome findings of the present project are undoubtedly positive in that they have moved the understanding of AM forward in several major areas, it will become apparent on reading the totality of the project reports that some major issues still await clearer explanation. Furthermore, the explanations for some issues that were previously thought would be relatively easily established have, in some cases, become less certain as a consequence of observations made under this project. These are areas where further work is recommended, as outlined in the conclusion.

At the time of the commencement of this project, a number of theories were being forwarded by various acoustics practitioners active in the field of wind turbine noise as to the likely causes of OAM. These included, amongst other factors:

- blade passing tower
- angle of attack changes
- high wind shear conditions
- stable atmospheric conditions (also leading to high wind shears)
- low-level jets
- high turbulence
- yaw error
- rotor/wake interaction effects
- interaction between turbines, particularly when arranged in a linear array;
- synchronisation or relative phasing between turbine rotations;
- propagation effects;
- ‘stubby’ towers.

It was one of the starting aims of the project to look at each of these theories and assess their merits. However, it was equally recognised at the outset of the project that to focus solely on such theories, often based purely on anecdotal evidence, could lead the investigation to miss other, truly significant, factors. The starting point of the project was, therefore, a diverse project team meeting. This project team inception meeting included invited contributions from other experts outside the immediate project team (including Professor Richard Sandberg, an aerodynamicist based at the University of Southampton) to look at all the evidence available to the project team at that time. This included listening to samples of AM which included both NAM and OAM (see the discussion in the introductory Section 1 for a definition of these terms) and consideration of circumstances under which each had been reported, as far as such information was available.

It was quickly established that the available supporting information was often contradictory. One of the outcome conclusions of the very first meetings of the project team was not that more examples of AM audio recordings were necessarily needed per se. Rather, what was required were AM audio recordings with more detailed supporting information, such as better defined meteorological information and turbine operational information. As the project progressed, efforts were made to collect such supported audio recordings from third parties under WPC, with some success. However, as a consequence of the identification of the various potential causal mechanisms of AM in its different forms, it was recognised by the project team that the validity of a number of these mechanisms could not be either proved or disproved on the basis of the available data. It was additionally recognised that it was highly unlikely the theories could be proved or disproved by the initial remit for WPD of the project which anticipated the

---

8 Turbines with a large rotor diameter relative to their hub height, although the ratio is not described precisely.
collection of recordings of wind farm noise at typical residential dwelling locations around a number of different UK wind farms, but again without any detailed supporting information.

It was conceived, however, that some relatively simple measurements could be devised to assist in identifying the validity of at least some of the postulated theories. The problem facing the project team was that these measurements, although relatively straightforward in concept, would require the close cooperation of a wind farm operator and wind turbine manufacturer, as they would necessitate access both to the full range of turbine control system parameters as well as the ability to manually vary the control of a turbine outside its normal operational envelope. Such tests were ultimately arranged and undertaken under Work Package D once wind farm operators and wind turbine suppliers had been identified and had offered to work in full cooperation with the project team. However, through no fault of the various parties involved, whose proactive contributions to the project are gratefully acknowledged, getting to this stage was a lengthy process and one which contributed significantly to the delay to the project.

The particular piece of information identified as being ideally required was that relating to the precise flow conditions on the surface of the turbine blades themselves. It was therefore unfortunate that the collection of such data was outside the scope of the present project and it was not possible to obtain such information from any third parties. However, interesting discussions were held as part of the present project with third party research organisations in Denmark. As a consequence of those discussions it remains possible that, in terms of future work, access could be made available to test turbines fitted with the necessary instrumentation to obtain this data on the back of unrelated research that is being carried out by those organisations.

Due to the manner in which the research undertaken under the project’s various work packages was interrelated, it is considered unhelpful here to summaries the findings of the project on a work package by work package basis. Instead, the present section is divided into a number of ‘headline’ issues that each call on the results of more than one work package to fully explain the project’s outcomes concerning each issue. These issues comprise:

- What is AM?
- What causes AM?
- Can AM be objectively identified and quantified?
- How does the theory for AM identification apply to real world data?
- What is the subjective impact of AM?
- What are the characteristics of OAM?
- Can OAM be predicted?
- Can OAM be mitigated?

Prior to attempting to answer the foregoing questions, it is first useful to set the scene as to the available anecdotal evidence that has been collated during the course of the project, and to see how this information may immediately impact on some of the previously postulated hypotheses for OAM. It should be remembered here that the definition of OAM adopted for the purpose of this project relates to any occurrences of AM observed to lie outside the characteristics of that which may generally be classified as ‘normal’ blade swish.

- the modulation depth (the difference between the levels of adjacent peaks and troughs) can be significantly greater than that of normal blade swish, with changes in A-weighted levels of up to 10 dB having been measured;
- the dominant frequency characteristics are lower than for normal blade swish, with a shift in the dominant frequency range to typically around the 300-400 Hz region;
- the effect has only been reported on a limited number of wind farm installations;
- the effect is not restricted to an individual turbine type;
- the effect has been reported both for individual turbines and for wind farm arrays;
a particular turbine type that exhibits the effect on one wind farm site will not necessarily exhibit the effect on another site;

- even on those sites where the effect has been positively identified to occur, it is intermittent;
- the effect may occur for just a few rotations of the blade, or it may persist for periods of several minutes or hours;
- the effect has been reported to be most common during evening and night time periods, although it has been observed at times during day-time periods;
- the effect is more dominant in the far field (typically 10 rotor diameters or more from the turbine) and may not be simultaneously discernible in the near field (typically less than 3 rotor diameters) of the turbines;
- the effect is generally strongest in the downwind direction and can also be present in the upwind direction of turbines, but it has not been clearly recorded in the cross wind direction in which normal blade swish is most prevalent;
- the effect has been reported on wind turbine installations on both flat and hilly terrain;
- the effect has frequently been associated with conditions when wind shear may be expected to be high, but has also been reported to occur on some hilly sites or during damp conditions of light or even heavy rain when wind shear may be expected to be low.

The foregoing observations, whilst only anecdotal, immediately lead to the conclusion that if any one factor or combination of factors were responsible then the effect would occur at all sites featuring those factors and it would occur frequently at those sites. However, neither of these situations has been observed to be the case in practice. As an example, the effect has been observed to occur on a single isolated turbine with a high tower, so interaction effects between linear arrays and too closely spaced turbines cannot be a decisive factor, neither can a large rotor on a short tower. As another example, the effect has been reported for one make and physical configuration of turbine on one site, whereas it has not been reported for that same make and physical configuration of turbine on all installations. Such contradictory observations serve to illustrate the problems that have been facing the wind energy industry, and reinforce the reasons why the resolution of the AM issue has been proving such a non-trivial task. It is the aim of the present project, as summarised over the remainder of this report, to draw together the various observations and theories in an attempt to provide answers to some of the questions raised.

The starting point of the discussion should naturally be, as proposed previously, to better define what is meant when we refer to ‘AM’.

4.1 What is AM?

Descriptions and definitions of AM, NAM and OAM have already been presented in some detail in the introduction to this report (Section 1). This was deemed necessary as these definitions are so important to placing all subsequent discussions into context and to avoid subsequent confusion over terminology. In order to avoid unnecessary repetition, it is assumed that the reader of the present section will have read the introduction, such that the basic terminology and issues under consideration are appreciated. The present section of the reports therefore expands on the discussion contained in the introduction section only where it is considered helpful to do so.

Given that the definitions of AM and also (at least for the purpose of the present project) NAM and OAM have already been provided as being various incarnations of the regular variation in level of wind turbine ‘aerodynamic noise’, it is perhaps useful to present a brief overview of wind turbine aerodynamic noise in general.

As discussed in greater detail in WPA1 and WPA2, all wind turbines generate aerodynamic noise when their blades rotate. This aerodynamic noise is caused by the interaction of the blades with turbulence in the air flow. Some turbulence is present in the inflowing wind itself. This turbulence causes so called ‘inflow turbulence’ noise. However, turbulence is also generated by the boundary layer of the flow over the blades, and this is the origin of a number of ‘self’ noise mechanisms. Self noise would be produced by
a turbine even in a uniform and non-turbulent flow in the absence of any inflow turbulence as it is produced by the displacement of the air as the blade moves through it.

There exist five key mechanisms for the generation of aerodynamic self noise from blades in general:

- boundary-layer turbulence passing the trailing edge - this is the dominant aerodynamic noise source on wind turbines under normal operating conditions;
- separated-boundary layer / stalled-aerofoil flow - this is a potentially major source in particular conditions, but it is not expected to be significant for wind turbines during normal operating conditions;
- vortex shedding due to laminar-boundary-layer instabilities - this is unlikely to contribute to wind turbine noise as the flow regime does not apply;
- vortex shedding from the blunt trailing edge of the blade - this is a known feature of wind turbines, but generally occurs at high frequencies;
- the turbulent vortex flow existing near the tips of lifting blades - this is normally a relatively high frequency problem and has also been largely controlled by careful tip design on modern blades.

The dominant self noise mechanism when dealing with the A-weighted spectrum of wind turbine noise is generally considered to be trailing edge noise. As indicated in the first of the preceding bullet points, trailing edge noise occurs when the turbulent boundary layer of the flow over the blade is convected past the sharp trailing edge. Due to the relatively higher speed of the tip of a blade as it passes through the air; trailing edge noise is more prevalent towards the outermost part of the blade lying closer to the tip than the root.

In the absence of any other factors, this trailing edge noise would be perceived subjectively as a constant ‘whoosh’ sound. The spectral content of this ‘whoosh’ sound would be controlled largely by blade geometry considerations. So, as previously indicated in the introduction, the physical size of turbines over the past two decades has seen an increase in the diameter, chord and thickness of the rotor blades. This increase in physical size of the blades has resulted in a general shift of the dominant frequencies radiated as a consequence of trailing edge noise generation mechanisms from between around 500 Hz to 1000 Hz for earlier turbines to around 300 Hz to 800 Hz for modern, large scale turbines, although there is some conflicting data on this decrease due to the overlap of the spectral regions between different turbine types of a similar size9.

However, it is commonly observed that the sound heard by a listener located on the ground in the vicinity of a wind turbine is not constant, but instead it goes up and down in loudness in a regular manner. This effect is termed the ‘Amplitude Modulation’ of the aerodynamic noise, or AM for short. In subjective terms, the presence of AM causes the otherwise constant level ‘whoosh’ sound of the trailing edge noise to be perceived as a ‘swish’ sound, commonly referred to as ‘blade swish’, that is regularly varying in level. The regularity of the occurrence of peaks and troughs in the ‘swish’ sound is related to the rate at which the blades pass by the listener. Due to the directional radiation characteristics of the trailing edge noise, the difference between the peaks and troughs in noise level is greatest in the plane of rotation of the turbine, and in particular when the listener is located on the downward stroke side of the turbine. The same directional radiation characteristics mean that little temporal variation in the loudness of the trailing edge noise is experienced when the listener is located upwind or downwind of a turbine, particularly as the observer’s distance from the turbine increases beyond a few rotor diameters.

This AM, which manifests itself as what is commonly referred to as ‘blade swish’ has been fully characterised through both theory and measurement. The theory has confirmed blade swish to be an inherent feature of wind turbine noise [6], although it has long been recognised as such. For example, blade swish is discussed in the ETSU-R-97 guidance document [3] published in 1996 (see, for example, pages 12 and 68 of that document).

9 See WPC data and Annex B to this report.
Given the apparent acceptance of blade swish as an inherent feature of wind turbine noise, the question must therefore be asked as to why, after approximately two decades of wind farm development in the UK, the issue of AM has come to the fore? The answer to this question can not be definitively formulated, but it is believed to result from reports of a change in the characteristics of the AM being heard at some residential dwellings neighbouring wind farms. These changes include a general shift to lower frequencies of the dominant noise spectrum, even on an A-weighted basis, and an increase in modulation depth, in particular with higher depths of amplitude modulation occurring in the far-field downwind (and sometimes even upwind) of the wind turbine. These characteristics cannot be explained by current models of AM based on trailing edge noise. It is for this reason, for the purpose of the present report and as set out in the introduction, that all occurrences of AM failing outside that which can be explained through the trailing edge noise generation mechanism (i.e. ‘normal’ AM, or NAM) are referred to herein as ‘other’ AM, or OAM. Where the term ‘blade swish’ is used, this historically relates to occurrences of NAM.

At the time of the formulation of ETSU-R-97 [3], blade swish was considered in some detail:

ETSU-R-97 page 12 - ‘an amplitude modulation of noise in the frequency range which is associated with trailing edge noise radiated from the outer portion of the turbine blade and discrete frequencies associated with trailing edge thickness. This rhythmic swishing sound, dependent upon tip speed and blade profile, is normally centred around the 800-1000Hz region of the frequency band for trailing edge noise and at higher frequencies for trailing edge discrete frequencies depending on edge thickness. ….. modulation of the A-weighted noise level is of the order of 2-3 dB(A) for typical wind turbine configurations. ….. this level of amplitude modulation may be greater if analysis is performed using third octave or narrow band analysis of the radiated noise from a wind turbine. This modulation may be caused by directivity effects associated with the generation of noise at the blade and is most apparent when standing close to a wind turbine, less than 50 m from the base of a supporting tower.

As observer distance increases from the turbine, the rhythmic swishing becomes less pronounced. This may be due to a number of single effects or a combination. As distance increases, the modulation caused by the directivity of the radiated sound wave emitted by a turbine blade will become less significant. Therefore, it would be expected that any directivity effects which may be audible close to the turbine will be reduced in audibility. Atmospheric attenuation will cause a reduction of high frequency blade noise relative to lower frequency blade noise. This removes the high frequency "swish" spectral content which increases its distinguishing character. As the observer distance increases, the level of sound from the turbine incident at the observer position will decrease. However, in exposed locations, it should be expected that the background noise level will remain, in general, the same. Therefore, increased masking by the background noise will reduce the subjective impact of the turbine noise. This rhythmic swishing has been noted to vary between turbine types and between sites where similar turbines have been installed.

ETSU-R-97 page 68 - The modulation or rhythmic swish emitted by wind turbines has been considered by some to have a characteristic that is irregular enough to attract attention. The level and depth of modulation of the blade noise is, to a degree, turbine-dependent and is dependent upon the position of the observer. Some wind turbines emit a greater level of modulation of the blade noise than others. Therefore, although some wind turbines might be considered to have a character that may attract one's attention, others have noise characteristics which are considerably less intrusive and unlikely to attract one's attention and be subject to any penalty

This modulation of blade noise may result in a variation of the overall A-weighted noise level by as much as 3dB(A) (peak to trough) when measured dose 10 a wind turbine. As distance from the wind turbine/wind farm increases, this depth of modulation would be expected to decrease as atmospheric absorption attenuates the high frequency energy radiated by the blade. However, it has been found that positions close to reflective surfaces may result in an increase in the modulation depth perceived at a receiver position remote from a site, if there are more than two hard, reflective surfaces, then the increase in modulation depth may be as much as ± 6dB(A) (peak to trough).10

10 The issue of increases in modulation depth close to reflective surfaces has subsequently been recognised as affecting both the peaks and the troughs of the AM noise to an equal extent, such that the effect in itself will not affect the difference in level between
WIND TURBINE AMPLITUDE MODULATION: RESEARCH TO IMPROVE UNDERSTANDING AS TO ITS CAUSE & EFFECT

The selection of the measurement position can also result in particular frequencies exhibiting a greater depth of modulation due to standing wave effects from reflected waves off the surrounding structures. These effects are very specific to the positions at which measurements are undertaken and are more the result of building layouts at the receiver position than a change in the character of the emitted wind turbine noise.

It is the opinion of the Noise Working Group that there is insufficient data available at this time to formulate an accurate measurement methodology for blade swish where it occurs. It is envisaged that further research will be required to enable proper measurement and assessment to be devised, if in the future this is felt to be necessary. Work is already under way aimed at establishing the causes of blade swish, the frequency and magnitude of its occurrence and developing an appropriate metric for its measurement.

Section 2 of this report, together with Annex A of WPC, has considered in greater detail the current state of knowledge concerning AM and the reasons why its consideration has risen to the fore over the past five or so years. This was largely driven in the UK by the publication of a UK Government sponsored report, undertaken by the Hayes McKenzie Partnership, into the study of low frequency noise from wind farms [2]. The outcome results of that report prompted a second study, undertaken by the University of Salford, specifically addressing the issue of the prevalence of ‘problem’ AM across UK wind farms [1]. The issue was further highlighted by the publication of various research papers (see WPC Annex A).

The desktop based study undertaken by the University of Salford [1] was based on responses to a questionnaire issued to all local authorities with wind farms within their areas of control, the study concluded that, out of the then operational 133 wind farms across the UK, the issue of ‘other’ AM could be identified at 4 wind farms. The study also raised the possibility that AM may additionally have contributed to complaints at a further 8 wind farms. Subsequent analyses of the responses to the University of Salford survey questionnaire [8] separately concluded that many more of the responses may have indicated the presence of AM as a contributory factor to the complaints. As pointed out by F. van den Berg, in all but one of the cases where a description of the sound was available (13 out of 14 cases) the sound was described with one or more words indicating a regular variation in level.

The foregoing perceived differences in positive responses to the questionnaire issued by the University of Salford serve to illustrate the difficulties facing the acoustics practitioner when interpreting responses to questionnaires of this nature. As so often proves to be the case, the devil is in the detail. In this case the detail concerns whether or not the complaints are related to ‘other’ AM, or merely to the fact that the ‘normal’ AM (blade swish) arising from the operation of a wind farm is audible and this, either in itself or in combination with the absolute level of turbine noise experienced, has caused those exposed to the noise to complain. This issue illustrates well the potential pitfalls associated with personal interpretations of subjective descriptors.

This brings us to the first question that needs to be answered in the context of the present project: exactly what is AM? As a consequence of collating available information during the course of the present project, what can be confidently stated is that the AM reported to occur from wind turbines covers the whole range of effects from mildly audible ‘swishing’ to much more pronounced ‘thrumming’, that the effects may vary with distance and direction from the source and that, for any given location, the effects may vary with time over periods of a few seconds or they may be present in a relatively constant manner over periods of several hours. Such observed variations may, however, sometimes be as much to do with variable masking noise effects as with variable AM effects.

Whilst the subjectively different audible effects of AM have previously been self-reported by those allegedly exposed to them using a whole raft of different descriptors, the problem with formally defining different types of AM is that there isn’t necessarily a clear-cut dividing line between them, either in terms of physical characteristics or in terms of people’s subjective response. Rather the observed effects exist along a continuum that may, or may not, see an abrupt change between states.

The issue of AM, and the differentiation between ‘normal AM’ (swish) and some form of ‘other AM’ has been usefully summarised by Bowdler and van den Berg [9] as follows:

---

peaks to troughs. Where increases in modulation depth have been observed close to reflective surfaces, they have generally resulted from the increases in the level of the peaks rising further above the general background noise.

11 Although the term ‘other AM’ is not used in [1], the definition of AM used was ‘A sharper attack and a more clearly defined character than normal blade swish […] like a distant train or distant piling operations’, which is consistent with the term as used in the present work.
The presence of ‘swish’ near a wind turbine is a well known phenomenon. We know that swish is the type of AM which is ubiquitous next to a turbine. […] [It] falls off rapidly up and down wind, but transmits over longer distance at 90 degrees to the wind direction. However, in the latter direction the absolute level is significantly lower, so overall it seems that swish does not generally transmit over distances of a few hundred meters at levels that are likely to be a significant problem to neighbours.

So what is the AM that troubles residents and why is AM a problem at some sites? […] Apparently residents are not bothered by this ‘normal’ swish but another form of AM which has been called ‘thump’.

It is for all the foregoing considerations that the present project has chosen, as already set out in some detail in the introduction, to differentiate between ‘normal AM’ (NAM) and ‘other AM’ (OAM) in terms of:

- NAM is all AM that can be explained through current aerodynamic trailing edge noise source theory;
- OAM is any AM that falls outside the definition of NAM.

The convenience of this definition is that it means the causal mechanisms of NAM are well understood. What the following sections therefore present is consideration of the observed characteristics of OAM, and how these characteristics impact on the potential understanding of how it is generated, how it may be measured and objectively quantified, and how it may impact on subjective perception of wind turbine noise.

4.2 What causes OAM?

WPA1 and WPA2 have presented overviews of the potential different noise generation mechanisms in relation to the modulation of wind turbine noise. It is useful to view these findings in light of the observations made around actual wind farm sites, as reported in WPC.

The analysis of WPA1 is based on detailed operational and aero-acoustic parameters derived from the results of a specialised turbine design and analysis package, which was then used to model the noise radiation characteristics of a typical large, modern turbine design. The model’s output has identified differences between AM in the near-field and the far-field. These differences represent a key consideration which has been relatively little studied to date. However, this represents a key issue at the heart of the question of amplitude modulation of wind turbine noise which may enable a better identification of the different potential AM effects, particularly through measurements in the far-field from wind turbines, as now discussed.

The expected decrease of NAM from wind turbines in the far-field may be due to several possible factors (see WPA2), as summarised below and addressed in further detail in the following section:

- air absorption dissipating the frequencies dominating the modulation of the turbines;
- the specific directivity of the modulating part of the noise produced;
- the reduction of directivity effects with increased separation distance;
- propagation effects such as refraction due to wind speed gradients;
- the effects of the noise from different turbines adding up together to ‘smooth out’ the modulation.

The situation is complicated by the fact that observations made in the far-field are undertaken in complex sound fields with low signal strength and therefore with the inherent potential for significant contamination from background noise sources. This is particularly problematic when considering measurements of modulation, as an increase in the noise floor will tend to reduce the measured depth of modulation (see WPB1). Therefore, studying the influence of periods of high wind shear, which has been cited by many observers as being a key contributor to higher levels of AM, is complicated by the fact that these periods often (in rural, relatively flat sites) correspond to increased levels of sound clarity because high wind shear often corresponds to reduced background noise levels. Thus it is not always possible to separate out the effects of the high wind shear at the turbine as opposed to its effects at the receiver (i.e. is the high wind shear actually causing higher levels of AM to be generated at source, or is the AM that was present in any event simply more audible under conditions of high wind shear due to the lower background noise at the receiver?).

One potential clue to the answer to this question can be found in the various observations WPC, WPD whereby high levels of AM are discernible at more distant receiver locations while there is no apparent
increase in the levels of AM measurable closer to the source. Whilst these observations do not provide a definitive answer to the question, they do at least provide an indication that the existence of higher levels of AM at more distant receiver locations (for whatever reason) may not be as a direct result of changes to the level of AM experienced ‘at source’.

Previous work

Initially, the work of Oerlemans [6] assumed stationary and uniform flow conditions which were considered ‘typical’ of standard operating conditions. This work established that, in close proximity to the turbine (i.e. less than 2 Rotor Diameters (RD)), substantial swish tended to occur to a similar degree in all directions around a turbine (as can be observed in practice in the field), whereas at increased distances (of 3 RD or more) significant AM only occurs in cross-wind directions, in which overall levels of noise are lower. Furthermore, as will be discussed below, we can also consider additional effects which will mean that the noise will tend not to propagate in these directions. As discussed in WPC, WPA1 the model was validated, to a high degree of success, based on field measurements of the type of turbine modelled for a range of measurements undertaken at a distance of approximately 3 RD from the turbine. Furthermore, the model was extended to far-field distances of up to 10 RD (WPA1).

It could be argued (in a perhaps naïve analysis) that the modulation will decrease with distance because the effect of the changing directivity of the trailing edge noise will decrease with distance due to purely geometric considerations. It may be thought that the relative angle of view to the blade may not change significantly at a greater distance away from the turbine. However, the results of the WPA1 analysis show that this is not the case in practice and that, in cross-wind directions, the predicted effects of directivity alone would remain significant out to large distances of at least 10 RD. A similar investigation was reported in [10] which was based on a flat plate model for the rotating blades. This paper reached similar conclusions in terms of directivity patterns as WPA1, specifically noting that the ‘variation range of the directivity angles […] is invariant with the distances’.

In both these models it was observed that the ‘45 degree’ direction (i.e. between the downwind and cross-wind directions) was the direction in which the combination of both overall noise levels and modulation reaches a maximum (see also WPC). It was therefore suggested (for example in [10]) that this would correspond to the maximum likelihood of audibility of the modulation. This does not, however, correspond to the observations of OAM in which high modulation levels were observed WPC in directly downwind directions rather than specifically in the 45 degree sector. This feature is also noted in WPA1, as well in [9] or in papers by di Napoli [11][12].

It should be appreciated, however, that it was in practice difficult to differentiate precisely between the instances of NAM and OAM and their respective directivity effects as a consequence of the non-optimised measurement data generally available at the commencement of this project. This is an area where the dedicated measurements undertaken under WPD add significantly greater certainty to the provisional observations based on the existing (generally ad-hoc with limited supporting information) measurements of AM reported under WPC. Notwithstanding this potential weakness of the existing available data, the work by di Napoli [12] further notes that the corresponding upwind OAM was less strong than the downwind OAM, and that it was weaker still in the crosswind direction. The observations of di Napoli also indicate that the AM was weakest close to the turbines but more prominent at larger distances (of up to 2 km) from the turbines [12].

One of the important conclusions of WPA2 was that a key theoretical condition necessary for high levels of OAM to be observed in the far-field downwind of a wind turbine is that the flow into the rotor is non-uniform. This would require either:

- that the wind profile is non-uniform, for example due to a vertical or lateral variation in wind speed or a spatial variation of the angle of the wind onto the rotor, where high wind shear or local wind gusts could provide the conditions for this to happen;
- that the turbulence entering the rotor disk is non-uniform due to upwind obstructions or meteorological conditions, thus causing time-varying levels of inflow turbulence noise as each blade enters the region of high turbulence.
Wind shear as a model of non-uniform flow

As part of the current research project, S. Oerlemans extended in WPA1 his existing model of trailing edge noise to account for non-uniform flow: using the specific and relatively simple case of an atmosphere with a certain degree of wind shear.

This analysis is based on a theoretical, engineering model, which does not necessarily aim to model every single aspect of what is admittedly a complex situation, but which provides an extension of an existing, well-validated model.

The approach undertaken in WPA1 also addresses concerns which have been raised in the past [13] that the wind profile due to high levels of wind shear would necessarily lead to increased modulation of the noise from the turbines. Such claims have centred on the possibility that the increase of wind with height, which can increase in magnitude in period of atmospheric stability, would directly lead to increased modulation as the noise emissions reach a maximum at the top of the rotation (TDC) where the wind speed will be higher, and that the modulation rate and depth would therefore be directly related to the rate of wind shear.

However, the results of WPA1 demonstrate that even a relatively strong rate of wind shear (a shear exponent of m=0.6) across the turbine rotor does not lead directly to a significant change in the predicted modulation pattern or rate, but only to a relative small bias in the directivity. This finding is consistent with the results of a model by Boorsma and Schepers [14] which showed that the predicted effect of wind shear and the influence from the downwind support tower were minimal compared to the effect of the directivity of the trailing edge. These results may perhaps not be directly intuitive, but result from the reality of this situation and, in particular, the fact that the acoustic contributions of all 3 blades of the turbine must be added together as they rotate so, whereas the variation in sound emission levels for the outer part of any one turbine blade may vary strongly across its rotation (see Figure 1 of WPA1), the contribution from the other 2 blades will ‘fill in’ the troughs between the maxima which is experienced during the downward stroke of the blade.

Inflow turbulence as a model of non-uniform flow

The potential effects of inflow turbulence are reviewed in WPA2. The characteristics of this potential source of noise are similar in some aspects to stall noise (which will be considered subsequently) in that:

- its directivity is thought to be very similar, i.e. it represents a dipole radiating outwards from the blade (see [14]);
- it results in an increased dominance in the spectra in the lower frequency region (below 200Hz).

However, for modern turbine designs, it is often assumed that inflow turbulence will not represent a significant contribution to the overall A-weighted levels from the turbine, which are expected to be dominated by the trailing edge noise mechanism (see [14]). There is, however, some uncertainty as to how valid these assumptions would be, particularly when considering discrepancies between models and predictions at the lower end of the frequency spectra (below 200Hz). The emission levels of this source will also, of course, be strongly related to the amount of atmospheric turbulence present at different times, which may be very variable depending on site-specific factors.

As noted in WPA2, in order to represent a significant mechanism of modulation of wind turbine noise, the distribution of turbulence would need to be non-uniform across the rotor blade. The scale of variation would need to be significant: for a 7 dB AM depth, WPA2 estimates a 10-fold increase in turbulence intensity would be required. Furthermore, to lead to sustained OAM would require an equally sustained period of non-uniform turbulence distribution. Finally the observation of OAM during periods of high wind shear during stable atmospheric conditions at some sites does not suggest this mechanism to be the root cause, at least in those cases, as atmospherically stable periods correspond to reduced rather than increased levels of turbulence.

Detached flow

WPA1 notes that, for particular flow conditions, there may be two possible situations that may occur for certain sections of the turbine blade: the flow may be attached or detached (this is the aforementioned ‘stalled flow’), as shown diagrammatically in Figure 1.
Assumptions are made in WPA1 in terms of the exact level of noise emission from the stalled region. This was a necessary approach given the relative lack of current knowledge on this aspect of the noise generation. Nonetheless, it stands to reason that the basic assumptions are quite reasonable that noise emissions would increase significantly as a consequence of stall, and dominant frequencies would reduce (by about half) given the increased length scales, coherence and levels of turbulence associated with a significant stall region.

Importantly, the model in WPA1 predicts that the effect of partial stall on part of the blade fundamentally changes the nature and directivity of the modulation. When wind shear causes the turbine blade to experience detached flow for only part of the turbine rotation, the level of modulation in the far-field becomes significant upwind or downwind (rather than in cross-wind directions in the standard model), whereas the directivity pattern of the overall levels does not change significantly. This is particularly evident when comparing instantaneous noise footprints between the two cases: see Figure 2.

When the modelled wind shear increases further, this increases the zone in which blade stall is predicted to occur but reduces the modulation amplitude: this is because the greatest variations in noise levels occur if the flow separation only occurs for a limited period of time.

WPA1 stresses that wind shear is only used as a simple model of non-uniform flow, for ease of computation but that, as detailed in WPA2, some other sources of flow non-uniformity may lead to similar localised stall effects, either temporarily or for more prolonged periods. Possible sources of non-uniformity are identified in WPA1 as wind veer, topography, large scale turbulence and the wake of other turbines.
The model presented in WPA1 doesn’t initially show directly how modulation amplitudes of more than 6dB could be experienced in the far-field. However, this is shown by the author to depend strongly on assumptions regarding the features of the stall noise source and by how much stall would increase the local noise radiation from the stalled region of the blade. WPA1 has initially made an assumption of 10 dB which results in a modulation depth in the far field of up to 6 dB. Were this instead 13 dB, then the maximum far field modulation depth would increase to 9 dB. As this type of aerofoil noise source has received relatively little study it is easy to see how the assumptions made can affect the outcome conclusions. It is also possible, in line with the discussions of WPA2, that propagation effects may also enhance the modulation depths observed in the far field over and above the effects depths observed ‘at source’ or in the near field of a turbine, as discussed below.

The model presented in WPA1 does not directly explain either why this type of OAM would be more likely to be experienced in the far-field of the turbines as opposed to the NAM model. We can, however, consider, in the next section the assumptions and limitations of the model of WPA1 and how additional effects may explain the observations made in some cases. The potential influences of such effects are considered further in WPA2.

Limitations of the model in WPA1 – propagation effects

The model presented in WPA1 does not take into account the longer-distance propagation effects, described in WPA2 (see also Chapter 3 of [9]), which are known to affect the long-range propagation of noise over larger distances. The model was effectively validated at distances of 3 RD, but not at further distances which are relevant to the far-field region in which wind farm neighbours can generally be found. Over these distances, the potentially most significant propagation effects are:

- spherical spreading of sound (which will reduce overall noise levels equally in all directions and is not considered further);
- refraction effects due to wind speed gradients in upwind/downwind;
- atmospheric absorption effects at high frequencies.

The potential influence on the predictions of WPA1 of the propagation effects to the far-field identified in WPA2 can be considered: this is developed in further detail in Annex B. It was noted that the effects of the foregoing factors were accounted for to some extent in a similar model developed in [14], but, as flow separation (stall) noise was not modelled by these authors, this could not be evaluated on this basis.

In summary of the considerations of Annex B, the following can be noted.

- Atmospheric absorption effects: are not considered to significantly affect the modulation predicted by the model, given the dominating frequencies characteristic of the dimensions of modern turbines. For OAM, it is predicted in the model that the peaks and troughs of the modulation will have different spectral characteristics (dominated by stall and trailing edge noise respectively), but because of the above conclusion, the effect of atmospheric absorption is not predicted to further enhance the difference in A-weighted levels in the observed modulation.

- In down-wind conditions, in addition to the inherent directivity of the turbine noise, the atmospheric refraction effects mean that far-field turbine noise levels are significantly higher in the downwind direction than in other directions. It therefore seems significant that, in the case of detached flow, significant modulation is predicted in the downwind direction. This key change in directivity is due to the inherent characteristics of stall noise compared to trailing edge noise, as shown in Fig 12 of WPA1 report. This is particularly evident when comparing instantaneous noise footprints between the two cases, as shown in Figure 2 above.

- In upwind conditions, overall levels tend to be lower generally, but the effect of the changing source height (as the blades rotate) may conceivably lead to this attenuation varying in some frequency bands as the blades rotate, as discussed in WPA2. This may combine with or affect the changed directivity effects of OAM illustrated in Figure 2. The influence of turbulence then provides a further complicating factor and can alter these predictions slightly.

In addition, the above consideration of propagation effects may further enhance the predicted effects of partial blade stall. As noted above, the predicted (under neutral conditions) peaks and troughs of the modulation in the downwind direction (in the far-field) correspond to different source mechanisms with different directivities. It is therefore conceivable that the refraction effects highlighted may in reality affect
the resultant noise footprints in increasingly different ways when compared to the effectively neutral conditions modelled in WPA1. This effect could usefully be subject to additional, more detailed modelling to better understand the potential magnitude of such combined source and propagation effects.

Finally, the fact that propagation effects are being considered here as a possible contributor to OAM, as opposed to just source effects, is noteworthy, especially in the light of the (admittedly arbitrary) definitions of NAM and OAM proposed at the start of this section: namely that NAM is AM that may be, and OAM is AM that may not be, described by current aerodynamic noise source theory. Clearly, if propagation effects may also affect NAM, then this may become a relevant consideration.

In summary of the foregoing discussion, which has mainly focussed on WPA1/2 (with supporting observations from WPC) to review the potential combination of source generation mechanisms and propagation effects in exacerbating the presence of AM, there are some clear indicators that appear to be supported by observations in the field. However, as previously suggested, the problem with the available observations is that they have generally been derived from noise data acquired on an opportunistic basis, without detailed supporting meteorological and turbine operational status data also being available. For this reason it is not possible to draw firm conclusions. This is not to say that the observations discussed above are not useful in their own right, particularly in providing much-needed circumstantial evidence for feeding into the experimental plan for the dedicated measurement campaign undertaken in fulfilment of WPD.

4.3 Can AM be objectively measured and quantified?

The preceding section has defined NAM and OAM in the context of different source generation mechanisms. This is a potentially convenient differentiator. However, the possible contribution of noise propagation effects to the AM experienced at far field receptor locations represents a complicating factor in this analysis. In particular, it has been observed that OAM may be discernible at typical residential locations in the far field of wind turbines whilst not being easily determined in the near field of those turbines: although this is consistent with the theory of WPA1, this must be borne in mind when considering an attractive, but perhaps over-simplistic, definition based on source effects only.

A second possible means of differentiating between NAM and OAM is via their resultant acoustical characteristics, as opposed to their origins. These acoustical characteristics may be based on subjective descriptors, or they may be based on the outcome of objective analysis. What is ideally required is an objective analysis leading to clearly defined and measurable parameters that can then be related to subjective descriptors and subjective response.

The present project has therefore included extensive work on investigating various methodologies for the automated discrimination, analysis and quantification of OAM. The key objectives of this element of the work were twofold:

- first, a method was sought for the automatic detection of OAM in the presence of extraneous noise, with the selected method needing to be robust and repeatable both in terms of its ability to effectively discriminate OAM from other sources of noise (i.e. it should be resilient to returning false positives or negatives) and also in its subsequent objective quantification of the identified OAM element of the noise;
- second, the objective quantification of the OAM was required to be capable of providing a rating level that will enable the correlation of that level against subjective response to the noise.

As a useful starting point, the concept of the degree to which a signal is modulated is a natural one to consider. It is for this reason that, hitherto, general attempts to relate a measurable characteristic of AM to subjective response have tended to focus on determining the variation in level of the overall A-weighted equivalent noise level, as measured on a short time basis of typically 100 ms or 125 ms: see [15] or [16]. In some cases the signal has been filtered in the frequency domain (typically by applying a low pass filter with a cut-off of around 500 Hz) prior to establishing the variation in the overall noise level, and in other cases the variation in individual octave or third octave frequency bands has been considered: see WPB1 or [17].

There are two key issues that arise from the foregoing. The first concerns the objectivity of the measurement itself, whilst the second concerns the appropriate measure of modulation depth in terms of
subjective significance. The latter is particularly problematic, being circular in nature. In order to correlate subjective response with acoustic characteristics one must have an objective descriptor for the relevant characteristics, but the development of an objective descriptor requires some knowledge of the characteristics of the signal that are of interest subjectively and are therefore required to be quantified. However, the problem is farther reaching than this, particularly given the potential confusion that can arise from the meaning of the term ‘modulation depth’. WPB1 provides a useful insight into this issue, from which it hopefully becomes clear that this apparently simple definition is anything but clear cut.

This particular element of the project, concerning the objective detection and quantification of AM, has been considered in WPB, with WPB1 focussing on the development of robust objective metrics (on the basis of the perceived dominant characteristics of OAM) and with WPB2 focussing on the subjective testing of the metrics derived under WPB1.

Developing a robust objective metric for AM

WPB1 presents an overview of various techniques allowing the quantification of modulated noise in general terms, and more specifically when applied to noise from wind turbines.

The first key result from this work is that there is no simple, single definition of the magnitude of modulation in an acoustic signal. When discussing the effects of the modulation of signals it is therefore crucial to be consistent in the definition of the metric and the normalisation that is adopted. This point cannot be emphasised strongly enough. A similar issue was identified in the research undertaken on behalf of ETSU for the assessment of tones [3], where the importance of applying a consistent set of analysis parameters to determine tonal levels was found to be central to the success of correlating objectively measured tone levels against subjective responses.

As a starting point for the quantification of modulation depth, the difference in peak to trough levels has understandably often been used (albeit, in retrospect, on a perhaps somewhat naïve basis) from readings of short term (typically 100 ms to 125 ms) equivalent continuous overall A-weighted sound pressure levels. This approach is not without merit. Indeed, WPB1 notes that the advantage of using this measure is that it will be invariant regardless of whether pressure signals are squared or not. However, whilst there is no ambiguity as to the definition of such a value for well-defined modulated signals, as is the case for the ‘artificial’ signals prepared for the present project to illustrate general principles, it is not so easy to apply this peak to trough measure in a consistent and repeatable manner for realistic field recordings. In particular, WPB1 notes that, primarily due to the compounding effects of extraneous noise, both the maximum and minimum (effectively instantaneous) values are particularly difficult to measure or evaluate when compared to the longer time averaged values (typically of at least 1 minute, and most often longer, duration) which are more generally used in the assessment of environmental sound fields.

Typical time-averaged metrics, such as $L_{\text{Aeq}}$ or $L_{\text{A90}}$, are often analysed over periods of several minutes to evaluate different noise sources. Whilst this averages out short-term variations and can assist their evaluation, conversely it also erases information relating to variations over timescales of less than a few seconds. However, it is precisely these shorter term-variations in sound pressure level that are of prime relevance to the types of noise being studied. It is therefore necessary to capture the variations of the signal over timescales equivalent to less than a few Hertz, with a sampling frequency of around 100 ms being preferred.

However, considering the variations in terms of maxima and minima of typical short-term acoustic metrics can be particularly prone to difficulty. See, for example, Figure 3 below which considers the evolution of a short (20 second long) sample of noise for a variety of averaging periods, both with and without A-weighting, short-term energy-averages ($L_{\text{A}}$) or for a time-weighted metric like the ‘Fast’ noise levels [$\text{dB}$. In this example, the short-term variations in the signal are mainly caused by bird noise. Given the significant variability in the real signal, it is not immediately obvious which ‘troughs’ and which ‘peaks’ should be considered when evaluating such differences, even when trying to consider subjective restrictions placed on the analysis, such as the need to consider ‘consecutive’ or ‘adjacent’ samples. Apparent variations of between 5 and 15 dB can be noted depending on the metric and/or the timescales chosen.

---

12 This time-weighting, using an exponential function with a constant of 125 ms = 1/8th of a second, is often considered representative of the response of the human hearing, although this may not be necessarily directly relevant to the present study in this sense.
The $L_{eq}$ metric in particular will be sensitive to very short-term energetically intense events, which may be averaged out using other metrics.

Further significant variation could still be obtained on a similar analysis if the signal was further filtered for particular frequency bands, depending on the composition of the signal, as also discussed in WPB1.

Figure 3 – Analysis of 20s of recorded audio data measured in a rural location in presence of wind turbine and bird noise (relative, non-calibrated levels) using a variety of short-term noise metrics

Short period measurement results can, in some cases, be usefully plotted out against time to graphically illustrate levels of AM (when present), although in practice only when there is a very clear and dominant contribution of the AM noise. With experience, it is possible in some cases to subjectively discern some patterns in the data which may be representative of different sources. This has led some [16] to suggest using such data to assess directly the character of the signal. However, as highlighted in the example of Figure 3, the process of trying to directly rate the modulation amplitude in this manner is too arbitrary, as picking peaks and troughs from all of those present is open to a degree of interpretation which is potentially too large to afford the method the required degree of objectivity and/or repeatability. Figure 3 is also an example of the potential for “false positives”, as other sources of environmental noise may lead to short-term variations in the measured noise levels which may be wrongly identified using this criteria, as shown in [15]. Perhaps most significantly, this type of method does not fully exploit the inherent characteristics of modulating wind turbine noise, as discussed below.

Other techniques which have been used in practice in similar contexts include:

- Comparing statistical metrics such as the difference between $L_{A10}$ and $L_{A0}$ when considering low-frequency tones [18]. Whilst such methods based on standard indices are easy to implement, and possibly effective in simple situations, the $L_{A10}$ index in particular is likely to become strongly influenced by extraneous noise sources.
- Comparing the difference between $L_{A0}$ and $L_{Aeq}$. A typical difference between $L_{A0}$ and $L_{Aeq}$ is described in ETSU-R-97 as being between 1.5 and 2.5dB for wind turbine noise (after excluding the influence of other sources). More recent experience has shown that this remains the case for modern turbines. As shown from the results of WPD, or even in the analysis of artificial stimuli derived as input to WPB(2) (see Table 22.1 of the WPB2 report), and perhaps contrary to informed intuition, this difference between $L_{Aeq}$ and $L_{A0}$ remains the case even for large modulation depths of up to 6dB(A) peak to trough.

---

Page 38 of 98
Defining the problem

Whilst the general question of analysing signal modulation is difficult, we know that the modulation of the aerodynamic noise produced by a wind turbine occurs at a set frequency which is determined by the blade passing frequency (BPF), which in turn is determined by the rotational rate of the rotor. For variable speed machines, the exact modulation frequency in question will vary to some extent depending on wind conditions, but generally not to a significant extent. Due to variations over time of the wind speed at any given turbine, or due to variations in wind speeds across a wind farm leading to different turbines simultaneously exhibiting different speeds, this variation may not be truly periodic but more likely “quasi-periodic”. However, this quasi-periodic character, with the basic frequency being set by the basic BPF of the turbines, means that the AM of WTN can usually be set apart from other sources of changing noise present in rural or urban environments but which don’t exhibit the same periodicity. This periodicity also allows the possibility for a model to be fitted to the data in order to rate the AM aspect of the noise more precisely.

Objective techniques

On the foregoing basis, WPB1 presents more refined signal analysis techniques which can determine more precisely the variations of particular features of a signal at a particular frequency. Importantly, WPB1 shows that the techniques presented represent the optimal way (in a precisely defined sense) of determining the modulation parameters in a measured acoustic signal.

- **The first method** assumes the basic signal being modulated is a white noise.
  - First a short-term envelope of the signal is obtained by squaring the signal and deriving energy averages over a short timescale (a Hilbert transform envelope technique produces similar results).
  - The Fourier transform of the envelope of the signal then provides a modulation spectrum

- **The second method** relaxes the assumption of white noise, allowing signals of more defined spectra (as will be the case in reality).
  - First, the signals are filtered in narrower frequency bands: this can be done through Fourier transform (narrowband analysis as in WPB1) or using 1/3 octave band filtering for example;
  - Another Fourier transform is then applied for each band in the time domain;
  - Finally the modulation spectra for results for all the different frequency band are summed up with a suitable weighting (such as A-weighting for example).

- **The third method** studied is more general in scope, in that it could detect a wider range of periodic signals. However, it was found in WPB1 to require a relatively high signal to noise ratio and is not discussed further.

Importantly, for improved analysis methods such as those described in WPB1, the analysis methods are much less sensitive to the resolution in time of the envelope data in terms of the returned levels, which was one of the issues noted for the naïve techniques described above based solely on consideration of variations in short term signal levels. The resolution of the more advanced methods would, however, affect the range of modulation frequencies which can be detected: to detect a modulation frequency of \( f_m \) requires data to be captured at a sampling frequency of at least \( 2 f_m \) (in accordance with sampling theory). For example, using a 100 ms time resolution (or 10Hz sampling rate) would allow modulation of up to 5 Hz to be detectable, whilst using 200 ms would decrease this to 2.5 Hz. However in both cases, the calculated modulation amplitude at 1Hz would be similar whereas, for example, the peak-trough variations in \( L_{eq,200ms} \) and \( L_{eq,100ms} \) shown in Figure 3 differ strongly.
Potential confusion

When considering this type of modulation analysis, it is important not to confuse audible frequencies and modulation frequencies. By performing a modulation analysis, the envelope of the signal (as opposed to the signal itself) is transformed from the time to the frequency domain, as in the example below. The resultant frequency spectrum reveals the modulation frequencies. For the example considered in Figure 4 the modulation frequencies is approximately 0.8 Hz, with harmonics at approximately 1.6 Hz and 2.4 Hz. Had the noise signal itself (as opposed to the envelope of this signal) have been transformed from the time to the frequency domain, the dominant audible frequencies would have been found to exist over a range more typically extending from 300 Hz to 1000 Hz (i.e. a factor of typically 100 or more times the modulation frequencies).

Normalisation and parameters

As discussed above, before considering subjective relationship and response to modulation at a certain level, it is crucial to consider how this level has been determined (method) and how the rating has been defined and scaled (normalisation), and also what inputs were considered (parameters). Despite the apparent theoretical simplicity of the subject for simple signals, and even some consistency in the overall methods, there is some variation in the latter two aspects in the literature.

For example, [19] uses the ratio of the stationary to the modulated components of the signal envelope as provided by a Fourier analysis (which is akin to the second, filter bank method referred to previously) to estimate a modulation factor based on the decibel peak-to-trough variation in the acoustic signal envelope.

In WPB1, the depth of modulation is initially defined as \(10 \log_{10}\) of the amplitude of the peak of the power spectral density obtained. WPB1 then describes a further normalisation to make the measure scale-invariant in which the data is scaled by a level corresponding to the mean of the quietest 25% of the signal as an approximation of the stationary part of the signal. The resulting amplitudes are, however, not intuitively intelligible.

Given the common use and consistency (albeit only when applied to signals dominated by AM) of the simpler peak to trough metric defined above, it may be considered more appropriate to design the AM detection algorithm so that it is normalised to provide identical values for well-defined, artificial signals for which the peak to trough values can be determined with precision.
It is important to consider the parameters for which the analysis is undertaken, in particular the duration of the data period blocks over which the modulation spectrum analysis is undertaken, as, in effect, the modulation depth represents an average over the time period of analysis. WPB1 proposes 10s as a practical example, but states that this will depend significantly on the stationarity of the modulation process, which is an indicator of how the amount of AM changes over time. A stimuli sample length of 20s was used for the stimuli of WPB2, which had a relatively constant modulation. Typical observed instances of intermittent modulation, shown for example in WPC, show variable levels of modulation over a scale a few seconds, and in some cases certainly less than 10 seconds. Intervals of less than 10 seconds would not provide enough data for a meaningful analysis.

Additional filtering

As explained in WPB1, given the nature of the signals encountered in the far-field of wind turbines, it can be useful to apply a low pass filter to the measured data prior to further envelope analysis. This will exclude most common bird call signals, as they are usually high-pitched sounds, and are most likely by their repetitive nature to corrupt the analysis of modulated signals in rural environments.

It is thus apparent that there exist a number of different facets of signal analysis that may come into play when determining the ‘optimal’ signal processing algorithm for the detection and objective quantification of AM. Whilst the various types of algorithm may be tested using both artificially generated AM signals, or real world signals containing high levels of AM, the performance of each algorithm is best judged against more typically encountered real world signals in which AM may well be immersed in a general ambient noise of a similar level to, or higher than, the AM itself. It is this application to real world data that is considered in the following section.

4.4 How does the theory for AM identification apply to real world data?

Whilst WPB1 provides an in-depth discussion of possible analysis tools for use in the investigation of AM, and in doing so highlights some of the pitfalls of adopting differing definitions of seemingly similar metrics, the test of any method designed for the automatic identification and objective quantification of AM must rely on its robustness when applied to real world data. Bearing this in mind, the techniques identified in WPB1 have been implemented as computer codes and tested on various data sets: this is detailed in Annex C of this report. The metric method used for this analysis will now be described.

A computer code implementing a signal envelope Fourier analysis technique in the MATLAB software was kindly provided by RES as part of their input into this project. This algorithm effectively represents an implementation of the first type of the methods described in WPB1, as it undertakes a frequency analysis of the acoustic signal envelope, using a Fast Fourier Technique (FFT), to produce a modulation spectrum. But if applied to the envelope of a narrower-band signal (such as 1/3 octave band data), it effectively becomes closer to the second type of method described in WPB1.

In this implementation:

- the signal is A-weighted;
- short term (1/8th or 1/10th of a second as in WPB1) LAeq energy averages are calculated from audio signals or directly provided as input;
- the envelope is separated into ‘blocks’ of a set length (typically 10s to 1 minute);
- the stationary component of the signal is removed using a de-trending technique;
- a power spectral density (PSD) of the envelope is calculated using standard windowing and fast-Fourier transform techniques;
- the PSD is normalised as $2\sqrt{2 \cdot PSD}$;
- the resulting spectrum is then integrated in the frequency domain using a moving average of width equal to 10% of the estimated likely modulating frequency;
- a local maximum or ‘peak’ in the integrated modulation spectrum can then be determined close to the modulation frequency (with a defined tolerance, typically +/- 0.4Hz);
The method therefore requires a likely estimate of the modulation frequency (BPF) to be provided as an input, in addition to the parameters discussed above. The output provided for each data block comprises:

- a modulation spectrum;
- the amplitude and frequency of the main peak in this spectrum (near BPF).

Annex C to this report presents detailed results of the analysis of the implementation of this routine to signals of increasing complexity, starting with simple signals, and progressing to the artificial stimuli used for WPB2 as well as actual recordings of modulated wind turbine noise collected as part of WPC.

The normalisation and integration process undertaken means, when applied to simple and well-defined artificial signals with a trivial modulation pattern, the amplitude provided in the spectrum at the modulation frequency matches the peak-to-trough modulation depth of the A-weighted signal envelope.

The analysis of Annex C also shows that, using this AM metric routine for more complex signals, the calculated amplitude of the peak\(^{14}\) of the modulation spectrum identified at the modulation frequency (as highlighted in blue on Figure 4) generally represents a useful and representative measure of the amount of modulation present in typical signals, which provides values which are consistent with subjective response and are similar to those used to date in the literature\(^{15}\). WPA2 has shown that the annoyance was not significantly related to the shape or duration of the signal, which suggests the effect of the higher harmonics\(^{16}\) was not significant in the response and the main peak amplitude is sufficiently representative.

Annex C or WPB2 (Figure 9.6) show that, for the test stimuli used in the listening tests, the resulting AM metric values are approximately 1dB lower than those obtained from estimated peak-to-trough variations in A-weighted levels. The use of frequency filtering allows spurious sources to be excluded in most cases, and results in marginally more elevated values (close to the estimated peak-to-trough values).

This code will therefore be designated as the main 'AM metric routine' throughout the rest of this report for clarity, although it must be stressed that based on the review of the literature undertaken, there is currently no standard or generally accepted implementation of such metrics.

**Modulation analysis - practical considerations**

It is important, in the context of this project, to consider current practice in the environmental field measurement of wind farm noise immissions.

Planning requirements for most wind turbines in the UK follow the guidance of the ETSU-R-97 report [3], and measurements of noise levels are made at noise-sensitive properties on the basis of overall statistical indices over 10minute periods (L\(_{90}\) in particular). The measurement of the shorter-term variations in noise levels is therefore not directly required, and would in general not be stored by many integrating sound levels meters which will only record these time-averaged metrics.

As the criteria on overall noise levels relate to A-weighted values, more detailed frequency information (such as octave-band or third-octave band data) is generally not collected or stored.

Audio records are also not directly needed for the analysis of overall noise levels or even to exclude spurious periods which could have been affected by anomalous sources of noise, as the analysis of the time history of noise levels or their relation to wind speeds is generally sufficient. However, the requirement to undertake tonal analysis will require audio samples at regular intervals, in order to collect representative recordings in a range of operating conditions. It is then general practice to collect 2 minute

---

\(^{14}\) Local maximum in the modulation spectra.

\(^{15}\) Normalisation of the output results is not an essential step. Rather, it is undertaken to produce output results for which the value at the modulation frequency is similar in level to the peak to trough difference seen in the original signal when that envelope is created using a time average of approximately 100 ms. In this sense the output results are easier to interpret on a physical basis. It should be noted, however, that for real world (time variant) signals, the output results will never match up exactly to the peak to trough level difference in each sample, even with such normalisation, as the peak to trough difference will vary with each modulation. Instead the method will provide an averaged measure of the peak to trough level differences across the sample. What is important is that, whatever normalisation process is adopted, it must be consistently carried through to all aspects of the analysis including any attempts to relate the metric to subjective response. The comparison of results obtained either using different analysis methods, or using different normalisation processes for the same analysis method, would not be meaningful.

\(^{16}\) Peaks in the modulation spectrum which are found at integer multiples of the modulating frequency: see Fig 4b).
samples, as required by the method of ETSU-R-97, which can be done at regular 10-minute or hourly
intervals.

Storage and power requirements to record detailed frequency or audio information are considerable,
particularly when considering measurements made over periods of several weeks typical of wind turbine
immersion measurements (due to the need to capture a range of wind conditions). For example,
continuous recording of A-weighted and 1/3 octave band at a 10Hz sampling rate, and period recording
(recorded nearly continuously, i.e. for 80% of the time) of uncompressed audio at a 25.6kHz sampling
frequency (therefore effectively capturing the frequency range of 0-10kHz), may require more than
800 Mb storage for 3 hours of recording. 99% of this size was taken by the audio data. This represents
considerable practical and logistical difficulties, in addition to the significant costs involved.

The latest developments in the capabilities of noise measurement equipment have made this more
accessible, as power and processing capabilities continue to improve. This type of complete and detailed
measurement is nevertheless considered challenging and may not be easily undertaken by most
consultants or local authorities.

Recording audio data therefore involves considerable difficulties, but the lack of this data limits the range
of post-processing that can be undertaken on the data, such as filtering out spurious noises (which is not
possible if only A-weighted levels are recorded). For the study of wind turbine noise however, relatively
low sampling frequencies may be sufficient as, for example, a 4 kHz sampling rate would capture with
reasonable accuracy audio frequencies of up to 2 kHz.

WPB1 describes filter bank methods, which are based on an analysis over a range of narrowly filtered
bands of data. The application of the first type of method in WPB1 to a single 1/3 octave-band represents
a simple example of such a filter bank method. But when considering the analysis of different WPC
samples which is undertaken in Appendix B, it can be observed that the analysis of the short-term
evolution of the variations in certain 1/3 octave bands can be sufficient to characterise the modulation in
many circumstances. This approach is also shown to be implemented with a good success in WPD to
large sets of data. It is then seen that this provides an efficient way of eliminating several types of
spurious types of sources such as bird or wind noise, without the need to record further detailed audio
information.

Compared to acquiring audio data, octave band data is more difficult to interpret subjectively when trying
to evaluate the character of the noise environment being analysed. To this end, it may be useful to also
acquire shorter term samples audio data on a periodic basis throughout any measurement campaign (as
is done for the narrow-band, tonal analysis in which 2 minutes of audio data is required to be recorded for
every 10 minute period).

It may also be useful to investigate in further detail the application of such filter techniques to multiple 1/3
octave band simultaneously, which would allow this full frequency information to be used meaningfully,
along the lines discussed in WPB1. However, it is thought that this may provide relatively limited
advantages compared to the consideration of a single, well-chosen band which is representative of
dominant modulation frequencies, provided the latter can be determined (as shown was possible through
the results presented in WPD).

The expected modulation frequency would in practice be relatively well known, as it will be determined by
the blade passing frequency. This can therefore represent an input to the analysis of modulation. For a
typical three-bladed turbine rotating at R rotation per minute (RPM), \( f_m = \frac{3R}{60} \). For variable speed
machines, as is the case for most modern turbines at present, the main shaft rotational speed of the
turbine will usually be recorded by the turbine SCADA control system, and this could therefore inform the
variation in \( f_m \) with time. The range of variation may not however be very significant in practical terms. For example, for a typical large turbine with a rotation rate varying between 10 and 17 rpm over its typical
operating range, this would represent a variation between 0.5 and 0.8Hz. Knowing the expected range of
modulation frequencies may be sufficient to identify modulation likely to be associated with the turbine.
Again, WPD shows an example of how this can be applied in practice to provide more certainty to the
analysis.

WPB1 did not consider in detail metrics such as fluctuation strength [7], which are based on
psychoacoustic models, but these were considered in WPB2. However the practical implementation of
such methods is subject to considerable difficulties, particularly in the presence of complex realistic
signals (rather than test stimuli), and would in practice rely on specific software implementation of such
methods which often depend on specific models of loudness and simplifying assumptions to some extent.
4.5 What is the subjective impact of AM?

WPB2 identifies the difficulties arising with characterising AM, and the lack of sufficient knowledge in the literature about listener response to its characteristic physical properties. The scope and also the potential limitations of the exercise undertaken are summarised in the following table. Bearing in mind that practical considerations will always result in some limitations of any such exercise, the important consideration here is that any conclusions drawn from the results do not stray outside the bounds of what can reasonably be concluded within the identified limitations.

<table>
<thead>
<tr>
<th>FEATURE</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use of synthesised AM samples</td>
<td>Necessary as control required over signal parameters, and removal of variability of real world signals and extraneous noise</td>
</tr>
<tr>
<td>Use of short term samples each with fixed (i.e. non-variable) AM effects</td>
<td>Although the level of AM is known to be highly variable and intermittent, it was not practicable to assess these effects in a laboratory setting</td>
</tr>
<tr>
<td>Considering external noise environments only</td>
<td>Based on previous experience, simulating internal levels cannot be done conclusively and involves significant difficulties regarding the necessary assumptions concerning outside to inside sound transmission and the resultant low signal levels. There would also be limited relevance to the current practice of assessing free-field levels from wind turbines.</td>
</tr>
<tr>
<td>Use of headphones in the sensitivity measurements</td>
<td>Done to assess relative impact of different parameters to restrict test size as opposed to directly rating AM noise</td>
</tr>
<tr>
<td>Seemingly arbitrary choice of objective metric against which to assess the subjective test results</td>
<td>A simplistic metric was chosen as a starting point to help design the stimuli, and then all results were subsequently evaluated over a wide range of objective metrics</td>
</tr>
<tr>
<td>High scatter in test results</td>
<td>Seen as inevitable when testing affective responses such as annoyance, but needs to be taken into account when interpreting significance of results</td>
</tr>
<tr>
<td>Limited sample size</td>
<td>It might be useful to extend the sample size, but this has been considered unlikely to fundamentally change the outcome results</td>
</tr>
<tr>
<td>Use of ‘Direct Annoyance Rating’ based on subjects relaxing at home in their garden</td>
<td>Very difficult to ascertain true annoyance unless subjects actually exposed to the noise at their own homes, but equally difficult to consider an alternative in a laboratory environment given overall aims of the study, which is to provide comparative results.</td>
</tr>
<tr>
<td>Use of ‘Paired Comparison’</td>
<td>Following from above point: this allows more direct measure of a modulated signal compared to a similar level of un-modulated noise, without relying on an arbitrary absolute rating of annoyance in a non-home environment</td>
</tr>
<tr>
<td>Comparison between ‘Direct Annoyance Rating’ and ‘Paired Comparison’ results</td>
<td>Care needs to be exercised with any such comparison due to the dominant effect of increases in overall noise level over and above the effect of increased modulation depth (which had little statistical significance)</td>
</tr>
</tbody>
</table>

The first objective of Work Package B2 was to test whether the AM metrics developed in Work Package B1 would provide a meaningful measure of AM ‘value’ that correlates with subjective annoyance ratings. The second objective was to quantitatively investigate the relationship between the AM value and a measure of average annoyance in the form of a dose-response relation.

Key to obtaining representative results was the design of stimuli which were representative of the spectrum and character of actual noise experienced by wind farm neighbours exposed to AM. Extensive work was done to obtain this. Based on input from WPC, test signals were synthesised for a characteristic...
WIND TURBINE AMPLITUDE MODULATION: RESEARCH TO IMPROVE UNDERSTANDING AS TO ITS CAUSE & EFFECT

Collation of Work Package Reports and Final Reporting

range of wind turbine sounds, with a wide range of input parameters. This model is described in an annex to WPB1. The model consisted of "pulses" of modulation overwritten on a constant "masking noise" which determined the effective modulation depth. It was the general consensus of the project team that the artificial stimuli obtained were representative of AM experienced in the field, as collated under WPC.

In a first phase, sensitivity tests were undertaken to find the AM parameters that listener response was most sensitive to. A total of 80 test sounds, each of at least 20 second duration, were presented via calibrated headphones in a quiet room and 11 volunteers were asked to score the annoyance on a numeric 11 point scale. The outdoor sounds included test wind turbine noise at typical levels, with varying AM characteristics and some natural background noise.

Using the results of the sensitivity tests, a sub-set of samples was selected to cover those variables having the greatest impact on subjective response. A final set of tests was then undertaken in a quiet listening room with a sound reproduction that mimicked the outdoor directivity of one wind turbine in the distance. A total of 34 test sounds were generated and presented to 20 participants. Two validation tests, containing another 158 and 34 test sounds respectively, were also conducted to clarify results from the headphone based sensitivity tests in the better-controlled listening room. Participants rated annoyance directly as before, but were additionally requested to adjust an un-modulated test sound in level such that they judged it equally annoying as the modulated test sound.

The sensitivity tests showed, in line with previous literature, that annoyance crucially depended on the overall A-weighted level of the test sound, as measured in \( L_{Aeq} \), and to a lesser extent on modulation depth, which is a measure of the modulation strength. It was shown that the response to the noise was not significantly affected by the modulation waveform. Modulation depth was shown to be also best expressed in terms of A-weighting to give consistent results, as initial differences in the response to different types of spectra was found to be explain by increased overall dB(A) levels. The use of \( L_{A90} \) as an alternative to \( L_{Aeq} \) produced similar results at the low and medium modulation depths most often observed from wind turbines, as the difference between \( L_{Aeq} \) and \( L_{A90} \) was comparable for most stimuli below modulation depths of about 9dB(A).

In the final test there were three sets of test sounds that were played back with constant \( L_{Aeq} \) of 30, 35, and 40 dB(A). For each of these sets the modulation depth was systematically varied from 0 to 12 dB(A) in increasing steps. After taking into account the effect of \( L_{Aeq} \), which was found to always dominate the annoyance rating, the modulation depth was found to increase the annoyance rating slightly, but consistently. However, the effect was not statistically significant because there was a large spread of ratings. See Figure 5 for an example representation of these results.

The above suggests that, given a large enough group of participants, it could possibly be shown that annoyance increases slightly but consistently (monotonically) with modulation depth. In contrast, the \( L_{Aeq} \) level of the adjusted un-modulated wind turbine noise remained broadly constant as the modulation depth increased above about 3 dB(A). This answered the question of how much louder would an equivalent un-modulated sound have to be to be equally annoying to a modulated sound. The adjustments were on average 1.7 dB(A) for a 40 dB(A) test sound and 3.5 dB(A) at 30 dB(A). Validation tests at two additional levels of 45 dB(A) and 25 dB(A) confirmed this trend. See Figure 6 for an example representation of these results.

A clear onset of annoyance at a particular modulation depth was not found for either of the two rating methods.

When levels were measured as \( L_{A90} \), results suggest that annoyance ratings were similar for modulation depths of up to 6 dB(A) and generally increased with both modulation depth and \( L_{A90} \). Because results for sets of stimuli with constant \( L_{A90} \) and changing modulation depth are not available simple average adjustments cannot be identified and further work would be necessary.
WIND TURBINE AMPLITUDE MODULATION: RESEARCH TO IMPROVE UNDERSTANDING AS TO ITS CAUSE & EFFECT

Collation of Work Package Reports and Final Reporting

Figure 5 - Mean annoyance rating of AM test stimuli as a function of estimated modulation depth. Solid lines are results from final test, dotted lines from the validation tests with reduced participant numbers.

Figure 6 - Levels of adjusted un-modulated noise in comparison to AM stimuli level, as a function of estimated modulation depth – Solid lines are results from final test, dotted lines from the validation tests with reduced participant numbers. The legend specifies the $L_{Aeq}$ of the test stimuli in dB(A).

In a validation test with a subgroup of 11 participants, the spectral characteristics of the test sound were changed to represent Mid-Frequency AM, often described as ‘swish’, as opposed to Reduced Frequency AM which is sometimes described as a ‘swoosh’ or ‘whoomp’. Also, a limited amount of garden noise was added at a low level to change the character of the sound for both types of AM sounds. For all four groups the results for both absolute annoyance ratings and un-modulated level adjustments appeared very similar. This suggests that the relative effect on annoyance is small as long as the garden noise does not reduce the audibility of the modulated sound.

In a last step the annoyance ratings were compared for 6 different metrics, four of them based on different physical definitions of modulation depth and two using the perceptive measure of fluctuation strength [7]. Given the low sensitivity of the response to modulation depth, the comparison showed that the main effect of the physical metric is to change the range of modulation depths. The same stimuli

---

17 The term ‘garden noise’ is used here to describe a typical ambient noise expected to be experienced in a rural outdoor environment due to the natural sound of the wind blowing through the trees. The use of the more usually encountered terminology of ‘masking noise’ is avoided as, for the purpose of WPB2 in which the feature under investigation was the modulating component of wind turbine noise, ‘masking noise’ included both ‘garden noise’ and the steady component of wind turbine aerodynamic noise.
would have a range of 0 – 12 dB(A) modulation depth in one metric but 4 – 32 dB in another metric: this highlights the importance of relating any specific response to measured AM levels in a consistent way. Fluctuation strength results showed an improved correlation with listener response, accounting to some extent for the overall level of the noise, but, as noted above, these psychoacoustic methods are difficult to apply in practice to realistic field data. As noted above, even a perception-based metric can never fully account for contextual and attitudinal aspects of annoyance rating, and the result of survey studies should be considered in parallel.

The effect of factors such as the frequency of occurrence of OAM ‘events’ and their duration not addressed in the current research. The project team’s view is that the significance of these factors would have to be assessed using professional judgment and experience and that it would not be practicable to assess them via further subjective testing.

4.6 What are the characteristics of OAM when measured

In the light of the results of WPD as well as Annex C of this report, it should be borne in mind that: even a carefully filtered and scrutinised analysis of a real measured dataset in a typical rural environment, using the main type of AM metric routine considered in this work (defined above in 4.4), will produce values of the AM rating metric of up to 2 dB (with a limited amount of sporadically higher values), even in the absence of any significant modulation. This is mainly due to residual noise, uncertainties associated with digital processing and the integration process used.

The presence of OAM was able to be detected and rated effectively using the main AM routine described above (see Figure 7 for example). Perhaps counter-intuitively, it is remarkable that, even in periods of marked modulation, the difference between the measured $L_{A_{eq}}$ and $L_{A_{90}}$ metrics remained typical of that expected from wind turbine noise, at between 1.5 and 2.5 dB.

Figure 7 – Evolution over a period of 3 hours of the calculated modulation spectrum based on the 315Hz 1/3 octave band (for contiguous 10s data blocks) at site A, location 1

Based on the different measurement results, and particularly those at Site B, it has been concluded that the general characteristics of OAM noise are consistent with the expected directivity and spectral characteristics of transitory stall noise (as derived in WPA1). Indeed, in the far-field, instances of clear OAM were enhanced in the downwind direction and reduced in the cross-wind direction. Observations in which OAM was discernible in the far field of wind turbines but not simultaneously in the mid- or near-field suggest that AM may be strongly influenced or exacerbated by noise propagation effects (such as ground effects).
At site A, the presence of OAM was clearly established during conditions in which the surveyed locations were downwind of the turbines (see Figure 7 above), whereas for another period in which the location was upwind, no significant levels were detected, which matched subjective reports from one of the residents.

The effects in the near-field were more difficult to discern, although the expected presence of NAM was clearly characterised by higher modulation depths of up to 5 dB in the cross-wind direction, as illustrated in Figure 8 below, which is consistent with the standard AM model [6].

**Figure 8 – WPD, site B: time history of measured $L_{Aeq,100ms}$ levels for a sample period showing: two far-field (downwind and cross-wind) and two near-field locations (cross- and down-wind)**

The magnitude of OAM rating levels in the far-field were strongly variable and did not seem to be simply associated with the existence of certain meteorological conditions. In terms of the various hypotheses that have historically been as possible causal mechanisms for other AM, whilst the results could not generally rule out any of these as potential contributory factors, they did confirm the ability of OAM to exist in situations where the factors are known not to contribute. In summary, significant OAM was positively identified under conditions of:

- low wind shear (see Figure 9 for example);
- low wind veer;
- uniform turbulence;
- single operational turbines (i.e. no interaction effects);
- on both flat and hilly sites;
- turbines with high tower to rotor diameter ratios.

The only positively identified association between the occurrence of OAM and the operational characteristics of the turbines, in the detailed measurements undertaken at site B of WPD, was that OAM only occurred when active power generation was occurring, and it also appeared to be sometimes exacerbated during periods when changes in the estimated relative angle of attack of the blades also occurred.
Figure 9 – Time history of the AM rating for a sample period at site B, in parallel the changes in wind profile at different heights.

Other source mechanisms may be at play. It is conceivable that particular blade designs could experience partial blade stall in certain conditions without the influence of non-uniform inflow conditions to trigger it. For example, aero-elasticity effects may vary the blade geometry in such a way that it departs significantly from its design conditions. There is, however, very limited information available to study this in the current state of knowledge.

HLA has also seen some evidence of measurements undertaken at another site (not reported in WPD), in which periods of OAM were associated with night-time periods in which extremely high values of wind shear were regularly experienced, which suggests it could be a contributory factor in some cases, but the above considerations show this is not generally necessary or sufficient and may therefore be site-specific.

It is also the case that, on some sites, the impact of wind shear on effective modulation may be more important at (non-sheltered) residential location surrounded by vegetation. This is because increased wind shear will correspond to relatively reduced wind near the ground, and this will have an effect on the level of masking background noise which may otherwise reduce the effective modulation depth.

In conclusion to this question, the definitive answer as to what causes OAM remains elusive. What has been proven, however, is that many of the causal factors previously claimed to be indicators of an increased likelihood of OAM are not, in their own right, sufficient to trigger the effect. The observed far-field OAM directivity pattern was also shown to be consistent with predictions of the effect of transitory blade stall.

It has additionally been noted that, for the purpose of the present project, NAM and OAM have been defined in the context of different source generation mechanisms. This is a potentially convenient differentiator. However, the possible contribution of noise propagation effects to the AM experienced at far field receptor locations represents a complicating factor in this analysis. In particular, it has been observed that OAM may be discernible at typical residential locations in the far field of wind turbines whilst not being easily determined in the near field of those turbines; although this is consistent with the theory of WPA1, this must be borne in mind when considering an attractive, but perhaps over-simplistic, definition based on source effects only.
4.7 Can OAM be predicted?

As discussed above, a variety of causal factors have been hypothesised by various acoustics practitioners as potential causal factors for OAM. In light of the available evidence, and the theoretical consideration summarised in the appendix to WPA2, as supplemented by the results of WPD, the main factors are considered in the following table 2.

<table>
<thead>
<tr>
<th>Cause raised</th>
<th>Significance</th>
<th>Evidence and factors</th>
</tr>
</thead>
</table>
| High wind shear: stable atmospheric conditions or presence of ground obstacles such as vegetation | Low-medium   | • Large variety of sites with different shear characteristics in which OAM was still experienced; for example: presence of OAM in hilly sites with low shear conditions.  
• May cause transitory stall in some conditions.  
• Weak/negative correlation evidence in WPD.  
• But increase of signal to noise ratio in high wind shear conditions may increase OAM perception if present. |
| Complex flow/turbulence (large-scale)            | Low/medium   | • Presence of OAM in flat sites with high wind shear conditions (low turbulence).  
• Large non-uniformity of turbulence required in theory, or large-scale turbulence triggering stall.  
• High variability of AM in time would be consistent with turbulence variations, but sustained periods of OAM sometimes observed are clearly not.  
• May cause transitory stall in some conditions.  
• Weak/negative correlation evidence in WPD. |
| Interaction between turbines / linear arrangements | Low          | • Presence of OAM with single turbine operation as shown in WPD and [11].  
• Theoretical considerations and presence of OAM with single turbine operation as shown in WPD and [11]. |
| Synchronisation between turbines                  | Low          | • Weak/negative correlation evidence in WPD.  
• See high wind shear above as both are often related. |
| Yaw error or wind veer                            | Low          | • Turbines at one of the sites in WPC were stall-regulated (DTI HMP study [2], site 2).  
• Pitch-regulated turbines present in many of the OAM cases considered, but these are generally more prevalent today in any case. |
| Power regulation (pitch or stall regulated)       | Unclear      | • Turbines at one of the sites in WPC were stall-regulated (DTI HMP study [2], site 2).  
• Pitch-regulated turbines present in many of the OAM cases considered, but these are generally more prevalent today in any case. |
| Non-uniform inflow                                | Unclear      | • Likely to be strongly related to incidence of stall.  
• Some correlation shown in WPD with periods of high power and variations of angle of attack. |
| Angle of attack                                   | Medium/High  | • Likely to be strongly related to incidence of stall.  
• Some correlation shown in WPD with periods of high power and variations of angle of attack. |
| Ground interference, atmospheric attenuation      | Low          | • Little AM effect in theory, present at all sites.  
• Some evidence in WPD suggested ground interference reduced modulation peaks in some conditions. |
| Background noise masking                          | Medium       | • Will limit the modulation depth at large distances. |
| Temperature gradients                             | Low          | • Likely to be limited except in calm conditions. |
| Aero-elastic effects                              | Unclear      | • May trigger stall, but complex and little evidence. |

Table 2 – OAM causal factors and review of evidence

Several of the potential causal factors which have been suggested were shown through the present project to have little or no association to the occurrence of OAM. However some of these factors may represent potential contributory factors. It is not therefore possible to be prescriptive as to whether any particular site is more or less likely to give rise to OAM being generated at source. This is considered likely to be due to a combination of site and installation specific factors.
WIND TURBINE AMPLITUDE MODULATION: RESEARCH TO IMPROVE UNDERSTANDING AS TO ITS CAUSE & EFFECT

Collation of Work Package Reports and Final Reporting

It is only where background noise at noise sensitive receptor locations is high enough under all circumstances to effectively mask any potential OAM noise that it can be positively concluded that the chances of OAM causing problematic noise issues are reduced.

4.8 Can OAM be suitably mitigated?

It would be desirable to develop OAM mitigation measures based solely on the operational characteristics of the affected turbines (i.e. modifications to the turbine control systems, and in particular the blade pitch control systems) as opposed to physical modifications to the turbines themselves or operational curtailment of turbines.

Partial blade stall has been identified as a key potential causal factor in the occurrence of OAM. The effective angle of attack of the flow on the blades in theory represents a key parameter affecting the likelihood of this occurring. The results of WPD have also shown that this variable sometimes demonstrated a correlation with clear instances of OAM, although the overall picture was relatively complex. As noted previously, additional work may usefully identify the exact on-blade conditions in more detail using further investigative measurements which were outside of the scope of the current study.

For modern variable speed, pitch-regulated turbines, the turbine’s control system will change its operating parameters to vary the pitch and rotational speed as a function of different observed parameters. Detailed information on this process will often be proprietary and subject to commercial confidentiality considerations. It was speculated during the progress of the project that certain power regulation control approaches for pitch-regulated turbines may result in a greater effective ‘stall margin’, by which is meant a greater difference between the actual angle of attack and the angle of attack corresponding to full blade stall, as this may conceivably reduce the likelihood of partial blade stall occurring.

Given the current state of knowledge in the field, the Annex of WPD presents indicative analysis techniques which may assist in evaluating the changes in relative angle of attack on the blades, from an analysis of long-term data provided by the turbine SCADA system. Although based on considerable simplifications, and the general need for the analyses to be based on coarse 10-minute resolution SCADA data, the general approach may enable key operational conditions to be identified which are more conducive to blade stall. The identification of any such operational conditions could assist in the development of modifications to the turbine’s operational characteristics in collaboration with turbine manufacturers which could positively mitigate against the occurrence of blade stall.

However, the project team are not aware of a situation where this potential method of mitigation has been applied successfully. Evidence has been seen from one site where OAM was being experienced at several locations. At this site, alternative power regulation modes of the pitch-regulated turbine installed were designed to minimise the incidence of potential stall from a turbine, by reducing the relative angle of attack experienced by the turbine in certain conditions identified (based on similar techniques to those of the Annex of WPD). Some initial results suggested that the measures implemented in this regard were not sufficient to fully mitigate the incidence of OAM, and further work in this regard was required.

In some situations, the use of serrated edges on blades has led to a significant reduction in the noise emission from some turbines without the associated reduction of power generation generally obtained with reductions in blade rotational speed. This is because this reduces the radiating efficiency of the trailing edge of the turbine [see Ref. 9, chapter 2]. This type of measure is, however, not considered likely to affect the radiation of stall noise from the blades, which tends to occur at other parts of the blade.

Standard ‘reduced noise modes’ are commonly used to reduce the levels of overall A-weighted noise produced by many modern turbines. These are often based on reducing the rotational speed of the turbines (and therefore the tip speed). Given the foregoing discussion, there is also no evidence or theoretical grounds suggesting that the use of such modes would affect OAM. In fact, the use of reduced noise modes may even be counter-productive as a reduction in rotational speed could increase the effective angle of attack of the flow.

There is, therefore, currently no clear case history of successful mitigation of OAM noise, except through curtailment of turbine operation in the specific conditions in which it is encountered in the far-field, which can in some case only cover a restricted range of wind speeds and/or wind directions. Given the impact

18 Supervisory Control And Data Acquisition system, generally installed on wind farms to control and monitor the operation of all turbines.
this can have on power production, it is strongly recommended that additional research is undertaken to identify clear and efficient mitigation strategies that minimise or eliminate the generation of OAM whilst retaining the power generation capacity of the wind farm.

This would require the future involvement and close cooperation of wind turbine manufacturers, and possibly involve detailed measurements that focus on better understanding the surface pressure distributions on the turbine blades themselves, particularly as the stall point is approached. Additional research would then result in methods for avoiding local stall conditions. The Annex of WPD presents some simple calculation methods which have been identified as likely to assist in identifying the most likely relevant conditions likely to lead to stall, based on an analysis of standard turbine operational data.

Such methods may involve software ‘fixes’ that seek to modify the logic of the control system algorithms, perhaps even through the application of more advanced cyclical pitch control, and therefore a limited impact on the operation of the turbine. More fundamental, physical design changes may also prove worthwhile, such as innovative blade designs or the addition of blade vortex generators, for example, as the latter may delay the onset of stall. More advanced numerical modelling, such as for example extending the model of WPA1 but including propagation effects, may also provide further insight.
5.0 CONCLUSIONS

It is an inherent feature of wind turbines that they generate noise when their blades rotate. This is caused by the interaction of the blades with turbulence in the flow and is therefore called ‘aerodynamic noise’. The dominant self-noise mechanism when dealing with an A-weighted spectrum of wind turbine noise is so-called trailing-edge noise.

For a listener located on the ground in the vicinity of a wind turbine, the rotation of a turbine’s blades results in this aerodynamic trailing edge noise going up and down in loudness in a regular manner. These peaks and troughs in the noise will therefore occur regularly and their occurrence is related to the rate at which the blades pass by the listener.

This regular variation in the trailing edge noise is termed the ‘Amplitude Modulation’ of aerodynamic noise, or AM for short. This type of AM has been fully characterised through both theory and measurement. It is an inherent feature of wind turbine noise and has long been recognised as such. For this reason this type of AM has been termed in the present work as ‘normal’ AM, or NAM for short.

Due to the directional radiation characteristics of trailing edge noise, the difference between the peaks and troughs in NAM noise is greatest in the plane of rotation of the turbine, i.e. in a cross-wind direction. The same directional radiation characteristics mean that, in comparison, little temporal variation in the loudness of the trailing edge noise is experienced when the listener is located upwind or downwind of a turbine, particularly as the distance from the turbine increases beyond a few rotor diameters. Based on theoretical models and experience to date, NAM would not be expected to be apparent (except at insignificant levels) downwind/upwind of ‘far-field’ locations typical of wind farm residential neighbours.

However, in some circumstances the character and spatial distribution of the AM has been observed to alter from that known to result from NAM. Differences include a general shift to lower frequencies of the dominant noise spectrum, even on an A-weighted basis, and an increase in modulation depth, in particular with significant levels of amplitude modulation occurring in the far-field downwind (and sometimes even upwind) of the wind turbine.

The foregoing characteristics cannot be explained by current models of NAM. For this reason, the occurrence of any type of AM that falls outside the known characteristics of NAM is identified in the present work as ‘other’ AM, or OAM for short. Thus the definitions of NAM and OAM adopted for the project were based on consideration of the physical source generation mechanisms alone: NAM was defined as that element of AM which was capable of being fully described in terms of ‘standard’ models of trailing edge noise, whilst OAM was defined as being any form of AM lying outside this definition of NAM.

The occurrence of OAM has been cited in a number of complaints concerning noise from wind farms as being the prime cause for complaint. At the time of commissioning of the present project, little was known about OAM. Despite a limited number of reported observations, OAM has formed the subject of an increasing number of papers and publications over the past five or so years. However, whilst adding to the body of evidence relating to the existence of OAM, most such reports were either anecdotal or involved measurements at far-field locations. Little or no supporting information was generally available concerning the noise at the turbine(s), nor the local operating conditions of the turbine(s). Discussions on potential causal factors have been mainly speculative.

Since the causal mechanisms have not been understood to date, no specific information has been available to guide operators towards the likelihood of occurrence of OAM or remedial actions which may be required. Furthermore, where OAM is known to occur, there has been no universally accepted means of measuring its magnitude or determining whether complaints from neighbours are justified. The aim of the present project was, therefore, to investigate AM and in particular OAM further.
How does OAM differ from NAM?

Work undertaken by others prior to the present project has successfully demonstrated, both theoretically and experimentally, that the key acoustic characteristics of NAM (otherwise often referred to as ‘blade swish’) for modern, large scale wind turbines may be summarised as follows:

- characterised by an audible and regular variation in sound pressure level (i.e. an amplitude modulation of the noise);
- the frequency of the amplitude modulation is equal to the rotational rate of the turbine multiplied by the number of blades, which is otherwise termed the ‘blade passing frequency’;
- the typical frequency of the amplitude modulation for modern, large scale, variable speed wind turbines lies in the range 0.5 Hz to 1 Hz;
- the maximum ‘modulation depth’ (i.e. the variation in sound pressure level) exhibited is up to approximately 5 dB when considering the overall A-weighted noise level;
- the maximum modulation depth occurs in the 400 – 1000 Hz range;
- the depth of the amplitude modulation is most pronounced in the near to mid-field of the turbine (i.e. within a few rotor diameters) in cross-wind directions;
- the overall level of aerodynamic noise radiated from a wind turbine is at a minimum in the cross-wind direction (i.e. in the plane of the rotors) meaning that the maximum depth of the amplitude modulation (beyond a few rotor diameters) occur coincident with the lowest overall levels of noise;
- the amplitude modulation reduces significantly with distance, especially in the downwind or upwind directions, and is negligible in the mid- to far-field when the observer is close to the axis of the turbine (i.e. directly upwind or downwind);

Through the definition adopted for the present project OAM is, by default, any amplitude modulation that does not fit with the foregoing description. However, as a starting point for the project investigation, an analysis of available (often anecdotal) information indicated that OAM could be characterised by one or more of the following features:

- the modulation depth (the difference between the levels of adjacent peaks and troughs in the noise signal) can be significantly greater than that of normal blade swish, with differences in level of up to 6 to 10 dB having been measured, and subjective descriptions of “impulsivity”;
- the effect is generally strongest in the downwind direction and has also been reported (less frequently) in the upwind direction of turbines, but it has not been recorded in the cross wind direction in which normal blade swish is most prevalent;
- the dominant frequency characteristics are sometimes lower than for normal blade swish, with a shift in the dominant frequency range to typically around 400 Hz;
- the effect is more dominant in the far field (typically 10 rotor diameters or more from the turbine) and may not even be simultaneously discernible in the near field (typically less than 3 rotor diameters) of the turbines;

What causes OAM?

In terms of addressing the possible causes of OAM, in the first instance it was considered helpful to collate available reports of its occurrence from as many different sources as possible (wind farm operators, windfarm neighbours, researchers, internet published information, etc.). The results of this exercise (WPC) lead to the following observations:
the effect has only been reported on a limited number of wind farm installations;
even on those sites where the effect has been positively identified to occur, it is intermittent;
the effect may occur for just a few rotations of the blade, or it may persist for periods of several minutes or hours;
the effect is not restricted to an individual turbine type;
the effect has been reported both for individual turbines and for wind farm arrays;
a particular turbine type that exhibits the effect on one wind farm site will not necessarily exhibit the effect on another site;
the effect has been reported to be most common during evening and night time periods, although it has been identified during some day-time periods;
the effect has been reported near wind turbine installations on both flat and hilly terrain;
the effect has frequently been associated with conditions when wind shear may be expected to be high, but has also been reported to occur on some sites during damp conditions of light or even heavy rain when wind shear may be expected to be low.

If any one factor or combination of factors were responsible, then the effect would occur at all sites featuring those factors and it would occur frequently at those sites. Neither of these situations was observed to be the case in practice. In summary, therefore:

- NAM is an inherent feature of all wind turbines and can be fully explained as a consequence of the rotation of the wind turbine blades;
- OAM is not a common feature of all wind farms and, even for those wind turbines and wind farms where its occurrence has been reported, it is an intermittent and atypical feature.

The project team was therefore unable, based on the available information, to identify a single causal factor giving rise to OAM. It was therefore decided to focus on the identification of possible source mechanisms that could give rise to the observed acoustical characteristics of OAM, where these differ from those of NAM, and most notably in terms of their lower frequency content and different directivity characteristics.

The theoretical study undertaken in WPA2 identified two potential source mechanisms as being either high levels of inflow turbulence or stalled flow over part of the blade. However, the same analysis concluded that a key additional condition being necessary for high levels of OAM to occur in the far-field downwind was that the flow into the rotor would have to be non-uniform in order to result in the observed cyclical variations.

Possible causes of non-uniform flow into the rotor disc include:

- the wind profile being non-uniform, for example due to a vertical or lateral variation in wind speed or a spatial variation of the angle of the wind onto the rotor, where high wind shear or local wind gusts could provide the conditions for this to happen;
- the turbulence entering the rotor disk being non-uniform due to upwind obstructions or meteorological conditions, thus causing time-varying levels of inflow turbulence noise as each blade enters the region of high turbulence.

However, some of these factors are almost always present, for example variations in wind speed with height above the ground (vertical wind shear). Following the line of the first of these two potential causes of OAM, one plausible explanation was that a combination of environmental and turbine operational factors may come together to result in the airflow over small regions of blade becoming ‘detached’ from...
the blade surface and then quickly ‘re-attached’ such that the blade goes into ‘transitory stall’ in the affected regions.

A theoretical model was developed in WPA1 for the radiation of transitory stall noise from wind turbines. This model has demonstrated the following key characteristics:

- transitory stall occurring over a restricted blade area can cause a noticeable, but equally transitory, increase in noise radiation from the affected areas of the blade, with the dominant acoustic frequencies of this stall noise being lower than those resulting from NAM;
- this increased low-frequency noise radiation occurs repetitively at a rate related to the blade passing frequency of the rotor, which is the same as for NAM;
- the source directivity characteristics of the stall noise are such that it is preferentially radiated upwind and downwind of the wind turbine and not in the cross wind direction, which is opposite to the source directivity characteristics of trailing edge noise (associated with NAM);
- noise is also preferentially radiated and propagated in the downwind direction of a wind turbine so, unlike NAM, the maximum modulation depth of OAM will occur in the same direction relative to the turbine as the highest overall levels of noise.

In the light of the expected key characteristics of OAM noise, and in particular the notable differences between OAM and NAM, targeted measurements were undertaken across three separate wind farm sites to measure OAM and to confirm its characteristics. This included innovative procedures based on direct modifications of the operational characteristics of a turbine.

The results of these targeted measurements (WPD) have concluded that the general characteristics of the OAM noise observed were consistent with the expected directivity and spectral characteristics of the transitory stall noise: a significantly increased effect was particularly apparent in the downwind direction from the wind turbine, with a frequency composition consistent with this model. Modifying a turbine’s pitch when operating, in order to trigger stall, also appeared to generate some increased modulation events, as expected from the theory.

The project has additionally concluded, however, that the total validation of the foregoing conclusion would require further dedicated measurements. These measurements should focus on the surface pressures of the blades themselves in order to directly detect the occurrence of detached (stalled) flow, with the aim of correlating this blade-measured pressure data with measurements of the resultant radiated noise.

The available data and results of the targeted measurements have also been used to test various, previously proposed hypotheses as to possible factors that may give rise to for OAM. Whilst the results of the targeted measurements could not absolutely rule out any of these as potential contributory factors, they did confirm the ability of OAM to exist in situations where the factors were known not to contribute. In summary, OAM was reported or measured (WPC, WPD) under conditions of:

- low wind shear;
- low wind veer (wind direction variation with height);
- uniform turbulence;
- single operational turbines, without wake interaction effects;
- both flat and hilly sites;
- turbines having small or large rotor diameter size relative to their tower.

The only positively identified association between the occurrence of OAM and detailed turbine operational characteristics obtained at one site of WPD was that OAM only occurred when active power generation
was occurring, and it also appeared to sometimes be exacerbated during periods when changes in angle of attack of the blades were estimated to occur.

Thus, whilst the project has positively concluded that the source mechanism of OAM is almost certainly transitory stall effects, the results have not allowed the similar positive identification of the factors causing such transitory stall effects to occur. As set out above, several of the potential causal factors which have previously been suggested were shown through the present project to have little or no association to the occurrence of OAM. However some of these effects may represent potential contributory factors, and the evidence further suggests this would be very site-specific.

It is not therefore possible to be prescriptive as to whether any particular site is more or less likely to give rise to OAM being generated. This is considered likely to be due to a combination of site- and installation-specific factors, including meteorology.

This conclusion will, of course, depend on situation-specific circumstances, and most notably the level of ambient masking noise present at the location of the far field observer. If sufficiently high, such masking noise may serve to negate any subjectively perceptible OAM noise. One factor which can affect the relative level of masking noise on some sites is the level of wind shear, in particular for (non wind-sheltered) residential locations that are surrounded by vegetation. This is because increased wind shear will correspond to relatively reduced wind speeds near the ground, with little change to the wind seen by the turbines. So even if the amount of wind shear does not directly affect the generation of modulation, it may have an effect on the level of masking background noise which may otherwise reduce the effective modulation depth.

Other source mechanisms may be at play. It is conceivable that particular blade designs could experience partial blade stall in certain conditions without the influence of non-uniform inflow conditions to trigger it. For example, aero-elasticity effects may vary the blade geometry (as they bend and twist under load) in such a way that it departs significantly from its design conditions. There is, however, very limited information available to study this in the current state of knowledge. It is therefore recommended that further (blade-focussed) measurements be undertaken to establish the potential significance of such effects.

Notwithstanding the conclusion that changes in source effects are likely to be the primary cause of OAM, the project has additionally concluded that OAM may be strongly influenced or exacerbated by noise propagation effects. Observations in which OAM was discernible in the far field of wind turbines but not simultaneously in the near field adds some weight to this possibility.

Environmental noise propagation effects generally result in the upwind radiated sound being rapidly attenuated with distance due to upwards refraction effects, whilst the downwind radiated sound propagates further due to the downwards refraction of sound waves. In addition, turbines do not radiate high levels of noise in the cross-wind direction. So whilst overall levels of turbine noise are normally highest in downwind directions, they normally do not fluctuate significantly. OAM noise resulting from transitory stall on the surface of the wind turbine blade is preferentially radiated in the upwind and downwind directions, as opposed to the cross-wind direction for NAM. When associated with these general directivity effects, this would result in the OAM modulation being more subjectively audible in the far-field than NAM because of the increased overall levels.

A theoretical possibility has additionally been identified whereby propagation effects would result in modulation being perceived or even enhanced in the far field in the upwind direction at certain frequencies. This would be due to the interaction between source-receiver geometry and refraction effects: whereby the noise radiated from the uppermost part of the blade’s trajectory would be able to penetrate into the upwind acoustic shadow zone, whereas the noise radiated from the lower part of the blade’s trajectory would not similarly be able to penetrate this same zone. Thus, for a certain critical range of distances that would depend on local considerations, blade radiated noise would be perceived to increase and decrease at a rate related to the blade passing frequency. However, this has not been
commonly observed to be a feature of NAM. As OAM is predicted to radiate in the upwind direction as well, these identified propagation effect may influence this modulation and/or cause the upwind attenuation, which is generally expected, not to materialise in some instances: this may explain some limited observations of OAM upwind made in the field. Nonetheless, the existence of OAM has been found in practice to be prevalent mainly in downwind conditions (see for example site A of WPD), in which case its characteristics have been shown to be consistent with the existence of a source effect.

It has additionally been noted that, for the purpose of the present project, NAM and OAM have been defined in the context of different source generation mechanisms. This is a potentially convenient differentiator. However, it should be noted that OAM has been shown to be discernible in the far field of wind turbines whilst not being simultaneously discernible in the near field to those turbines, which indicates caution is required when regarding this attractive, but perhaps over-simplistic, definition based on source effects only. These observations also highlight the practical difficulties involved with this phenomenon as far-field measurements are always more complex in practice.

Can OAM be objectively identified and quantified?

The present project has included extensive work on investigating various methodologies for the automated discrimination, analysis and quantification of OAM. It has been discussed how short period measurement results (typically of $L_{Aeq,100ms}$ or $L_{Aeq,125ms}$) can, in some cases, be usefully plotted out against time to graphically illustrate levels of AM. However, it has also been demonstrated how this really only works in practice when there is a very clear and dominant contribution of AM noise. In all other situations, the process of trying to directly rate modulation amplitude in this manner proves to be too arbitrary, as picking peaks and troughs from all of those present is open to a degree of interpretation which is potentially too large, and too readily influenced by spurious noises, such as bird noise, to make the method sufficiently robust in terms of its objectivity and/or repeatability. The resultant derived modulation depths are also dependent on the analysis period used (e.g. 50 ms or 125 ms).

Crucially, WPB1 has highlighted how the analysis of OAM can rely on the fact that the noise is quasi-periodic.

For variable speed machines, the exact frequency of the quasi-periodic variation in level will vary depending on wind conditions, and from turbine to turbine across a wind farm site, but generally not to a significant extent. The fact that the modulation frequency will normally and consistently lie within a fairly restricted range (typically from 0.5 Hz to 1 Hz) means that OAM (when present) can be set apart from other sources of noise present in rural or urban environments, whose periodic variation in level may occur outside the expected frequency range for wind turbine noise, or indeed may not be periodic at all.

On the foregoing basis, the project has presented an assessment of Fourier Transform (FT) based signal analysis techniques with the aim of identifying a particular modulation frequency in a noise signal, and then establishing the variation in level at that frequency. It was shown that these methods are optimal in determining parameters of quasi-periodics signals.

It is important to note here that the transform from the time to the frequency domain using the tested analysis techniques is not undertaken on the signal itself, as this would merely result in the spectrum of audio frequencies within the signal. Rather, the transform is undertaken on the envelope of the signal such that the result is the rate at which the overall signal level modulates (i.e. the modulation frequency). The signal envelope adopted is usefully based on that calculated using, for example, the $L_{Aeq,100ms}$ metric. Thus the analysis techniques developed as part of this research use the recognised merits of the first method discussed above, whereby the $L_{Aeq,100ms}$ or $L_{Aeq,125ms}$ may be plotted out against time to graphically illustrate levels of AM, but adds an additional level of sophistication to isolate those variations.
in noise level that are specifically and consistently related to the rotational rate of the turbines, therefore lessening the dependence on the signal resolution.

The calculated amplitude of the peak of the modulation spectrum then represents a measure of the amount of modulation present in AM signals which is consistent with subjective response. Results from analysing field recordings of OAM, including those containing higher levels of extraneous noise, suggest that, in general, methods based on the Fourier Transform of the overall energy in a signal can perform well. The downside of such an approach, however, is that their performance tends to reduce as the relative amount of extraneous noise increases.

Applying appropriate frequency-domain acoustic filtering prior to the computation of the energy has been shown to enable the refocusing of the processing on the audio frequency band(s) where the modulation is significant (for example by applying a low pass filter with a cut-off frequency of around 500 Hz or by undertaking the analysis on octave band or third octave band filtered data), thereby reducing the effects of extraneous noise at higher frequencies.

Whilst the identified approach requires the a priori identification of a suitable frequency filter band (or bands) in which OAM is prevalent, and it cannot significantly reduce the effects of extraneous noise that may occur in the same filtered frequency range as the modulation, it has nevertheless been demonstrated to be generally robust when applied to actual field-recorded signals. Although there is currently no standard or accepted implementation of such routines, a particular implementation of this method was used principally in this work to analyse new and existing recordings, and was designated as the “main AM metric routine”.

In summary to the above, the project has concluded that an efficient and repeatable objective method for the discrimination and quantification of OAM can be developed. It was found that the resulting metric can be consistent with subjective response to OAM but that input parameters needed to be chosen with care. The key features of the preferred metric comprise:

- it is based on an analysis of noise that is pre-filtered to lie in an audio frequency range in which the effects of OAM are known or expected to be most prevalent;
- it is based on a Fourier Transform from the time to the frequency domain of the envelope of the resultant filtered noise, with the envelope typically being calculated from the short term (~100 ms) $L_{eq,t}$ of the filtered signal, with the choice of the same averaging period being consistently adopted;
- the Fourier Transform analysis is focussed on the range of frequencies for which OAM is known to occur for the turbines being measured (typically 0.5 Hz to 1 Hz for current large scale turbines);
- the resultant energy that is calculated to exist at the identified modulation frequency (the ‘modulation energy’) is normalised using a consistent methodology;
- if the resultant ‘modulation energy’ is used to rate OAM in terms of its subjective impact, it is of central importance that the subjective response tests used to derive a rating scheme were based on analyses undertaken using the same objective analysis techniques throughout.

What is the subjective impact of OAM?

Controlled subjective testing was undertaken in a specialist facility at the University of Salford to supplement the limited amount of available knowledge on the listener response to characteristic physical properties of AM wind turbine noise. Simulated recordings, based on an analysis of actual field recordings, and with a wide range of input parameters, were played back to a range of up to 20 subjects of different ages and sensitivity but normal hearing.

The study necessarily relied on tests carried out under controlled laboratory conditions. Rating annoyance is subject to contextual and attitudinal issues and these factors are thought to be responsible for the wide error bands in the plotted data. However, the results of the WPB2 listening tests are
generally consistent with those of existing research into subjective response to amplitude-modulated noise.

The frequency spectra and levels of sounds were intended to represent the characteristics of wind turbine noise as it might be perceived in a rural garden. Subjects were asked to rate the noise in two ways: an absolute annoyance rating, and a rating relative to un-modulated noise (by the subject adjusting the levels of modulated and un-modulated noise to achieve the same annoyance rating). These ratings were correlated with mean noise level and a range of metrics defining the degree of modulation.

The initial sensitivity tests first undertaken, as well as the more detailed and controlled final set of tests, concluded that the subjects’ response to the noise was not significantly affected by:

- the frequency spectrum of the modulated noise (either dominated by medium or lower frequencies), once the A-weighted level was taken into account
- the modulation waveform
- the presence of limited amounts of vegetation noise in addition to turbine noise

In contrast, the annoyance ratings were significantly related to:

- the frequency (rate) of the modulation;
- the A-weighted average level of the test sound;
- the modulation depth (a measure(s) of the modulation magnitude).

Regarding the first point: in the range studied, annoyance increases with frequency (i.e. a faster turbine rotational speed is more annoying), which is consistent with psychoacoustic theory. As discussed above and in Annex B, the increase in the size of modern turbines has been associated with a general reduction in the audio frequencies dominating the modulation: other parameters being equal, this does not appear to result in significant differences in the annoyance response. This was accompanied by a decrease in the rotational rate of the turbines, which would correspond to a relative reduction in annoyance. The other two key factors identified were then analysed in further detail.

After controlling for the mean overall level of sound, as measured by the $L_{Aeq}$, the final tests showed this parameter always dominated the annoyance rating. The modulation depth was found to increase the annoyance rating slightly, but consistently; however it should be noted that the effect was not statistically significant because there was a large spread of ratings. This is consistent with previous results in comparable studies. A clear (significant) onset of annoyance at a particular modulation depth could therefore not be determined.

The tests for which an un-modulated wind turbine noise was adjusted for comparable annoyance with the AM stimuli resulted in levels which were relatively constant from modulation depths of approximately 3 dB(A). The adjustments were on average 1.7 dB(A) for a 40 dB(A) stimuli and 3.5 dB(A) at 30 dB(A).

The use of the $L_{A90}$ as a measure of noise levels resulted in comparable results for moderate modulation depths of less than approximately 9 dB(A), although further work and testing would be required to establish alternative corrections directly. It should be borne in mind that field measurements have established that for real data, the difference between $L_{Aeq}$ and $L_{A90}$ remains close to 2dB(A) even for periods of sustained modulation. $L_{A90}$ levels remains strongly susceptible to corruption from other sources of noise in the environment, and that the $L_{A90}$ is therefore used in practice as a proxy for the $L_{Aeq}$ of the wind turbine noise in isolation.

Although psychoacoustic metrics can additionally represent the effect of overall noise level (to some extent), their practical application involves significant difficulties. For the other various objective metrics of modulation depth which were studied, including the main AM metric routine used in other parts of this project, the levels of subjective response were comparable, given the low sensitivity of the response to modulation depth. This comparison mainly highlighted the importance of relating any specific response to
measured AM levels in a consistent way; when discussing the effects of the modulation of signals it is therefore crucial to be consistent in the definition of the metric and the normalisation that is adopted. This point cannot be emphasised strongly enough.

The effect of factors such as the frequency of occurrence of OAM ‘events’ and their duration is not addressed in the current research. The view of the steering group and the research team is that the significance of these factors would have to be assessed using professional judgment and experience and that it would not be practicable to assess them via further subjective testing.

Can OAM be effectively mitigated?

In answering this question, the first issue that must be considered is whether the available evidence points to the fact that OAM is a ‘source’ issue, or whether it could potentially occur at distances typical of residential neighbours to a wind farm as a consequence of propagation effects in the absence of any source effects?

Although a theoretical propagation effect was identified which could produce a modulation effect in upwind conditions, this did not appear consistent with general observations. The existence of OAM has been found in practice to be prevalent mainly in downwind conditions, in which case its characteristics have been shown to be consistent with the existence of a source effect.

If the existence of OAM in the far field requires some effect to have occurred at source, even though the effect may be exacerbated by propagation effects, then the control of the source effect will remove the occurrence of OAM in the far field. Given that the primary source generation mechanism for OAM has been identified as being local stall on the blades, it is the case that any measures that prevent or reduce the onset of such local stall would result in the mitigation of OAM in the far field.

In the immediate term, the only guaranteed solution to mitigate fully against specific occurrences of OAM is the cessation of operation of offending turbines during those conditions under which problematic OAM is found to occur. These conditions leading to OAM, and the characteristics of that OAM when it occurs, appear to be very site-specific and would therefore need to be established specifically for each operational site considered. The use of the detection and rating methods identified, such as the main AM metric routine described in this report, could provide the basis for analysing these conditions based on the analysis of long-term monitoring.

It has been concluded that the effective mitigation of OAM in practice will require the future involvement and close cooperation of wind turbine manufacturers, and possibly involve detailed measurements that focus on better understanding the surface pressure distributions on the turbine blades themselves, particularly as the stall point is approached. Simple analysis methods have been identified in this project to assist in identifying the most likely relevant conditions. It is recognised that wind turbine design and manufacture are rapidly-advancing fields, the market is highly-competitive, and manufacturers must be protective of technical information relating to the design, manufacture and operation of their turbines. However, it is strongly recommended that wider collaboration is undertaken to devise effective mitigation methods.

It is believed that with such cooperation, methods will be capable of being developed for avoiding local stall conditions. Such methods may involve software ‘fixes’ that seek to modify the logic of the control system algorithms, perhaps even through the application of more advanced cyclical pitch control. More fundamental, physical design changes may also prove worthwhile, such as innovative blade designs or the addition of blade vortex generators, for example, as the latter may delay the onset of stall. Such mitigation would be likely to only have a limited or negligible impact on the generating capacity of the turbines.

It may also be concluded that there is nothing at the planning stage that can presently be used to indicate a positive likelihood of OAM occurring at any given proposed wind farm site, based either on its general characteristics or on the known characteristics of the wind turbines to be installed.
# GLOSSARY OF TERMINOLOGY

<table>
<thead>
<tr>
<th>TERMINOLOGY</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A-weighting</strong></td>
<td>a filter that attenuates low frequency and high frequency sound to better represent the frequency response of the human ear when assessing the likely impact of noise on humans</td>
</tr>
<tr>
<td><strong>acoustic character</strong></td>
<td>one or more distinctive features of a sound (e.g. tones, whines, whistles, impulses) that set it apart from the background noise against which it is being judged, possibly leading to a greater subjective impact than the level of the sound alone might suggest</td>
</tr>
<tr>
<td><strong>acoustic screening</strong></td>
<td>the presence of a solid barrier (natural landform or manmade) between a source of sound and a receiver that interrupts the direct line of sight between the two, thus reducing the sound level at the receiver compared to that in the absence of the barrier</td>
</tr>
<tr>
<td><strong>ambient noise</strong></td>
<td>All-encompassing noise associated with a given environment, usually a composite of sounds from many sources both far and near, often with no particular sound being dominant</td>
</tr>
<tr>
<td><strong>annoyance</strong></td>
<td>a feeling of displeasure, in this case evoked by noise</td>
</tr>
<tr>
<td><strong>attenuation</strong></td>
<td>the reduction in level of a sound between the source and a receiver due to any combination of effects including: distance, atmospheric absorption, acoustic screening, the presence of a building façade, etc.</td>
</tr>
<tr>
<td><strong>audible sound</strong></td>
<td>a sound that can be heard above all other ambient sounds</td>
</tr>
<tr>
<td><strong>audio frequency</strong></td>
<td>any frequency of a sound wave that lies within the frequency limits of audibility of a healthy human ear, generally accepted as being from 20 Hz to 20,000 Hz. The frequency represents the actual rate at which the acoustic pressure is oscillating. (see frequency below)</td>
</tr>
<tr>
<td><strong>background noise</strong></td>
<td>the noise level rarely fallen below in any given location over any given time period, often classed according to daytime, evening or night-time periods (for the majority of the population of the UK the lower limiting noise level is usually controlled by noise emanating from distant road, rail or air traffic)</td>
</tr>
<tr>
<td><strong>dB</strong></td>
<td>abbreviation for 'decibel'</td>
</tr>
<tr>
<td><strong>dB(A)</strong></td>
<td>abbreviation for the decibel level of a sound that has been A-weighted</td>
</tr>
<tr>
<td><strong>decibel</strong></td>
<td>the unit normally employed to measure the magnitude of sound</td>
</tr>
<tr>
<td><strong>directivity</strong></td>
<td>the property of a sound source that causes more sound to be radiated in one direction than another</td>
</tr>
<tr>
<td><strong>equivalent continuous sound pressure level</strong></td>
<td>the steady sound level which has the same energy as a time varying sound signal when averaged over the same time interval, T, denoted by LAeq,T</td>
</tr>
<tr>
<td><strong>external noise level</strong></td>
<td>the noise level, in decibels, measured outside a building</td>
</tr>
<tr>
<td><strong>filter</strong></td>
<td>a device for separating components of an acoustic signal on the basis of their frequencies</td>
</tr>
<tr>
<td><strong>frequency</strong></td>
<td>the number of fluctuations per second. Note that this can apply either to:</td>
</tr>
<tr>
<td></td>
<td>• Audio frequency: fluctuations in acoustic pressure about the atmospheric mean pressure (also known as the 'pitch' of a sound)</td>
</tr>
<tr>
<td></td>
<td>• Modulation frequency: this represents the rate of repetition of the modulation in time when periodic or quasi-periodic</td>
</tr>
<tr>
<td></td>
<td>• Sampling frequency: the number of times per second a particular signal will be measured. For example, for levels measured every 100 ms this will be 10Hz. Audio recordings are often made at sampling rates of 22 to 44 kHz.</td>
</tr>
<tr>
<td><strong>frequency analysis</strong></td>
<td>the analysis of a sound into its frequency components</td>
</tr>
</tbody>
</table>
## TERMINOLOGY DESCRIPTION

<table>
<thead>
<tr>
<th><strong>ground effects</strong></th>
<th>the modification of sound at a receiver location due to the interaction of the sound wave with the ground along its propagation path from source to receiver</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>hertz</strong></td>
<td>the unit normally employed to measure the frequency of a sound, equal to cycles per second of acoustic pressure fluctuations about the atmospheric mean pressure</td>
</tr>
<tr>
<td><strong>impulsive sound</strong></td>
<td>a sound having all its energy concentrated in a very short time period</td>
</tr>
<tr>
<td><strong>instantaneous sound pressure</strong></td>
<td>at a given point in space and at a given instant in time, the difference between the instantaneous pressure and the mean atmospheric pressure</td>
</tr>
<tr>
<td><strong>internal noise level</strong></td>
<td>the noise level, in decibels, measured inside a building</td>
</tr>
<tr>
<td><strong>$L_{Aeq}$</strong></td>
<td>the abbreviation of the A-weighted equivalent continuous sound pressure level</td>
</tr>
<tr>
<td><strong>$L_{A10}$</strong></td>
<td>the abbreviation of the 90 percentile noise indicator, often used for the measurement of road traffic noise (exceeded 10% of the time)</td>
</tr>
<tr>
<td><strong>$L_{A90}$</strong></td>
<td>the abbreviation of the 10 percentile noise indicator, often used for the measurement of background noise (exceeded 90% of the time)</td>
</tr>
<tr>
<td><strong>level</strong></td>
<td>the general term used to describe a sound once it has been converted into decibels</td>
</tr>
<tr>
<td><strong>loudness</strong></td>
<td>the attribute of human auditory response in which sound may be ordered on a subjective scale that typically extends from barely audible to painfully loud</td>
</tr>
<tr>
<td><strong>masking</strong></td>
<td>the effect whereby an otherwise audible sound is made inaudible by the presence of other sounds</td>
</tr>
<tr>
<td><strong>modulation (amplitude)</strong></td>
<td>for noise this characterises a change in amplitude (or perceived loudness) over time (i.e. going up and down). Over short periods of time these amplitude modulations may repeat themselves with an almost constant period, thus resulting in what is termed ‘quasi-periodic’ noise.</td>
</tr>
<tr>
<td><strong>modulation frequency</strong></td>
<td>The rate of repetition of the above modulation in time when it is periodic or quasi-periodic, in number of periods per second.</td>
</tr>
<tr>
<td><strong>noise</strong></td>
<td>physically: a regular and ordered oscillation of air molecules that travels away from the source of vibration and creates fluctuating positive and negative acoustic pressure above and below atmospheric pressure. Subjectively: sound that evokes a feeling of displeasure in the environment in which it is heard, and is therefore unwelcomed by the receiver</td>
</tr>
<tr>
<td><strong>noise emission</strong></td>
<td>the noise emitted by a source of sound</td>
</tr>
<tr>
<td><strong>noise immission</strong></td>
<td>the noise to which a receiver is exposed</td>
</tr>
<tr>
<td><strong>octave band frequency analysis</strong></td>
<td>a frequency analysis using a filter that is an octave wide (the upper limit of the filter’s frequency band is exactly twice that of its lower frequency limit)</td>
</tr>
<tr>
<td><strong>percentile exceeded sound level</strong></td>
<td>the noise level exceeded for n% of the time over a given time period, T, denoted by $L_{A,n,T}$</td>
</tr>
<tr>
<td><strong>pitch</strong></td>
<td>for a wind turbine, this denotes the orientation of its blades around their length-wise axis</td>
</tr>
<tr>
<td><strong>pitch-regulated wind turbine</strong></td>
<td>a wind turbine that sheds power at the highest wind speed to regulate its output by dynamically changing the orientation of its blades around their length-wise axis</td>
</tr>
<tr>
<td><strong>receiver</strong></td>
<td>a person or property exposed to the noise being considered</td>
</tr>
<tr>
<td><strong>residual noise</strong></td>
<td>the ambient noise that remains in the absence of the specific noise whose impact is being assessed</td>
</tr>
</tbody>
</table>
### Terminology Description

<table>
<thead>
<tr>
<th><strong>Terminology</strong></th>
<th><strong>Description</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>sound</td>
<td>physically: a regular and ordered oscillation of air molecules that travels away from the source of vibration and creates fluctuating positive and negative acoustic pressure above and below atmospheric pressure subjectively: the sensation of hearing excited by the acoustic oscillations described above (see also 'noise')</td>
</tr>
<tr>
<td>sound level meter</td>
<td>an instrument for measuring sound pressure level</td>
</tr>
<tr>
<td>sound pressure amplitude</td>
<td>the root mean square of the amplitude of the acoustic pressure fluctuations in a sound wave around the atmospheric mean pressure, usually measured in Pascals (Pa)</td>
</tr>
<tr>
<td>sound pressure level</td>
<td>a measure of the sound pressure at a point, in decibels</td>
</tr>
<tr>
<td>sound power level</td>
<td>the total sound power radiated by a source, in decibels</td>
</tr>
<tr>
<td>spectrum</td>
<td>a description of the amplitude of a sound as a function of frequency</td>
</tr>
<tr>
<td>stall</td>
<td>When the flow around an airfoil (or turbine blade) is interrupted or becomes detached from the surface of the airfoil, resulting in a loss of lift</td>
</tr>
<tr>
<td>stall-regulated wind turbine</td>
<td>a wind turbine that sheds power at the highest wind speed to regulate its output by allowing its blade to stall</td>
</tr>
<tr>
<td>third-octave band frequency analysis</td>
<td>a frequency analysis using frequency bands one third of an octave wide</td>
</tr>
<tr>
<td>threshold of hearing</td>
<td>the lowest amplitude sound capable of evoking the sensation of hearing in the average healthy human ear (0.00002 Pa)</td>
</tr>
<tr>
<td>tone</td>
<td>the concentration of acoustic energy into a very narrow frequency range</td>
</tr>
</tbody>
</table>
REFERENCES

Throughout this report, references to [WPX] refer to the report for Work Package X of this project, where X stands for the following:

<table>
<thead>
<tr>
<th>WP</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>Source generation effects modeling</td>
</tr>
<tr>
<td>A2</td>
<td>Fundamental Research into Possible Causes of Amplitude Modulation</td>
</tr>
<tr>
<td>B1</td>
<td>Development of an Objective AM Measurement Methodology</td>
</tr>
<tr>
<td>B2</td>
<td>Development of an AM Dose-Response Relationship</td>
</tr>
<tr>
<td>C</td>
<td>Collation and Analysis of Existing Acoustic Recordings</td>
</tr>
<tr>
<td>D</td>
<td>Measurement and Analysis of New Acoustic Recordings</td>
</tr>
</tbody>
</table>

Additional references are as follows:

[16] The Den Brook Amplitude Modulation Noise Condition, Dr Lee Moroney, Dr John Constable, Renewable Energy Foundation, published www.ref.org.uk

ANNEX A - A SUMMARY OF THE STATE OF TECHNICAL KNOWLEDGE

This Annex summarises how the current state of technical knowledge relating to AM has developed, largely as a result of the ReUK funded investigations that have been ongoing over the course of the past year.

The text may assist in making decisions as to how the issue of AM is treated in planning situations, particularly with regards the imposition of AM related noise conditions.

This note is set out on the basis of a direct comparison between the situation that generally existed twelve months or more ago, with a concurrent comparison as to the situation that exists now.

<table>
<thead>
<tr>
<th>PAST KNOWLEDGE</th>
<th>PRESENT KNOWLEDGE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>What is AM?</strong></td>
<td><strong>AM more correctly refers to the 'Amplitude Modulation' of wind turbine blade noise which is aerodynamic in its origin</strong></td>
</tr>
<tr>
<td>- AM refers to the 'Aerodynamic Modulation' or the 'Amplitude Modulation' of wind turbine blade noise</td>
<td>- AM can be divided into 'normal AM', or 'blade swish', and 'enhanced AM'</td>
</tr>
<tr>
<td>- AM can be divided into 'normal AM', or 'blade swish', and 'enhanced AM'</td>
<td></td>
</tr>
</tbody>
</table>

**What are the characteristic features of 'Blade Swish' or 'Normal AM'?**

Blade swish, or 'Normal AM':
- an inherent feature of wind turbine noise;
- typically 3 dB modulation depth close to source;
- decreases with increasing distance, although;
- its presence may be exacerbated by local reflections, even at larger distances, with modulation depths of up to 6 dB;
- dominated by 800 Hz to 1000Hz frequencies;
- acknowledged and accounted for in ETSU-R-97 in the above terms;
- since the publication of ETSU-R-97 it has become well understood in terms of its aerodynamic source generation mechanisms.

**What are the characteristic features of 'enhanced AM (EAM)' or 'other AM (OAM)'?**

EAM typically described as:
- an atypical feature of wind turbine noise;
- any AM falling outside the presumptions relating to blade swish in ETSU-R-97 (i.e. greater than 3 dB peak to trough free field, or 6 dB peak to trough in the presence of reflections);
- no systematic changes to the frequency characteristics set out in ETSU-R-97 for blade swish;

OAM more clearly identified as:
- an atypical feature of wind turbine noise;
- audible at distances close to or in excess of 1000 m;
- even under free-field conditions, modulation depths may exceed 5 dB at these larger distances, with modulation depths of up to 10 dB in overall A-weighted levels being reported;
- dominated by lower frequencies than 'normal AM', typically around 300–400 Hz ;
- modulation depths in the dominant lower frequency band generally exceed the modulation depths reported in overall A-weighted levels;
- subjectively more impulsive in character than 'normal AM';
- the foregoing features generally result in OAM being described as more of a 'whoompf' than a 'swish' sound;
## Past Knowledge vs. Present Knowledge

<table>
<thead>
<tr>
<th>What is the source generation mechanism of EAM or OAM?</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Source generation mechanism of EAM:</strong></td>
</tr>
<tr>
<td>• unknown, but various potential generation</td>
</tr>
<tr>
<td>mechanisms or factors were speculated on.</td>
</tr>
<tr>
<td><strong>Source generation mechanism of OAM:</strong></td>
</tr>
<tr>
<td>• still not fully proven, but local transient stall</td>
</tr>
<tr>
<td>on the rotor blades is most likely to be the</td>
</tr>
<tr>
<td>predominant source generation mechanism.</td>
</tr>
<tr>
<td>The ReUK project has additionally identified that</td>
</tr>
<tr>
<td>the following (non-source related) mechanisms may</td>
</tr>
<tr>
<td>add to the effects of OAM:</td>
</tr>
<tr>
<td>• propagation effects may increase levels of OAM</td>
</tr>
<tr>
<td>experienced at larger distances (particularly</td>
</tr>
<tr>
<td>upwind);</td>
</tr>
<tr>
<td>• local conditions at receptor (particularly</td>
</tr>
<tr>
<td>internal room effects) may enhance noise across</td>
</tr>
<tr>
<td>common frequency range of OAM;</td>
</tr>
<tr>
<td>• masking effects of background noise at receptor</td>
</tr>
<tr>
<td>location may be a key determining factor in</td>
</tr>
<tr>
<td>measured modulation depths (this may add to</td>
</tr>
<tr>
<td>the explanation as to why OAM is sometimes</td>
</tr>
<tr>
<td>reported as more prevalent under high wind shear</td>
</tr>
<tr>
<td>conditions).</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>How Common is AM?</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>'Normal AM', or blade swish:</strong></td>
</tr>
<tr>
<td>• an inherent characteristic feature of all wind</td>
</tr>
<tr>
<td>turbines.</td>
</tr>
<tr>
<td><strong>EAM:</strong></td>
</tr>
<tr>
<td>• reliance placed on HMP LFN study and</td>
</tr>
<tr>
<td>subsequent Salford study to indicate low</td>
</tr>
<tr>
<td>prevalence across the UK Wind Farm fleet;</td>
</tr>
<tr>
<td>however;</td>
</tr>
<tr>
<td>• once identified as a potential feature, increasing</td>
</tr>
<tr>
<td>reports by objector groups of EAM causing problems</td>
</tr>
<tr>
<td>at other wind farms;</td>
</tr>
<tr>
<td>• high profile of Deeping St Nicholas case raised</td>
</tr>
<tr>
<td>general awareness still further;</td>
</tr>
<tr>
<td>• increasing public availability of reports making a</td>
</tr>
<tr>
<td>direct link between EAM (amongst other features</td>
</tr>
<tr>
<td>of wind farm noise) and adverse subjective</td>
</tr>
<tr>
<td>responses</td>
</tr>
<tr>
<td><strong>OAM, generally still as per 'past knowledge'</strong></td>
</tr>
<tr>
<td>• seen to be acknowledged by the wind energy</td>
</tr>
<tr>
<td>industry as a 'key issue through the letting of</td>
</tr>
<tr>
<td>the ReUK AM Research Project;</td>
</tr>
<tr>
<td>• publicly reported as being 'a small problem' but</td>
</tr>
<tr>
<td>now 'too large to ignore';</td>
</tr>
<tr>
<td>• even on those limited sites where it has been</td>
</tr>
<tr>
<td>reported, its frequency of occurrence appears to</td>
</tr>
<tr>
<td>be at best infrequent and intermittent.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>What causes EAM/OAM?</th>
</tr>
</thead>
<tbody>
<tr>
<td>**Possible causes variously presented by different</td>
</tr>
<tr>
<td>authors as:**</td>
</tr>
<tr>
<td>• blade passing tower</td>
</tr>
<tr>
<td>• angle of attack changes</td>
</tr>
<tr>
<td>• high shear/stable atmosphere</td>
</tr>
<tr>
<td>• high turbulence (or tip vortex)</td>
</tr>
<tr>
<td>• yaw error</td>
</tr>
<tr>
<td>• rotor/wake effects</td>
</tr>
<tr>
<td>• interaction between turbines</td>
</tr>
<tr>
<td>• sync between turbines or phasing</td>
</tr>
<tr>
<td>• propagation effect</td>
</tr>
<tr>
<td>• 'stubby' towers</td>
</tr>
<tr>
<td>• etc.</td>
</tr>
<tr>
<td><strong>Based on reported occurrences of OAM, and the</strong></td>
</tr>
<tr>
<td>focus on the source generation mechanism being</td>
</tr>
<tr>
<td>localised transient stall, it may be concluded that:</td>
</tr>
<tr>
<td>• many of the possible causes listed opposite could</td>
</tr>
<tr>
<td>be possible contributory factors;</td>
</tr>
<tr>
<td>• some of these factors were clearly established as</td>
</tr>
<tr>
<td>not being associated with incidence or magnitude</td>
</tr>
<tr>
<td>of OAM;</td>
</tr>
<tr>
<td>• if any one factor or combination of factors were</td>
</tr>
<tr>
<td>solely responsible, then OAM would occur at all</td>
</tr>
<tr>
<td>sites featuring those factors and it would occur</td>
</tr>
<tr>
<td>frequently at those sites – neither of which has</td>
</tr>
<tr>
<td>been observed to be the case in practice;</td>
</tr>
<tr>
<td>• as an example, OAM has been observed to occur on a</td>
</tr>
<tr>
<td>single isolated turbine with a high tower, so</td>
</tr>
<tr>
<td>interaction effects between linear arrays and too</td>
</tr>
<tr>
<td>closely spaced turbines cannot</td>
</tr>
</tbody>
</table>
WIND TURBINE AMPLITUDE MODULATION: RESEARCH TO IMPROVE UNDERSTANDING AS TO ITS CAUSE & EFFECT

Collation of Work Package Reports and Final Reporting

<table>
<thead>
<tr>
<th>PAST KNOWLEDGE</th>
<th>PRESENT KNOWLEDGE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>be a sufficient factor, neither can a large rotor on a stubby tower;</td>
</tr>
<tr>
<td></td>
<td>as another example, OAM has been reported for one make and physical configuration of turbine on one site, whereas it has not been reported for the same make and physical configuration of turbine on all installations;</td>
</tr>
<tr>
<td></td>
<td>the interaction between the various site/turbine characteristics listed opposite coupled with the operational characteristics of the turbine control system and features of the specific blade design may lead to OAM occurring on some occasions at some sites.</td>
</tr>
</tbody>
</table>

Is EAM/OAM likely to be a feature at any particular site?

Based on the foregoing speculative causes it was generally proposed that EAM would be more likely to occur on:
- sites that exhibited high wind shear due to stable atmospheric conditions;
- flat sites on the east coast;
- sites where turbines were spaced too closely;
- sites where turbines were arranged in linear arrays;
- turbines with large rotors on relatively short towers.
- Etc.

Based on the current understanding:
- it is not possible to be prescriptive as to whether any particular site is more or less likely to give rise to OAM being generated at source;
- Several of the potential causal factors which have been suggested to date were shown to have little or no association to the occurrence of OAM: for example interaction between closely spaced turbines in linear arrays;
- However some of these features may represent potential contributory factors;
- it is only where background noise at noise sensitive receptor locations is high enough under all circumstances to effectively mask any potential OAM noise that it can be positively concluded that the chances of OAM causing noise issues are reduced.

Is there an accepted objective metric with associated dose-response relationship for AM?

No, but:
- a seemingly objective metric has been proposed by MAS Environmental (as implemented at Den Brook Wind Farm);
- the proposed metric is essentially based on observing whether the peak to trough modulation depth in the overall A-weighted level exceeds 3 dB under free field conditions (believed to be selected as this because this what is stated to be the expected maximum in ETSU-R-97);
- the foregoing metric was considered to be highly susceptible to the detection of ‘false positives’, even in the absence of any wind farm noise being present and quite apart from any OAM being present;
- the foregoing metric has not been substantiated in any way in terms of any dose-response relationship.

No, but:
- the metric referred to opposite has been demonstrated to be highly susceptible to the detection of ‘false positives’, even in the absence of any wind farm noise being present and quite apart from any OAM being present, effectively requiring difficult subjective consideration in its application;
- objective metric(s) methods which can effectively detect modulated wind turbine noise with a sufficiently reduced amount of ‘false positives’ have now been developed as part of this project;
- the dose-response relationship for the aforementioned metric(s) was found to be complex, although a significant effect due to the presence of certain levels of modulation was demonstrated, although there was relatively little additional effect beyond a certain level of modulation.
WIND TURBINE AMPLITUDE MODULATION: RESEARCH TO IMPROVE UNDERSTANDING AS TO ITS CAUSE & EFFECT

Collation of Work Package Reports and Final Reporting

<table>
<thead>
<tr>
<th>PAST KNOWLEDGE</th>
<th>PRESENT KNOWLEDGE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Can an objective planning condition presently be drawn up for EAM/OAM?</strong></td>
<td><strong>Yes, as listed opposite, but also:</strong></td>
</tr>
<tr>
<td>Yes, but:</td>
<td>arguments concerning necessity are finely balanced;</td>
</tr>
<tr>
<td>• this was not considered necessary given the recognized low probability of occurrence;</td>
<td>• tonality conditions are retained as standard even though it is argued that tones are not expected to occur, although gearboxes can fail and there is then a clear method for assessing the effects; however,</td>
</tr>
<tr>
<td>• whether or not this would survive the tests for a valid condition was debatable;</td>
<td>• current evidence suggests that some of the earliest proposed conditions may fail the tests of precision and reasonableness;</td>
</tr>
<tr>
<td></td>
<td>• although more objective and reliable methods have been considered as part of this project, there is still limited experience of their practical application and associated consequence;</td>
</tr>
<tr>
<td></td>
<td>• It is possible that OAM mitigation measures may be developed based solely on the operational characteristics of the affected turbines (i.e. modifications to the turbine control systems, and in particular the blade pitch control systems) or through physical modifications to the turbines themselves, as opposed to operational curtailment of turbines; however,</td>
</tr>
<tr>
<td></td>
<td>• The lack of definite technical experience in this regard, in the current state of the art, represents a key uncertainty. This may therefore necessitate operational curtailments in the meantime;</td>
</tr>
<tr>
<td></td>
<td>• ice throw from blades, which is unusual and part of technical design and is not conditioned, can be considered for parallels;</td>
</tr>
<tr>
<td></td>
<td>• it may still be argued that the known incidence of occurrence and frequency may not satisfy the necessity argument.</td>
</tr>
</tbody>
</table>
WIND TURBINE AMPLITUDE MODULATION: RESEARCH TO IMPROVE UNDERSTANDING AS TO ITS CAUSE & EFFECT

Collation of Work Package Reports and Final Reporting

ANNEX B – EVALUATION OF ADDITIONAL PROPAGATION EFFECTS ON AM MODEL RESULTS

The model presented in WPA1 does not take into account the longer-distance propagation effects, described in WPA2 or Chapter 3 of [9], which are known to affect the long-range propagation of noise over larger distances. The model was effectively validated at distances of 3 RD [6], but not at further distances which are relevant to the far-field region in which wind farm neighbours can generally be found. Over these distances, the potentially most significant propagation effects are:

- spherical spreading of sound (which will reduce overall noise levels equally in all directions and is not considered further);
- refraction effects due to wind speed gradients in upwind/downwind;
- atmospheric absorption effects at high frequencies.

The effects of the foregoing factors were accounted for to some extent in the similar model developed by Boorsma et al. [14], but, as flow separation noise was not considered, we can instead take the results of WPA1 and try to estimate potential influence of the additional effects identified in WPA2.

Dominant frequencies and atmospheric absorption

The ETSU-R-97 report [3] described blade swish as dominated by frequencies at and above the 800 – 1000 Hz range, which was typical of turbines at this time. As turbine designs have evolved, and have increased in size, it can be interesting to consider how this may have affected the characteristics of the amplitude modulated noise from the turbines.

The research undertaken by Delta as part of a large research project for Danish Energy Authority analysed a large variety of tested sound power spectra for turbines of different size categories (both less and more than 2MW generating capacity), to determine if certain types of turbines produced additional levels of low-frequency noise. It concluded that the noise emission spectra for the larger category of turbines, as averaged across all turbines tested, was only marginally more dominated by the frequencies in the range between 100 and 200Hz than the smaller category of machines. However, the observed difference was less than the variability found between turbines falling within the same size categories, such that a certain small turbine may have larger relative low frequency components than a larger and vice versa. This was characterised as a potentially noticeable but not an essential change.

Whilst this relates to the overall tested sound power results, we can consider further how the evolution of turbine designs may be considered in standard sound emission models of the modulated part of the turbine noise. With the increase of the size of turbine rotor diameters, the blade chord dimensions tend to increase (which will increase the thickness of the turbulent boundary layer over the aerofoil) whilst tip speeds may remain similar by design. This effectively results in a decrease in the ratio between the flow velocity and the boundary layer displacement thickness (and therefore the Strouhal number), which will tend to reduce the dominant frequency in the modulation spectrum. The figures A1(a) and (b) illustrate this potential effect based on the observations made for two different turbines types and the comparison of model predictions and experimental results. The peak frequency of the spectra for the larger turbine have approximately halved. The results of the more general study by Delta suggest this may be affected by a degree of variability, due to differing designs, which means the comparison between the 2 turbines may not necessarily be of general significance.

---

19 Wind turbine measurements for Noise source identification - ETSU W/13/00391/00/REP - Dr A J Bullmore, Mr J F Lowson, Dr J H Bass, Dr P Dunbabin, 1999.
20 Delta Acoustics for the Danish Energy Authority, EFP-06 Project - Low Frequency Noise from Large Wind Turbines, 2010.
21 By approximately 2 dB in relative terms. In the range 200-500Hz this reduced to approximately 1dB.
22 In accordance with the IEC 61400-11 standard
23 $S = f \delta /U$, where $\delta$ represents the boundary layer displacement thickness, and $U$ the flow speed.
WIND TURBINE AMPLITUDE MODULATION: RESEARCH TO IMPROVE UNDERSTANDING AS TO ITS CAUSE & EFFECT

Collation of Work Package Reports and Final Reporting

(a) 94m rotor diameter turbine    (b) 58m rotor diameter turbine

Figure A1 - Predicted and measured spectra for two different turbine models (from [5]).

This would be consistent with the observations of Legarth24,25, which noted that the most relevant frequencies for the modulation was in the 350-700Hz band, in comparison with frequencies centred around 1kHz in a 1989 study. This was based on a study of recordings of turbines of rotor diameters of 30 to 80 m, made at distances of between 1.5 and 3 hub heights from the turbines.

The effects of atmospheric absorption are highly frequency dependent, and higher frequency sound experiences greater atmospheric attenuation than lower frequency sound (with a rapid increase above 1kHz). For modulation spectra dominated by the 500Hz region, the effect of atmospheric absorption will therefore not be as significant as when dominated by the 1kHz region.

WPA1 notes that, for the situation of a detached flow in the downwind direction, the peaks of the modulation are dominated by the stall noise, whereas the troughs are dominated by the trailing edge noise. This effect is illustrated in Figure 25 of the WPA1 report, reproduced in Figure A2 below. As the periods of stall have increased low-frequency content, it is natural to consider whether atmospheric absorption effects may enhance the difference between peaks and troughs and therefore the levels of modulation.

Figure A2 shows the same spectra after applying a correction for these effects based on standard data26 presented for conditions of 10 degrees Centigrade and 70% humidity (corresponding to relatively low absorption) for a propagation over a distance of the order of 10 RD (say 800 m). It can be seen that as the A-weighted spectra in this case is dominated by frequencies close to 500 Hz, and the relative difference between the different instantaneous spectra is not significantly affected. The main difference between the periods of stall and non-stall in the modulation, the higher relative prominence of the spectra below frequencies of 200 Hz (of the order of 5 dB), is only marginally increased, but this would not tend to affect the overall A-weighted levels to a noticeable degree.

The effect of air absorption on the spectra of turbines dominated by frequencies closer to 1 kHz would be more significant.

24 Auralization and assessments of annoyance from wind turbines, Wind Turbine Noise 2007 Conference, Lyon, France.
26 ISO 9613-1 Acoustics – Attenuation of sound during propagation outdoors, part 1: Calculation of the absorption of sound by the atmosphere.
WIND TURBINE AMPLITUDE MODULATION: RESEARCH TO IMPROVE UNDERSTANDING AS TO ITS CAUSE & EFFECT

Collation of Work Package Reports and Final Reporting

Figure A2 – Instantaneous spectra for ‘case 4’ as studied in WPA1 (detached flow, m=0.3), modelled in the downwind direction 10 RD away. Dotted lines show modified spectra accounting for air absorption. $\psi = 250$ corresponds to the peak of the modulation (stall) and $\psi = 310$ to the trough.

Additional considerations – refraction effects

We can extend the results of the WPA1 model, which effectively assumed a neutral atmosphere (for propagation purposes), by accounting for far-field refraction effects occurring in different wind directions.

It is well-known (see WPA2] or Chapter 3 of [9]) that the wind speed gradient present in downwind conditions will correspond to favourable propagation conditions (Figure A3), whilst inverse gradients found in upwind conditions will represent unfavourable conditions. These effects tend to become significant in the far-field region only, between 5 and 15 hub heights.

For broadband signals, the former favourable conditions will represent an increase up to around 3dB relative to neutral conditions; in upwind conditions, measurement studies have shown that levels can be 10 dB or more lower than the received noise levels under neutral conditions. It is also generally accepted that such downwind conditions may effectively be present with a wind speed vector component of 2 m/s from source to receiver, which may occur from angles of 10 degrees from downwind propagation.

Figure A3: sound curvature under different wind speed gradients

---

27 Although temperature gradients (under temperature inversion and lapses) can results in comparable sound speed gradients, wind-related effects are generally dominant for situations relevant to wind turbine noise.

These effects can be (simplistically) modelled through a noise propagation directionality function, with effects ranging from +3 dB downwind of a turbine to -10 dB upwind. These corrections can be applied to the far-field corrected directivities presented in WPA1: this is done for the "case 2" and "case 4" studied, as presented in Figures 17 and 19 of the WPA1 report, which correspond to a case of moderately high wind shear (m=0.3), both without and with detached flow respectively. In Figure A4, the calculated directivity function for the overall noise levels is shown for both cases as shown in the report (dotted line); in addition, solid lines show a corrected directivity function which accounts for the additional effects of refraction for the far-field directivity, based on the model described above.

It can be seen that, once the effect of the upwards refraction of the sound and the associated "shadow zone" in upwind conditions are taken into account in addition to the intrinsic directivity of the source, that: outside of a zone of +/- 45 degrees from downwind of the turbines, the overall level of noise experienced in the far field decreases significantly. This means that this direction is key when considering noise emissions from turbines, as it will tend to be masked by other sources as the overall levels reduce.

However it should be noted that the model used of reduction in upwind conditions is crude and that, as noted in WPA, the effects of source height and turbulence could have significantly more complex effects. A clear summary of the situation highlighted in WPA2 is presented in [9], page 126:

‘There are some propagation effects that theory suggests may not only moderate AM … but might actually cause it. One of these is an upwind effect. The reason sound is not heard over long distances upwind is because of the effect of wind shear. This has the effect of bending sound waves upwards and away from the ground so that beyond some distance there is a sharp reduction of sound level. ….. However, the higher the noise source, the greater the distance at which it can be heard. So with turbine noise it is possible that, at say 600 metres distance, the sound of the turbine blade at the top of its trajectory could be heard, but not the sound at the bottom or half way down. So a form of AM could be generated in this way [note: the effects of refraction would also cause the relative contributions of the lower frequencies to be enhanced relative to the higher frequencies, which is one of the observed characteristics of OAM]. It is also possible that at certain frequencies the ground effect (interference of the direct sound and the sound reflected at the ground) could reduce turbine noise at the bottom of the trajectory more than at the top or vice versa. This could cause a form of AM in certain frequency bands.

It nevertheless seems significant (as highlighted in Figure A5 which overlays the modelled swish amplitude) that, in the case of detached flow, significant modulation occurs in the downwind sector. This is because of the significantly different directivity of the stall noise (a dipole in perpendicular to the rotor plane) compared to the trailing edge noise (a cardioid in the direction of blade rotation), as shown in Fig. 12 of the WPA1 report. This is particularly evident when comparing instantaneous noise footprints between the two cases (see Figure 2 in the main body of this report).
Figure A4 – Modelled trailing edge noise directivity from WPA1 (dotted lines), cases for $m=0.3$ with both detached and attached flow (dotted lines); corrected directivity accounting for far-field refraction propagation effects (straight lines).

Figure A5 - Modelled trailing edge noise directivity from WPA1, corrected for directivity.
ANNEX C – APPLICATION OF AN AM METRIC ROUTINE TO A RANGE OF SIGNALS

A principal AM metric routine has been developed and applied to a variety of signals. It is similar to the first category of methods described in WPB1, i.e. Fourier analysis of the acoustic signal envelope. This was based on an implementation done in MATLAB originally developed by RES. This method is described in section 4.3.

C.1 Application to simple test signals

This implementation has first been applied to a set of simplified test signals to assess the normalisation process used and the effect of different input parameters. A simple sinusoidal signal is defined directly in terms of the $L_{Aeq,100\text{ms}}$ signal envelope directly, and the analysis applied to this signal. The modulation frequency $f_m$ is fixed to 0.5Hz. The peak-to-trough modulation amplitude is defined when generating the signals. For this pure signal, one clear peak at $f_m$ can be seen in the spectra: see Fig. C1. The amplitude of this peak in the modulation spectrum can be compared to that expected from the artificial signal: this is done for a range of modulation depth in Fig. C2. A good agreement is obtained both in terms of the absolute values obtained and the general trend observed.

When considering the 20s signal period, a standard Blackman-Harris windowing function was used to produce the results in a first instance. A rectangular window could be considered instead: as expected, the resulting spectrum has less accuracy in the spectral domain, with the apparition of side lobes: Fig. C3. But the peak at the modulation frequency in the raw Power Spectral Density (PSD) is finer than when using the Blackman-Harris window, and with a higher amplitude; however, the use of integration over the PSD over a frequency window (of width set to 10% of $f_m$) means that similar amplitudes are obtained for the amplitude of the integrated modulation spectra at $f_m$ with either window function: see Fig. C2.

Figure C1 – Time history ($L_{Aeq,100\text{ms}}$, left) and resulting modulation spectra (right) of artificial sinusoidal signal envelope (with Blackman-Harris window) – example of 10dB(A) modulation depth
ANNEX C - APPLICATION OF AN AM METRIC ROUTINE TO A RANGE OF SIGNALS

Figure C.2 – Amplitude (dB) of peak modulation in spectra for different sinusoidal signals of defined modulation depth

Figure C.3 – Resulting modulation spectra for signal of Fig. C.1, using rectangular windowing

For a stimuli of 10dB(A) modulation depth, similar integrated peak values are obtained for either windowing method, with differences of 0.3dB. In contrast, the peak of the raw PSD is 6dB for the Blackman-Harris window, and 8dB for the rectangular window. In effect, the spectrum integration process compensates for the diffusion of the reduction in frequency resolution introduces by the windowing effect, and therefore the significance of the windowing function used is reduced.

As discussed in WPB1, modulation signals might not necessarily be sinusoidal, and this introduces some additional considerations. This can be illustrated by considering the (unrealistic) extreme example of an ideal saw-tooth signal, modulating at a similar rate (f_m=0.5Hz): see Fig. C.4. The resulting modulation spectrum contains secondary peaks at harmonics of the main frequency f_m. WPB1 notes that, if we maximise a metric that includes the sum of the amplitudes of the modulation spectrum at this frequency (f_m) and integer multiples of it (k f_m), we can determine the fundamental frequency of the modulation of such signals in an optimal way. Whilst this may be a good way of identifying the modulation frequency in certain applications, this is less of a consideration for wind turbine noise applications in which the modulation rate is related to the rotation of the turbine(s) which is more likely to be well-known. This does not tell us what is the correct way (if any) of determining the modulation amplitude corresponding to these more complex signals.
We can examine what this means for the example of the saw-tooth modulation. It can be seen that the amplitude of the peak at the fundamental frequency in this case does not match the overall peak-to-trough amplitude of this modulated signal envelope. For this ideal signal, it can be shown that multiplying the first harmonic by a factor of $\pi/2$ results in a good estimate of this total amplitude. A reasonable approximation is obtained by adding the amplitude of the first two harmonics, although it can be seen that adding further harmonics (3 and more) will result in artificially high results: this is because this summation does not take into account the phase information of the spectral analysis. It should also be noted that for real signals (as will be seen below), high-order harmonics will become increasingly ‘swamped’ by noise. As above, the use of a rectangular window will result in a marginally higher value: for a design modulation depth of 10dB, after multiplication with $\pi/2$ factor, results in a total amplitude of 9.8dB instead of 9.4dB).

It should be noted that there is no reason why a metric which accounts for the harmonics in the signal would correspond better with the subjective response: it is equally conceivable that the main harmonic would have the most significant effect. Importantly, the consideration of any subjective response should be made consistently with the consideration of the metric normalisation, including the way signal harmonics are accounted for. We therefore next consider the artificial stimuli used in the work for WPB2.
C.2 Application to artificial stimuli developed for subjective testing under Work Package B2

The analysis method was applied to a representative selection of the artificial AM stimuli signals used in the study of subjective response as part of the current project, for the final tests described in Appendix V of WPB2. The artificially generated stimuli were played back in the listening room and recorded as audio signals to allow post-processing and analysis.

As discussed in section 17.4 of WPB2, the peak-to-trough variation in the short-term RMS levels of the signal was used as a guide to aid the design of a range of stimuli, with typical variations between 0 and 12 dB(A). This simple modulation depth metric is designated as ‘MD’ for clarity and consistency with WPB2. It was reasonably well-defined (through the use of averaged peak and trough levels) for these artificial signals, but this type of analysis becomes more difficult to apply in practice to realistic signals, and therefore the application of more precise analysis methods will be compared to the design metric MD.

The modulation peaks (with a defined frequency content) were overlaid on top of a masking signal (un-modulated ‘wind turbine noise’ in this instance). The spectrum of the modulation signal was centred on the 300Hz region, with a 180 Hz bandwidth and a slight low-frequency bias. The envelope of the pulses was also asymmetric in time, and assumed a Gaussian profile: the modulation was therefore effectively non-sinusoidal: see Figure C6.

This translates in a clear modulation spectra, with several peaks visible at integer multiples of the modulation frequency of \( f_m = 0.8 \text{Hz} \) which was used. The modulation analysis was done using the main metric routine for a range of stimuli, after A-weighting the recorded stimuli using the dBFA software from 01dB. The resulting modulation spectra corresponded to the entire duration of the stimuli signal (20s).

To make the analysis scale-invariant and eliminate the 0Hz component of the spectrum, a de-trending analysis is made, by calculating an average value for the spectrum and subtracting it: this can be done for example using a 5th order polynomial, overall average or moving average (the ‘optimal’ method will depend on the evolution of the signal).

The modulation analysis is first made of a full set of stimuli, all normalised to 40dB LAeq,20s. It was subsequently verified that the analysis results were similar for stimuli designed to different normalised levels, which is consistent with the stimuli design procedure (in which the overall gain was changed), and confirms that the procedure is scale-invariant. The lack of substantial component near 0Hz shows that the stationary component of the signal has effectively been supressed: see for Figure C6.

![Figure C6](image-url)

**Figure C6** – Time history (LAeq100ms, arbitrary scale, left) and resulting modulation spectra (right) of artificial AM stimuli – example of 6 dB(A) design modulation depth
WIND TURBINE AMPLITUDE MODULATION: RESEARCH TO IMPROVE UNDERSTANDING AS TO ITS CAUSE & EFFECT
Collation of Work Package Reports and Final Reporting

ANNEX C - APPLICATION OF AN AM METRIC ROUTINE TO A RANGE OF SIGNALS

Figure C7 - Blackman-Harris window, 20s analysis period, de-trending using 5-th order polynomial – harmonics analysis

The calculated amplitude of the peak in the modulation spectra can be compared to the design (MD) value for the range of stimuli considered: see Figure C7. It can be seen that for the un-modulated signal, some residual modulation appears to be detected, and this was at frequencies close to the modulation frequency used in the other stimuli (peak at 0.7Hz instead of 0.8Hz). This could be a combination of the inherent characteristics of restricted-band signals (see WPB2), or to the inherent noise present in the analysis itself. For the actual modulating stimuli (MD ≥ 2dB), the calculated modulation amplitude peak at $f_m$ increases in relation to MD, with a similar slope, but giving results which are consistently of the order of 1dB below MD. It should be noted that this difference of 1dB is comparable to the uncertainty in the determination of the MD quantity. As shown in Figure C8, the peaks and trough are determined as mean values of peaks of short-term dB(A) values that may vary by this amount in any case (because of masking effects): this is represented by error bars on Figure C7.

Figure C8 - WPB2 Figure 17.9: evolution of measured short-term A-weighted RMS values for an artificial stimuli at MD = 6dB and representation of mean peak and trough levels used to determine this value of MD
Because of the non-sinusoidal nature of the signal, as evidenced by the presence of harmonics in the spectrum, it is natural to seek to reflect this in the overall modulation metric. As the WPB2 stimuli pulse shape is asymmetric, we can make reference to the analysis of the pure saw-tooth signal above: firstly, a factor of π/2 was applied to the calculated amplitude of the fundamental; secondly, the sum of the amplitude of the first two harmonics was also considered (with reference to the above analysis and as harmonics of higher order were often difficult to distinguish in the calculated spectra). The resulting corrected values (Figure C7) are close to MD for the lower modulation values, but then diverge strongly for MD>5dB. The slope of the change with increasing modulation for these alternative metrics is also different from the one obtained when considering only the fundamental peak, and does not seem consistent with the results of the subjective testing shown in WPB2, which do not exhibit such a dramatic increase in annoyance with increasing MD.

These results suggest that corrections which were relevant to idealised saw-tooth signals may not necessarily be applicable in the same way to more general stimuli which were based on actual recordings of wind turbines AM. We can also consider the results of the sensitivity tests of WPB2 (see report section 7), which determined that the degree of asymmetry in the shape of the modulation pulses, as defined by a ratio of rise time versus fall time, did not have a significant effect on the subjective response to the stimuli. Finally, considering increasing harmonics of the fundamental modulation frequency will in practice be increasingly affected by noise in the signal and the analysis process.

In the Figure C9, a similar analysis of the calculated modulation amplitude of the first fundamental at f_m, is undertaken for a range of different parameters. A different signal de-trending method is used, with a moving average over a window of 10s centred on each interval period (instead of a polynomial fit). A rectangular windowing function is also used. Finally, a filtered version of the signal is analysed by applying a band-pass filter covering the 315Hz 1/3 octave band, as this is the frequency region which dominates the modulating part of the signal (as is known in this case because these are artificial stimuli).

Figure C9- Analysis of the artificial stimuli using different modelling parameters

The changes in the windowing or de-trending method used in the analysis do not appear to significantly affect the analysis outcomes. Considering a filtered signal (315Hz 1/3 octave band) results in consistently higher values of peak modulation at BPF, which appear closer to the MD metric although this not
necessarily significant and is likely specific to the present stimuli signal. The increase can be attributed in part to the reduced level of masking present in the filtered signal, although a contribution from the increased irregular nature of the resulting modulation spectra (see Figure C10) seems to be a factor.

Figure C10 - Comparison of modulation analysis for an artificial stimuli sample (MD = 4dB) for both the unfiltered signal (left) and that obtained filtering only the 315Hz 1/3 octave band (right).

WPB2 shows the results of the analysis of the final tests of subjective response for a range of different metrics, including the peak modulation amplitude (first harmonic) given by the implementation developed by RES. This highlights that the results of the subjective testing must be considered in relation to the appropriate metric.

Application to recorded noise samples from operational turbines

As a result of Work package C WPC, a selection of samples was collected. Specific periods corresponding to worst-case levels of modulation experienced during quiet periods were selected and were analysed using the technique used above. The goal of this study was to evaluate the application of such techniques to real data and evaluate its robustness, practical outcomes and the effect of range of analysis input parameters on the outcome metrics.

Some of the key feature of realistic recordings as opposed to simulated or idealised signals are:

- The presence of spurious sources of noise from background sources present in the environment, which either produce masking effects (which ‘drown out’ the modulation) or produce changes in noise levels which can affect the modulation analysis itself
- Even when dominated by wind turbine noise and/or wind turbine AM, the signals will tend to be highly variable, and levels of modulation experienced will change significantly with time

Regarding the latter point, the modulation spectra analysis using the techniques based on Fourier analysis of the signal envelopes effectively represent an average over the analysis period. The whole period will be split in segments of varying length, over which the modulation analysis is made. The selection of longer analysis periods may average out spurious effects but conversely may dampen the calculated amplitude of the periods of highest modulation.

It is useful to consider the evolution of the whole modulation spectra over the entire analysis period. This helps to highlight the range of frequencies experienced and may highlight for example the presence of harmonics of a fundamental modulation frequency, changes in modulation strength as well as periods where the analysis was affected by spurious noises (see WPB1), and the spectrum is unlikely to correspond modulation at the turbine blade passing frequency. For example: see Figure C12.

This highlights the need to isolate modulation components which may be related to the operation of the turbine (see WPB1) by concentrating on the region located close to the BPF: in the following analysis, the following will be considered separately:

- the overall peak in the modulation spectrum (as in WPB1)
ANNEX C - APPLICATION OF AN AM METRIC ROUTINE TO A RANGE OF SIGNALS

- local peaks in the modulation spectrum which are located within 10 spectral lines of the expected BPF for the turbine, which was set as an input of the analysis

From the data collected as part of work package C, the analysis focused on periods in which clear modulation was identified. These represent particular periods which may not be representative of a typical situation, even at the properties identified, but were considered representative of periods of AM of interest.

The following files will be considered, with a naming convention consistent with WPB1: Table C1.

<table>
<thead>
<tr>
<th>Sample File</th>
<th>Name</th>
<th>Duration (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>DTI LFN [2] study - Site 1</td>
<td>570</td>
</tr>
<tr>
<td>2</td>
<td>File 1 - extract, last 20s</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>DTI LFN study – Site 2 - external</td>
<td>83</td>
</tr>
<tr>
<td>4</td>
<td>DTI LFN study – Site 2 - internal</td>
<td>81</td>
</tr>
<tr>
<td>5</td>
<td>Van Den Berg sample (JSV article)</td>
<td>173</td>
</tr>
<tr>
<td>6</td>
<td>Web-sourced audio (extract)</td>
<td>23</td>
</tr>
<tr>
<td>7</td>
<td>Other AM example</td>
<td>60</td>
</tr>
</tbody>
</table>

Table C1 – sample file list obtained from WPC as input to modulation analysis

File 1 - DTI LFN study - Site 1

The period selected (9’30’) was a period identified in the DTI LFN report [2] as one for which turbine noise modulation particular audible. This was measured during the middle of the night/early morning which was relatively quiet. Noise levels were measured externally outside the complainants’ property at a free-field location.

The overall time history of Figure C11 was divided into 10s analysis blocks which are then analysed using the above methodology. The resulting set of modulation spectra for the entire data period is Figure C12 for the following parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPF fundamental modulating frequency ($f_m$)</td>
<td>1.3Hz</td>
</tr>
<tr>
<td>Detrending Method.</td>
<td>5th order Polynomial</td>
</tr>
</tbody>
</table>
Figure C11 - Evolution of the time-history of short-term $L_{Aeq,100ms}$ level over the entirety of file 1.

Figure C12 - Evolution of the modulation spectra for file 1 for different 10s analysis blocks (dB scale shown on the right)

In Figure C12, a clear trend highlighting the presence of fundamental modulation close to 1.3 Hz can be seen as a vertical line of varying intensity. This frequency is consistent with the reported rotational speed of the turbines of 26 RPM [2], and the turbine model operating in a fixed speed operation. A secondary, fainter line can just be distinguished: it represents the second order harmonic close to 2.6 Hz. An example of a period of relatively clear modulation is shown in Figure C13. Other periods also appear to be affected by extraneous sources of noise, as identified by an unrepresentative modulation spectrum which contains components at the lowest frequencies or over a wide range of the spectrum (horizontal lines): an example is also shown in Figure C14. This justifies the choice of $f_m$ which was made for the analysis. This is
illustrated in a graph of the frequency of the peaks in the spectrum: Figure C15. When the frequency of overall peak in the spectrum deviates from \( f_m \) (as in the example of Figure C14), then the peak modulation does not represent modulation of the wind turbine noise, it is just an artefact. A metric which sums up the amplitude of the integrated spectrum at the first two harmonics (\( f_m \) and \( 2f_m \)) is also shown, although this does not necessarily provide a particularly relevant quantity, particular when considering that the component at \( 2f_m \) is not necessarily visible in the spectrum (Figure C12).

Figure C13 - Example of a modulation spectrum corresponding to clear modulation at BPF (block 12)

Figure C14 - Example of a modulation spectrum contaminated by spurious data (block 2, unidentified ‘whistling’ noise) - in this case the peak at 1.3Hz is lower than that content <1Hz
Figure C15 - Frequency of peaks in the modulating spectra: peak of maximum amplitude overall or local peak in proximity to the expected BPF.

Figure C16 - File 1 – 10s analysis period – peaks in modulation spectrum shown both overall and close to fm. The sum of the amplitude of the first two harmonics of fm is also shown.

Furthermore, considering a sample of several minutes means that it is possible consider different durations for the segments or blocks over which the analysis is undertaken, as discussed above. For example, Fig. C17 presents the evolution of the modulation spectra (comparable to Fig. C12) when using 1 minute time blocks: this results in a coarser analysis. Although the modulation frequency and its harmonic are still clearly identifiable, the amplitude is affected due to an effective averaging process. Fig. C18 presents the evolution of the calculated peak modulation amplitude (close to $f_m$) for analysis over different time scales.
ANNEX C - APPLICATION OF AN AM METRIC ROUTINE TO A RANGE OF SIGNALS

Figure C17 - Evolution of the modulation spectra for file 1 for different 1minute analysis blocks (note change in horizontal scale)

Figure C18 - Amplitude of modulation spectrum peak (near fm) for analysis of the file 1 sample, when analysing the time series in blocks of different size: 10s, 20s and 60s.

File 2 – DTI LFN study - Site 1 (extract of file 1)
This considers in more detail the results above, as this sample corresponds to the last 20s of the sample above. The evolution of $L_{Aeq}$ with time (including the effect of filtering for different frequency ranges) is shown in Fig. C18, and along with the resulting modulation spectra in Fig. C19. The calculated modulation depth at $f_m$ is 3.6dB.

Page 87 of 98
If the 20s file is separated into two 10s blocks, the peak amplitude for each block reduces to approximately 1.5dB. This demonstrates that the choice of the duration and position of the analysis period has non-trivial consequences on the calculated modulation amplitudes for cases in which it varies significantly with time.

Further analysis – files 1 and 2

WPB1 notes that using a low-pass filter on the recorded audio signal to exclude all frequencies above 1kHz may assist in eliminating many sources of spurious noises present in rural environments and would not significantly affect the wind turbine noise signal. For the signal in files 1 or 2 this does not make a significant difference to the overall analysis as the spurious noise sources cover a large frequency band.

But as noted in [2] and WPC, the modulation is dominated by the frequencies in the region 400-800 Hz. We can therefore undertake the analysis after filtering for this region, considering for example the 630 Hz 1/3 octave band. The resulting modulation spectra evolution for file 1 is given in Fig. C21, and the change in the BPF peak in modulation amplitude with and without filtering is also shown in Figure C22. When looking at the 20s extract in particular (file 2), the resulting modulation depth at $f_m$ increases marginally from 3.6 dB to 4.4dB, when analysing over the entire 20s period.

Filtering the audio signal in a narrower octave band has therefore assisted the exclusion of spurious noise sources, but this requires a knowledge of the dominant frequency content of the modulation signal.
can be determined through a spectrogram of the signal such as shown in WPC, Fig. C2a. The effect on the modulation amplitude was also noted but this did not appear to be unrepresentative.

Figure C21 - Evolution of modulation spectrum for file 1, 10s analysis periods, signal filtered in the 630Hz 1/3 octave band

Figure C22 - Evolution of modulation spectrum amplitude at BPF for file 1, for 10s analysis periods, with the signal filtered in the 630Hz 1/3 octave band
Files 3 and 4: DTI LFN study – Site 2 - measured externally and internally

The available measurements from this site were made in parallel both at a free-field location outside the dwelling (file 3) and at an internal location (file 4) in a bedroom facing the wind farm (windows open). The period for the extract of file 3 and 4 correspond to a period of relatively marked modulation. A detailed time-history is shown below, as well as results of the modulation analysis undertaken with the following parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPF fundamental modulating frequency ($f_m$)</td>
<td>1.35Hz</td>
</tr>
<tr>
<td>De-trending Method</td>
<td>5th order Polynomial</td>
</tr>
</tbody>
</table>

The results show the presence of modulation at the BPF, which then dominate the modulation spectrum, except at some periods where peaks are below <0.5Hz and are therefore not related to the wind turbine. The value of the peak at BPF is shown for different analysis periods in both cases: it can also be seen that the values calculated outdoor and indoor are comparable. Further detailed analysis in 1/3 octave bands was not conclusive because of the lack of clarity in the frequencies dominating the modulation.

Figure C23 - Evolution of the time-history of short-term $L_{Aeq,100ms}$ levels for both the external and internal levels (file 3 and 4 respectively) at Site 2 DTI LFN study

Figure C24 - Evolution of the modulation spectra for file 3 and 4 for different 10s analysis blocks
File 5 - Van Den Berg sample (JSV article)
A sample of approximately 3 minutes was extracted from the data supplied, in which some variable levels of AM are present as described in WPC. The data was already supplied filtered to exclude frequencies above 1kHz. Following an analysis in 10s blocks, the resulting modulation spectra evolution (Figure C26) exhibits a clear trend as a vertical line, highlighting the presence of fundamental modulation close to the $f_m=1$ Hz (likely to be BPF).

Figure C25 - Amplitude of modulation spectrum peak (near $f_m$) for analysis of the file 3&4 samples, when analysing the time series in blocks of different size: 10s and 20s.

Figure C26 - Evolution of the modulation spectra for file 5 for successive 10s analysis blocks
Figure C27 - Evolution of the time-history of short-term $L_{Aeq,100ms}$ level for file 5 (extract).

Figure C28 - Example of a modulation spectrum corresponding to clear modulation at BPF (block 18) (please note that noise levels are represented on an arbitrary scale, as the audio data was not calibrated)

Figure C27 shows a time history for a period of clear modulation towards the end of the recording, and Figure C28 another example in which several harmonics appear visible in the spectrum (as is also apparent in Figure C26).

File 6 - Web-sourced audio (extract)

There is limited information available on the recording, but it appears to be an example of turbine AM noise measured in the far-field. The A-weighted energy time history and the corresponding modulation spectrum for a representative 20s extract from the recording are shown in Figure C27. A modulation peak is apparent close to 1Hz, which could be associated with the operation of neighbouring turbines, however there are other apparently spurious peaks which could be due to artefacts in the recording.
ANNEX C - APPLICATION OF AN AM METRIC ROUTINE TO A RANGE OF SIGNALS

Figure C28 – Time history of 100ms noise levels (arbitrary scale, non-calibrated data) derived from an extract of the recording and corresponding modulation spectrum

File 7 – OAM example

Figure C29 shows the time history for a sample period of ‘other’ AM described in WPC, measured at a free-field location in the far-field of a wind farm site (>800m from the turbines), during a quiet period where little other sources of ambient noise were present. The corresponding modulation spectrum when undertaking the analysis is shown in Figure C30, with peak modulation levels of up to 5.5 dB present at a frequency of approximately 0.8Hz. The analysis of this data sample in 20s results in marginally lower peak modulation amplitudes in this example: Figure C31.

Figure C29- Evolution of the time-history of short-term $L_{Aeq,100ms}$ level for file 7
Figure C30 - Evolution of the modulation spectra for file 7 for successive 10s analysis blocks

Figure C31 - Comparison of peak modulation amplitudes at 0.8Hz between an analysis of file 7 over contiguous periods (10 or 20s).
Background noise analysis

A sample of audio recordings made in the absence of any wind turbine noise at a typical rural locations were analysed using the Fourier techniques described earlier. These were based on the recordings which were used for a systematic analysis of proposed AM investigation techniques [15]. Each of the recordings was approximately 10 minutes long. A selection of recordings was selected at random but reviewed to represent a range of conditions, from quiet periods with or without the presence of bird noise, to noisier periods in which winds were higher or which were affected by agricultural noise. The ‘modulation’ analysis was made based either on the 100ms $L_{Aeq}$ levels or on the 315Hz 1/3 Octave band (for consistency with the above analysis).

Quiet conditions
Windier period
Bird noise can be highly variable in time and sometimes dominant in some rural locations, particularly during some early morning periods. Because of its regular nature it may sometimes appear to modulate at frequencies characteristic of wind turbine noise. Because it is generally dominated by high-frequencies, it can be suitably filtered, for example by considering the 315Hz octave band considered above.
Agricultural activity

This type of noise is an example of one more difficult to filter out, but will tend not occur for limited periods only. Whilst some high values are detected, their isolated nature is not similar to that observed for WTN.
Contents

8. Mechanisms and causes of Amplitude Modulation (AM) and Other Amplitude Modulation (OAM) of aero-acoustic wind turbine noise, *DTU Wind Energy*
Mechanisms and causes of Amplitude Modulation (AM) and Other Amplitude Modulation (OAM) of aero-acoustic wind turbine noise

DTU Wind Energy
Mechanisms and Causes of Amplitude Modulation (AM) and Other Amplitude Modulation (OAM) of Aeroacoustic Wind Turbine Noise

Helge Aagaard Madsen
Andreas Fischer
Knud Abildgaard Kragh
DTU Wind Energy I-0095 (EN)
ISBN: xxx-xx-xxxxx-xx-x
August 2013
Authors: H. Aa. Madsen, A. Fischer and K. A. Kragh
Title: Mechanisms and Causes of Amplitude Modulation (AM) and Other Amplitude Modulation (OAM) of Aeroacoustic Wind Turbine Noise inflow measurements

August 2013

Pages: 46
Tables: 0
References: 13

Technical University of Denmark

www.vindenergi.dtu.dk
Contents

1 WP1: Compilation of Results 8
   1.1 Objectives 8
   1.2 Observed wind shear 8
   1.3 Correlation of wind shear to AoA 9
   1.4 Modelling rotor aerodynamics with wind shear inflow 14

2 WP2: Aero-acoustic Modelling 17
   2.1 HAWC2 computations on NREL 5MW turbine 17
   2.2 HAWC2 computations on modified NREL 5MW turbine 19
   2.3 Surface pressure characteristics of NM80 2.3MW wind turbine (DANAERO) 20
   2.4 Aeroacoustic modelling 27

3 WP3: Mitigation Strategies 32
   3.1 Collective Pitch Control 32
   3.2 Individual Pitch Control 32
   3.3 Yaw Control 34

4 WP4: Effect of Stall on Noise Emission 37
   4.1 Airfoil aerodynamics 37
   4.2 Far field Sound and Surface Pressure for High AoAs 37
   4.3 Far field Sound Modelling for high AoA in Pre Stall 40
   4.4 Conclusions 40

A Turbines used in the investigation and influence of turbine size 43

B Difference between angle of attack AoA and inflow angle IA 45
Executive summary

The work explores the mechanisms and causes of amplitude modulation (AM) of aeroacoustic noise from wind turbine rotors and specially the occurrence of lower frequency amplitude modulation identified by RenewableUK at different sites and denoted “other amplitude modulation” (OAM). The work has been organised in four work packages (WP) according to: "Description of Contract Work for RenewableUK on Mechanisms of AM and OAM", DTU Wind August 15, 2012 and Revised January 28, 2013.

WP1: Compilation of Results

The objectives with this WP are:

- Illustrate from literature what variations of wind shear have been measured.
- Show the correlation of wind shear to variations in angle of attack (AoA).
- Show modelling capabilities of influence of wind shear on rotor aerodynamics.

A characterisation of measured wind shear from 40-160m height over one year at the Høvsøre wind turbine test site shows that the strongest wind shear with a variation in wind speed of about 4.5 m/s from 40-160m occurs 2.7% of the time. The experimental proof of the link between wind shear and angle of attack variations (AoA) comes from the DANAERO experiment carried out from 2009 to 2010 in Denmark. As explained in Appendix A, AoA cannot be measured directly on a rotor but instead a local inflow angle (IA) to a blade section of the blade can be measured and, in the present case, at radius 36m on a 52m blade. In figure 8 it is shown how the IA as a function of blade azimuth position varies during a period of 7 hours where the wind shear develops from an extreme level during night conditions to almost no shear at 11.00am. This data is further processed so that the range of IA variations over one rev is shown as a function of the slope of the linear wind shear approximation, figure 12. To show the link between wind shear and AoA, simulations were run for the same wind shear slopes and the computed AoA were converted to IA, which can then be compared with the measured IA curve, figure 12. The overall conclusion from the measurements and the computations is that there is experimental evidence of AoA variations of at least 4°-5° for extreme wind shear, based on the data in figure 12. Finally, some results from using different computational models of a wind turbine operating in strong shear conditions are presented, illustrating, for example, how the low speed flow on the ground can move up into higher levels a few diameters down in the wake due to wake rotation. This could cause quite different AoA variations on a downwind turbine operating in this wake.

WP2: Aero-acoustic Modelling

There are three parts in WP2. In the first part, (sections 2.1 and 2.2) a number of simulations results are presented to illustrate how different wind shear and turbulence conditions in the inflow to the rotor cause AoA variations. The simulations are carried out on a 5MW reference wind turbine; a turbine defined within the research community, with all design data freely accessible. Further description of the turbine can be found in Appendix A. A range of AoA variations are depicted in figure 17 for different wind shears and turbulence intensities. Overall there is an almost constant level from 7-10m/s wind speed and both the mean and the
amplitude increase slightly from 10-12m/s before the mean then decreases when the turbine reaches rated power. It can be seen that turbulence increases the range compared with only shear conditions.

As shown on the left part of figure 21, the turbine operates on the lift coefficient curve well below beginning stall. However, if the planform is modified as shown in figure 18 to a more slender blade design, as has been the tendency in blade design for some years, the operating point moves upward as seen on the upper curve in figure 20. Now the variation around the mean AoA level is seen to reach the non-linear part of the lift curve slope due to initial trailing edge separation.

The second part of WP2 is an analysis of high frequency surface pressure measurements on a NM80 turbine carried out within the DANAERO project. The present analysis is focused on time series where the turbine was forced to approach stall by pitching the blade to $-5^\circ$, and running the turbine at constant speed but at a reduced level compared with rated speed. Further there was a considerable shear in the inflow. The signal from a microphone close to the trailing edge was analysed representing the source of trailing edge noise. During a period AoA variations were up to a range of $4.5^\circ$. with the maximum AoA reaching $13^\circ$, figure 28. During this period an extreme level of AM was seen with a range over rotor rev of 14dB in the frequency range below 200 Hz, figure 29 and 30.

The third part of WP2 contains simulation results of turbulent inflow (TI) noise and trailing edge noise (TE) for different inflow conditions to the turbine. The directivity of TE noise is at a maximum for the blade in the 3 o’clock position as seen in figure 35, whereas the peak inflow angle for a strong shear is in the 12 o’clock position, figure 34. For a listener 70m downstream, this combination of directivity and AoA leads to a peak sound from the rotor at around a 1-2 o’clock position, figure 33. For the TI noise the peak value for the same listener position is at the 6 o’clock position, figure 36.

WP3: Mitigation strategies

Three mitigation strategies are investigated: 1) collective pitch control for decreasing the mean AoA and in this way move the operating point on the lift curve away from stall; 2) individual pitch control (IPC) in order to reduce the AoA variations and 3) yaw control also to reduce AoA variations.

The use of the collective pitch system to reduce the mean AoA is a well-known procedure for reduction of broadband noise from a wind turbine. However, it may also be an efficient method to reduce AM of noise if the rotor is operating close to stall. A demonstration of reducing the mean AoA is shown in figure 37 where the minimum pitch setting in the control has been increased from 0$^\circ$ up to 5$^\circ$. However, in particular for mean pitch angles greater than 2$^\circ$, the power loss increases significantly as shown in the right graph of figure 37.

Next the effect of applying IPC is demonstrated. In the present case it is a standard IPC that is set up to reduce the blade root bending moments. However, in most cases it will also reduce the AoA variations and in particular what is due to wind shear (see left graph in figure 38). When there is considerable turbulence in the inflow the effect of IPC is less promising (right graph in figure 38). The power loss by applying IPC is in general small and less than 1% as seen in figure 39.

Finally, the effect of operating the turbine at different yaw errors is simulated. For operation in wind shear it seems that a yaw error can be found as a function of wind speed which leads to an AoA variation that is less that running the turbine at zero yaw error, figure 41. A reduction of about three quarters of a degree, can be obtained. On the other hand; if the turbine is operating at a yaw error to the other side this can cause considerable AoA variations, figure 41.
WP4: Effect of Stall on Noise Emission

The study was carried out as an extension of a previous analysis of an existing data set measured by DTU Wind Energy in the Virginia Tech University wind tunnel in 2011. In particular the study was focused on analysis of data measured at high AoA in the wind tunnel to see the effect of stall on the airfoil. The experimental set-up comprised two airfoil sections with around 60 surface pressure microphones each, plus an acoustic array outside the tunnel. Also the surface pressure distribution on the blades was measured.

Due to limitations of the operational frequency range of the microphone array it did not provide data below 1000 Hz, figure 45, so the main conclusions have to be done on basis of the surface microphones. Considerable increases in the surface pressure spectra below 1000 Hz are seen when entering into stall, figure 46. The level increase is more than 10dB at a frequency of 200Hz when going from pre-stall to stall. A numerical model is applied to derive the far field sound based on the surface pressure measurements for AoA up to pre-stall. At a frequency of 200Hz the far field sound is modelled to increase with 2.8dB for just one degree increase in AoA.
1 WP1: Compilation of Results

1.1 Objectives

The objectives with this chapter are to:

- Illustrate from literature what variations of wind shear that have been measured
- Show the correlation of wind shear to variation in angle of attack (AoA) or inflow angle (IA)
- Show modelling capabilities of influence of wind shear on rotor aerodynamics and the influence on AoA variations

Deriving results on these subjects will constitute the basis for using numerical investigations in the next chapter to further investigate what the influence wind shear and turbulence in the inflow of a MW turbine has on AoA variations and to see if this can lead to initial trailing edge separation.

1.2 Observed wind shear

The information presented in this section is from a paper by Antoniou et al. [1] from 2007 where the wind shear characteristics measured over one year at the wind turbine test site at Høvsøre in Denmark have been presented.

Citation from paper:
"The Høvsøre test site is the National Danish Test Station for Large Wind Turbines, which is situated in the northwest of Denmark, close to the North Sea. The test site is flat, surrounded by grassland with no major obstacles and is situated a distance of 1.7 km from the west coast of Denmark. The prevailing wind direction is from the west. Figure 1 shows the site layout and the instruments used. The wind profiles have been produced combining the measurements from two met masts at the Høvsøre test site. The two met masts are the aviation light met mast, and the met mast to the right of the picture."

![Figure 1. The test site and the heavily instrumented met tower along with a list of the available instruments.](image)

The analysis was carried out using data from the cup wind speeds at 40m, 60m, 80m, 100m, 116m and 165m. An example of the wind speeds measured during one day in March 2007 is shown in figure 2. The wind shear is mainly determined by...
the atmospheric stability. At night the atmosphere is stable and we see a large wind shear but during daytime when the sun heats up the atmospheric boundary layer the atmosphere becomes unstable and the wind shear almost disappears.

For the analysis procedure of the data we cite from the paper: "the wind profiles from 6m/s to 8m/s for the height of 80m and for one year period were chosen. Within this period, 2340 profiles were found from the easterly directions between 60° and 120°, which were binned and categorised according to their shape into 173 profiles, non-equally weighted, figure 3. Subsequently all mean profiles were normalised so that the wind speed at 80m became equal to 7m/s, \( U_{80} = 7 \) m/s, using the ratio \( R_i = \frac{7}{U_{80}} \), where \( i \) is the profile number, see figure 3(b)."

For the strongest wind shear occurring 2.69% of the time, the variation in wind speed from 40m height to 160m height is close to 4.5m/s. The wind shear with a variation of 3m/s occurs more than 13% of the time. In summary wind shear with a variation from 3m/s to 4.5m/s over 120m heights can occur regularly.

1.3 Correlation of wind shear to AoA

Most of the information on this subject is from the paper of Madsen and Fischer [2] but results from new analysis of data are also included. In ref. [2] the results on measuring the inflow to the rotating blade of a Siemens 3.6MW turbine at the Høvsøre test site were presented. These measurements were part of the DANAERO MW experiment [3] carried out in the period from 2007 to 2010. The objective with this part of the project was to investigate experimentally the inflow to a MW turbine during different atmospheric conditions. The inflow measurements
were made with a five hole pitot tube\(^1\) mounted at 36m radius on the rotor with a diameter of 123m (59% of the blade length), figure 4. These measurements were then correlated with wind speed measurements in a nearby meteorology mast instrumented with anemometers at heights position 10m, 40m, 60m, 80m, 100m and 116.5m and wind direction vanes at height position at 10m, 60m and 100m. Results from analysis of data during the day March 28 in 2007 are presented. That day was selected because it is a typical example of inflow conditions varying strongly from day to night with very stable atmospheric conditions during night time and thus strong wind shear, whereas during daytime the sun heats the atmospheric boundary layer creating a lot of mixing with the result that the wind shear almost disappears. In figure 5 the wind shear measured during one week in March 2007 is shown and the same daily pattern with strong shear during night and almost no shear during the day can be seen. The March 28 wind shear data are shown in more details in figure 6. The wind direction measured at three heights is also shown and a strong wind veer of 20° – 25° occurs during night time but during daytime it disappears completely.

The inflow to the rotating blade of the Siemens turbine was measured during the same period. The inflow angle IA to the blade measured with the pitot tube is shown in figure 7 as a function of azimuth and each curve was derived for a period of 10 min. by binning the instantaneous IA on azimuth position. It should be

\(^1\)A flow sensor that can measure the inflow velocity vector (two angles and the magnitude of the velocity vector) relative to the blade.
Figure 6. Variation of wind shear and wind veer during March 28, 2007 at the Høvsøre test site.

Figure 7. Inflow angle variations as a function of azimuth (10 min average) measured from 8 o’clock to 11 o’clock each hour on March 28, 2007. See the shear in inflow above. It should be noted that this is local inflow angles measured on the blade and not corrected for upwash.

noted that the IA is influenced by the local flow around the airfoil (upwash) and therefore not equal to AoA but typically showing bigger amplitudes. Further, it should be mentioned that the mean value of IA has not been calibrated.

Comparing now the four curves measured at each hour in the time interval from 8 to 11 o’clock in the morning it is seen that the amplitude over azimuth is reduced considerably. The blade top position is 90°, the blade bottom position is 270°. The biggest variation of IA is seen at 8 o’clock where it is about 9° with the maximum value reached 10° – 20° before the blade is in top position. It is also seen that the curve is quite smooth but with a small irregularity around 270° where the blade passes upstream of the tower. Comparing now with the curve measured at 9 o’clock it is seen that the reduction in amplitude only can be seen on the lower part of the rotor. Then the further reduction in amplitude during the next hour is seen over the whole rotor disc and finally at 11 o’clock the variation in IA is reduced to about 1°. Correlating the observed variations in IA with the development in wind shear shown in figures 5 and 6, the decrease in IA amplitude follows the decrease in wind shear.

Besides the data from reference [3] additional analyses of data from the night of
March 28 have been added to the previous IA data set and are shown in figure 8. The new data at 4 and 5 o’clock at night show even bigger amplitude with a maximum of $9^\circ - 10^\circ$. In the left figure the raw data is shown whereas in the graph to the right an offset of $-5^\circ$ has been added to better compare the amplitudes. The measured relative velocity profiles are shown for the same period in figure 9.

The measured relative velocity at an azimuth of $90^\circ$ and at $270^\circ$. This is probably caused by the wind shear which has most influence on the relative velocity and less on the IA.

Based on the wind shear data in figure 6 the development of the wind shear profiles in the time from 4 to 11 o’clock on March 28 were derived and are shown in figure 10. To parameterize the profiles, the exponential wind shear law was tested but did not fit so well and it turned out that a linear wind shear approximation in the height range of the rotor worked better and is shown in figure 11. With this parameterization of the wind shear profiles we can now form the link to the IA variations for the rotor blades that was shown in figure 8. The correlation between wind shear and IA variations is shown in figure 11 and it is seen that it is quite non-linear. The causes for this are not clear. Now we would like to establish the link to AoA instead of IA because AoA can give us the link to the operational point on the airfoil lift curve and thus also investigate possible beginning stall.

However, it is easier to convert simulated AoA to IA than correct measured IA to...
AoA. The procedure chosen was therefore to take the approximated linear shear profiles and run a simulation with the aeroelastic code HAWC2\(^2\) to simulate the corresponding AoA variations for these linear wind shear profiles. The AoA variations are the red curve in figure 12. Finally, the simulated AoA were corrected to simulated IA shown as the green curve in figure 12. Ideally, this curve should have coincided with the measured blue curve but deviations occur. This can be ascribed to different uncertainties: 1) the uncertainty in the conversion procedure from AoA to IA; 2) simulations were done for the wind shear profiles approximated with a linear wind shear variation and finally 3) the model uncertainty of

\(^{2}\)HAWC2 is an aeroelastic code developed at DTU and can simulate the rotor aerodynamics and the aeroelastic response of a wind turbine for specified inflow such as wind shear and turbulence.
HAWC2. However, we have established the relation between the wind shear and AoA variations and for the extreme wind shear conditions we can expect a range of AoA variation over one rotor revolution up to 4° and maybe 5°.

1.4 Modelling rotor aerodynamics with wind shear inflow

Wind shear in the inflow makes the rotor aerodynamics much more complicated compared with uniform inflow and therefore this has been an important research subject during recent years e.g. within the EU funded project UpWind finished in 2011. The results presented in this section are mainly from a paper by Madsen et al. [4] that contains the major results from the work on rotor aerodynamics in combination with wind shear in the inflow. In particular the aim here is to prove that the influence of wind shear can be modelled with reasonable accuracy using the aeroelastic model HAWC2 which later in this study will be used for a more systematic investigation on how wind shear affects AoA variations and whether this can lead to initial trailing edge stall.

Advanced models such as computational fluid dynamics (CFD) codes and vortex codes were in reference [4] used to gain insight into the rotor and wake flow in combination with strong wind shear in inflow. Contours of axial velocities at two downstream positions 1D and 3D from a CFD rotor computation with a wind shear exponent of 0.5 are shown in figure 13. The major influence of the rotor is the reduction in axial velocity but also some interaction with the ground is seen in the form of an acceleration just below the rotor. Another major characteristic is that the swirl of the flow in the wake causes the low velocities at the bottom part of the rotor to slowly turn anti-clockwise in the wake and at 3D downstream it covers almost one side of the wake from ground to top. This would give an even more complex inflow situation for a turbine positioned in the wake of the first turbine.

The advanced models (CFD and vortex codes) were, in the UpWind project, used to investigate the uncertainty of the computations from the simpler models, typically the aeroelastic codes used for time simulations of aeroelastic response in industry as well as by research institutes. The very simple reason to use the simpler
Figure 13. Computed flow field around a 126m diameter rotor operating in extreme wind shear with an exponent of 0.5. Computations are from computations with the 3D CFD code EllipSys3D and the axial wind speed contours are shown at a position of 1D and 3D downstream the turbine.

The comparisons carried out in the UpWind project showed that during uniform inflow all the models gave very similar results with power and thrust within a range of 1%. However, for strong shear in the inflow the deviations between the codes become bigger as shown in figure 14 where the induction along the blade is shown for four blade positions; blade pointing upwards is pos. 0°. The advanced models is that they are an order of magnitudes faster than the CFD models.

Figure 14. Computed induction for the 5MW reference turbine with a 126m rotor using a number of different codes of different complexity.

Model results in this figure are: the CFD codes EllipSys3D and ACL and the vortex codes GENUVP and AWSM. The other codes HAWC2, FLEX5 and GAST are the simpler engineering codes with the Blade Element Momentum BEM model for the induction. It is seen that in particular for the blade pointing upwards, the induction computed with the HAWC2 code and the GAST code seems to exceed the advanced model results. However, for the three other positions the results
are rather close. The influence of the observed deviation in induction is that the HAWC2 code might compute an AoA for the blade in top position that is slightly lower than the true value for the cases with strong wind shear in the inflow.
2 WP2: Aero-acoustic Modelling

2.1 HAWC2 computations on NREL 5MW turbine

The NREL 5MW reference turbine is a conceptual turbine developed by Jonkman [5]. All the details needed for aeroelastic modelling of this turbine are publicly available. The design is close to the REpower 5MW turbine, but there is also a significant difference to real turbines. The blades of the NREL 5MW turbine operate at comparatively low angles of attack. Hence there is a large margin to the stall angle and transient stall over one rotor rotation is therefore very unlikely. But this design leads to large chord lengths and heavy blades. Modern MW wind turbines have more slender blades and the airfoils operate at higher angles of attack.

We simulated different normal operation conditions. The inflow was either uniform or sheared according to a power law. The exponent of the power law was varied from 0.1 to 0.5 in steps of 0.1. Inflow turbulence is simulated with the Mann turbulence model [6]. We simulated with a turbulence intensity of 0.0 (no turbulence), 0.1 and 0.2. The wind speed was varied in steps as shown in figure 15. The typical behaviour of the turbine is presented for the case with uniform inflow and no turbulence by means of the AoA at r=50m and the rotor power, figure 16. The AoA at radial position r=50.67m (79.4% of the total blade length) varies periodically with the rotor rotation. The average value as well as the amplitude

Figure 15. Wind speed at 90m (hub height) in the simulation without turbulence.

Figure 16. Simulation with uniform inflow and no turbulence.
of the modulation grow with increasing wind speed. A maximum is reached for a wind speed of 11 m/s when the turbine is close to rated power. When rated power is reached, the controller starts to pitch the blades and the AoA is decreased. The highest AoA obtained in the operational range is $\alpha = 6^\circ$. The airfoil sections at the outer part of the blade have maximum lift at $\alpha = 14^\circ$. The airfoil drag starts to increase more rapidly at AoA $\alpha = 10^\circ$. That means that flow separation at the rear part of the suction side is possible at this AoA. However, for this turbine it is very unlikely that transient stall occurs in uniform inflow with no turbulence. The impact of turbulence and wind shear is visualized in figure 17.

Figure 17. Amplitude and mean values of the AoA as function of the wind speed.
The figures were generated by extracting the mean value and the maximum and minimum of the AoA for each 60 second time segment within a step of the wind speed. The first 15 sec after stepping the wind speed were discarded to avoid the unrealistic peaks. Wind shear has an influence on the amplitude of the AoA only at low wind speeds. Turbulence has a stronger influence on the amplitude and the influence is noticeable in the whole wind speed range. The mean value of the AoA is not much affected by shear or turbulence. In no case did the highest AoA obtained in operation exceed $\alpha = 6^\circ$ by very much. Transient stall will not occur on such a blade.

2.2 HAWC2 computations on modified NREL 5MW turbine

The design of the NREL 5MW reference turbine is very conservative. In a more realistic design the airfoils are operated at higher AoAs to achieve a higher lift. This leads to slender blades, because the chord length of the airfoils can be reduced. It is very important to reduce the weight of the blades of MW wind turbines. Therefore the slender blade is a more realistic setup. We redesigned the blade of the reference turbine by decreasing the chord length and twisting the blade to higher AoAs in compensation for the loss in lift. The new chord distribution compared to the old one is displayed in figure 18. The lift coefficient was increased by 30% at the outer part of the blade and the chord was reduced accordingly to achieve the same lift force as on the original blade. The behaviour of the turbine with modified blades is qualitatively the same as for the NREL 5MW reference turbine, figure 19. The whole figure is simply shifted to higher AoAs. With inflow turbulence the maximum AoA is $\alpha = 10^\circ$. In this case there is still a margin to the stall AoA, but flow separation close to the trailing edge of the airfoil on the suction side is possible. This change illustrates, in principle, how a more aggressive wing design can lead to the blade undergoing transient separation. Figure 20 illustrates in which range of the airfoil polar the blade is operated with the new designed blade. The airfoil is operated above the linear part of the polar, but still below maximum lift angle. For the highest AoAs the region with a steep drag rise is reached. In the original design the blade is operated well within the linear part of the airfoil polar, figure 21. All AoAs are located in the region with the lowest drag. The lift to drag ratio is better than for the modified blade design and flow separation is better suppressed.
Figure 19. Amplitude and mean values of the AoA as function of the wind speed for modified blade design.

Figure 20. Range of operational AoAs in terms of the airfoil polar for modified blade design.

2.3 Surface pressure characteristics of NM80 2.3MW wind turbine (DANAERO)

Note on the presented data: The pressure distribution and the AoA are measured at the radial position \( r=31 \) m. The surface pressure fluctuations are measured at radial position \( r=37 \) m with the microphones. The other systems failed at this position, but CFD computations [7] showed that the AoA at \( r=31 \) m and \( r=37 \) m is almost identical and the airfoil characteristics are similar. Hence, the pressure distribution should be similar as well.

We chose measurement data from Sept. 1st, 2009 at 10:00 when the turbine experienced extremely sheared inflow conditions. The wind profile measured by a met mast nearby is displayed in figure 22. The measured wind profile is well approxi-
Figure 21. Range of operational AoAs in terms of the airfoil polar for original blade design.

Figure 22. Wind profile measured by a met mast close to the turbine on Sept. 1st, 2009 at 10:00.

The measurements of the angle of attack at radial position $r = 31m$ as a function of time reveal a periodic variation, figure 23. The variation is linked to the blade azimuth position, as can be seen in the polar plot figure 23(b). The maximum AoA is measured for the blade pointing upwards ($\theta = 0^\circ$) and the minimum is reached when the blade pointing down passes the tower ($180^\circ < \theta < 225^\circ$). The variation of the AoA is hence caused by the combined effects of wind shear and tower shadow.

The surface pressure spectrum; the main source of the sound emission, depends on the AoA and the relative velocity of the blade section. The contour plot of...
the surface pressure spectrum in the low frequency range ($f < 1000\text{Hz}$) as function of time, figure 24, shows amplitude modulation in the frequency range up to $f < 500\text{Hz}$. High surface pressure levels are associated with high AoAs. The peak to peak difference of the surface pressure level is about 6dB. In the far field the amplitude modulation will be less pronounced. Unfortunately our data is not sufficient to clarify whether the amplitude modulation of the surface pressure is high enough to cause amplitude modulation in the far field.

To illustrate the correlation between the shape of the surface pressure spectrum and the AoA, we rearranged the data of the 10 second time series by gathering samples within $\pm 0.5^\circ$ of a centre AoA, figure 25. A shift to higher surface pressure levels in the low frequency range with increasing AoA can be observed. But the shift is very smooth and the rise in level is moderate. The pressure distributions, figure 26, show that even for the highest AoA ($\alpha = 11.2^\circ$) an adverse pressure gradient can be observed at the aft part of the airfoil on the suction side.
Figure 26. Measured pressure distribution at radial position r=31m on Sept. 1st, 2009 at 10:05 (data is 0.5sec averaged).
Flow separation, characterised by a flat pressure distribution on the aft part of the airfoil on the suction side, does not occur in the whole operational range. At 11:40 a higher wind speed was measured by the met mast, figure 27. The shear is very high below the hub height of the wind turbine (60m), but above the inflow profile is nearly constant. The variation of the wind speed over the rotor disc is less than for the previous time series. Due to the higher wind velocity, the wind turbine operates at higher AoAs at radial position r=31m, figure 28. At AoA $\alpha = 13^\circ$ the blade is likely to begin to stall. Such a high AoA is reached at azimuth position $\theta = 315^\circ$ to $\theta = 0^\circ$. The corresponding contour plot of the surface pressure spectrum, figure 29, shows a very strong amplitude modulation in the low frequency range ($f < 200$Hz). The difference in level in the low frequency range in time is up to 14dB. The high levels occur when the AoA is around 13$^\circ$. The results of binning the data on the AoA and computing the spectrum is shown in figure 30. The energy in the spectrum is shifted gradually from high to low frequencies when going from AoA $\alpha = 8^\circ$ to $\alpha = 12^\circ$. Comparing the spectrum for the AoAs $\alpha = 12^\circ$ and $\alpha = 13^\circ$ one can see a very strong increase in the low frequencies and also an increase in the high frequency range. This abrupt strong increase in the low frequency range is the reason for the amplitude modulation. As the difference in surface pressure level is much higher than for the previous example, it is very likely that the amplitude modulation occurs in the far field as well. It is also very likely that the high rise of surface pressure level in the low frequency range is associated with the onset of stall. The pressure distributions, figure 31 are not conclusive for high angles of attack. Problems with the pressure measurement system occurred and the calibration of the pressure sensors is only valid in the lin-

![Figure 27](image1.png)

*Figure 27. Wind profile measured by a met mast close to the turbine on Sept. 1st, 2009 at 11:40.*

![Figure 28](image2.png)

*Figure 28. Measured angle of attack at radial position $r = 31m$. red dots: half second averages.*
ear range of the airfoil polar. The pressure distributions for AoAs higher than 11° are very irregular as a consequence. One can guess an even pressure distribution on the suction side for $x/c > 0.5$ for both cases with the AoA $\alpha = 12.9^\circ$.

Figure 29. Narrow band spectra of surface pressure at radial position $r=57m$ measured on Sept. 1st, 2009 at 11:48. SPL in dB(1/12th octave).

Figure 30. Narrow band spectra of surface pressure binned on angle of attack measured on Sept. 1st, 2009 at 11:48. SPL in dB(1/12th octave).
Figure 3.1. Measured pressure distribution at radial position r=31m on Sept. 1st, 2009 at 11:48 (data is 0.5sec averaged).
2.4 Aeroacoustic modelling

The computations in this section are carried out with the aeroacoustic model for wind turbine rotors described in the appendix of [8]. A simple BEM model is used to compute the rotor aerodynamics and provide input to the aeroacoustic models. The aeroacoustic part of the code contains engineering models for turbulent inflow (TI) and trailing edge (TE) noise. The programme does not contain a model for stall noise. Hence, it is not very accurate when the blade operates at high angles of attack and it can only be used to describe AM, but not OAM. An error existed in the implementation of the TI noise model, which could not be corrected within the scope of this work. The model therefore gives noise levels that are too high - by about a factor 10. However, qualitatively the output seems reasonable. This will be discussed in the following sections.

The computations are performed for the turbine geometry of the NM80 turbine. The turbine was run with constant rotational speed of 1.7rad/s (16.2rpm or 0.27Hz). The wind speed at hub height was 10m/s and the turbulence intensity was 10%. The latter is not used in the aerodynamic computations and serves only as input for the TI noise model. The varying parameters of this study were the shear exponent and the pitch setting of the blade. The wind profile was described by an exponential law and we performed computations with a shear exponent of 0.2 (moderate wind shear) and 0.5 (high wind shear). The pitch setting influences the operating point of the blades. The AoA at the blade is shifted to higher values the more we pitch the blade. The computations were performed for a pitch setting of 1.0° and 4.5° corresponding to the experimental conditions described above.

For the computations the blade was discretized in 40 sections and the noise was evaluated at 12 different azimuth positions. We evaluated the noise emitted from each of these discrete positions and received at an observer position located 70m downstream of the rotor at a height of 2m. Figure 32 shows this kind of contour plot for the SPL integrated over all frequencies. This result has to be compared to the SPL computed with only the TE noise model switched on, figure 33, to evaluate the influence of the error in the TI noise model on the overall sound pressure level.

---

3 Communication with Franck Bertagnolio
Figure 32. Integrated SPL as a function of the rotor position for an observer 70m downstream of the rotor centre and at 2m height. The rotation of the rotor is clockwise.

Figure 33. Integrated SPL of TE noise as a function of the rotor position for an observer 70m downstream of the rotor centre and at 2m height. The rotation of the rotor is clockwise.
The comparison of figure 32 and 33 shows that the TE noise mechanism dominates the overall emitted noise in 3 of 4 cases: both cases with high pitch setting and the case with low pitch setting but high shear exponent. With a turbulence intensity of 10% TI noise plays no role in practice, because even with a model overestimating the TI noise source heavily, the SPL generated by the TI noise source is much smaller than the one generated by the TE noise source. For the case with a shear exponent 0.2 and pitch angle 1.0°, the model predicts that the maximum TI noise source is 4dB louder than the maximum TE noise source. But as the TI noise model is assumed to over-predict the SPL by at least 10dB, the TE noise source should be dominant in this case as well. Hence, we assume that the noise source distribution with only the TE noise source modelled is representative for the overall rotor noise source distribution.

For the high pitch setting (θ = 4.5°), figure 33(b) and 33(d), the noise source distribution is qualitatively similar. The maximum of the SPL is obtained for the blade moving downwards, starting from a 12 o’clock position until the 3 o’clock position. The difference in SPL over one revolution of the blade is about 12dB in the case of shear exponent 0.2 and about 16dB in the case of shear exponent 0.5. For the low pitch setting the overall SPL is significantly reduced compared to the high pitch setting. The noise source distribution is dependent on the shear exponent. With low shear (exponent of 0.2) the highest SPL is emitted when the blade moves from the 1 o’clock position to the 4 o’clock position. The SPL changes only about 6dB over one revolution. With high shear (exponent of 0.5) the highest SPLs are emitted when the blade is at the 12 o’clock position. The difference in SPL over one revolution is more than 16dB. The maximum SPL is 10dB higher for the case with high shear compared to the case with low shear.

TE noise depends mainly on the local flow speed and the angle of attack. The local flow speed to the blade is very similar in all 4 cases, because it is mainly given by the rotational velocity of the blade section and only weakly dependent on the local wind speed. Hence, most of the TE noise is emitted from the outer part of the blade. The angle of attack at the outer part of the blade has its highest values at the 12 o’clock position, figure 34. The maximum TE noise emissions are found at the same position as the maximum AoA at the outer part of the blade, but the apparent noise source strength at the receiver position does not coincide with this in all cases. This is due to the directivity pattern of TE noise. The directivity factor of the noise emission for the specified observer position are shown in figure 35. The directivity is modelled relative to the inflow to the airfoil. Hence it is dependent on the local AoA and we can observe small differences in the directivity factor for the 4 different cases.

The highest directivity factor are observed for the 3 o’clock to the 5 o’clock position. The position of highest AoAs and highest directivity factor to the observer position are clearly shifted towards each other.
Figure 34. Local AoA at the blade section as a function of the rotor position. The rotation of the rotor is clockwise.

Figure 35. Directivity factor of TE noise as a function of the rotor position for an observer 70m downstream of the rotor centre and at 2m height. The rotation of the rotor is clockwise.
Figure 36. Integrated SPL of TI noise as a function of the rotor position for an observer 70m downstream of the rotor centre and at 2m height. The rotation of the rotor is clockwise.
3 WP3: Mitigation Strategies

Both the mean AoA and the AoA variations that have been observed in the results presented in the previous chapters can be decreased using different control strategies. In this chapter, the possibilities of using collective pitch control for decreasing the mean AoA, and the possibilities of using yaw and individual pitch control (IPC) for mitigation of AoA variations are explored.

3.1 Collective Pitch Control

Variable speed turbines are normally operated such that at below rated wind speeds, the pitch is kept at a specified minimum value and the tip speed ratio is kept at its optimal value via regulation of the generator torque. The mean AoA at below rated operation can be decreased if the minimum pitch value is increased. Increasing the minimum pitch will, however, lead to suboptimal operation and decreased power output. The possibilities of decreasing the mean AoA by increasing the minimum pitch angle are investigated by calculating the steady state mean AoA and power production using HawcStab2 (HawcStab2 is an aeroelastic stability simulation tool developed at DTU Wind Energy). In figure 37, the resulting, simulated reductions in mean AoA and power production at different minimum pitch angles are shown. The results have been normalised with the mean AoA and power production a 0\(^\circ\) minimum pitch. From this figure it is evident that it is possible to achieve large reductions of the mean AoA and thus operate further away from the stall region. However, it is also seen that these reductions are obtained at the expense of decreased power production.

![Figure 37. Steady state mean AoA and power production as a function of wind speed when different minimum pitch angles are specified for the variable speed controller. The results are normalised with the mean AoA and power production at a minimum pitch angle of 0\(^\circ\).](image)

3.2 Individual Pitch Control

Usually, IPC is applied at above rated wind speeds for load alleviation, and a variety of individual pitch control schemes have been suggested in the literature. IPC is aimed at alleviating the lift variations that are encountered by the blades during rotation. The lift variations are caused by local inflow variations, such as AoA variations. Therefore, alleviating the azimuthally varying loads using IPC is likely to also lower the AoA variations. To assess the possibilities of mitigating the AoA variations using IPC, a simple IPC is integrated in the turbine controller, and a number of simulations are performed. The IPC that is implemented is similar
to the one described in [9]. The same simulations are performed as those for the modified rotor presented in Chapter 2. The results are shown in Figure 38. The figure shows the steady state AoA variation amplitudes of the IPC controlled turbine relative to the AoA variation amplitudes of the collective pitch controlled turbine.

For the uniform inflow, it is seen that the AoA variations are only reduced slightly. This is because the AoA variations are small for a uniform inflow. Furthermore, it is seen that for the uniform inflow, the AoA variations are actually increased by the IPC at wind speeds below 8 m/s. This increase is caused by the IPC that seeks to mitigate blade root bending moment variations. At low wind speeds and uniform inflow the blade root bending moment variations are caused by the gravitational loading on the blades. The gravitationally induced blade loads are mitigated by pitch actuation in phase with the AoA variations, which hereby are increased. For the sheared inflow, it is seen that the AoA variations are significantly lowered at both above and below rated wind speeds. The results for the turbulent simulations are not as consistent as the results for the deterministic simulations. It is therefore possible that the results would be more consistent if the simulations were run with wider wind speed steps allowing longer time and therefore better statistics at each wind speed.

The costs of applying the IPC are increased pitch actuation rates and lowered power output. The power loss is illustrated in Figure 39 that shows the mean power output of the IPC case relative to the non-IPC case. The greatest power loss is observed for low wind speeds (0.35% for uniform inflow and 5.5% for the sheared inflow). At above rated wind speeds there is no power loss due to the IPC. However, in most cases the power loss is below 1%.

The IPC applied in this study is a standard IPC for load mitigation. It is possible
that even larger reductions of the AoA variations could be achieved using on-blade inflow measurements and a controller design for AoA variation mitigation.

### 3.3 Yaw Control

Yaw control is usually applied to ensure that the rotor is aligned such that the rotor plane is perpendicular to the mean inflow direction. However, yaw control can also be applied for load alleviation [10]. Introducing a certain amount of yaw misalignment in situations with vertical wind shear can also lead to decreased AoA variations. This effect is explored through simulations of the NREL 5MW turbine. Figure 40 shows results from a number of simulations where the yaw misalignment angle is varied at one particular wind speed. It is seen that a yaw misalignment angle can be found that minimizes the range of the AoA variations. Such an optimum yaw misalignment angle can be found for all wind speeds. In Figure 41, the optimum yaw misalignment angles and the resulting range of the steady state AoA variations found from simulations are shown. The ragged appearance of the graphs in Figure 41 is due to the rather rough yaw misalignment angle discretization (5 deg). With a finer resolution a more smooth curve should be obtained.

It is evident that the AoA variations are lowered in the entire wind speed range. However, as seen from Figure 41 significant yaw misalignment is required. Thus, for below rated operation a significant power loss is expected if the AoA variations are mitigated through yaw misalignment. The power loss due to yaw error in uniform inflow can be estimated as:

\[ P_{\text{loss}} = (1 - \cos(\theta_E)^3) \cdot 100 \quad \text{[%]}, \]

where \( \theta_E \) is the yaw misalignment angle. At well above rated wind speeds yaw
misalignment can be introduced without power loss because the power is regulated to the rated value. The power loss introduced by the identified optimal yaw misalignment angle applied in the simulation is shown in Figure 42. It is seen that the power is actually increased at below rated wind speeds when the optimal yaw misalignment angle is applied. Recalling Equation (1) it is surprising that the power is not decreased at below rated wind speeds when the optimal yaw misalignment is applied. However, the increased power might be explained by the asymmetric inflow to the turbine. This phenomena should be investigated further.

The results related to yaw misalignment are all from simulations in deterministic inflow with no turbulence. Thus, the results only indicates the potential of using yaw misalignment for mitigating AoA variations. Simulations in turbulent inflow remain to be performed.

Figure 40. Results of simulations with varying yaw error at a mean wind speed of 8 m/s, no turbulence and a power law wind shear with an exponent of 0.2. A positive yaw misalignment corresponds to an inflow where the wind is approaching the turbine from the right, when seen from the turbine.

Figure 41. Results of simulations with varying yaw misalignment and mean wind speeds, no turbulence and a power law wind shear with an exponent of 0.2. a) Optimal yaw misalignment angles are identified from the simulations as the yaw misalignment angles that minimizes the AoA variations. b) Range of the simulated AoA steady state variations with 0 zero misalignment and with the optimal yaw misalignment.
Figure 42. Simulation results. Fraction between the mean power with the optimal yaw misalignment applied and the mean power at 0° yaw misalignment.
4 WP4: Effect of Stall on Noise Emission

The data presented in this section was obtained by measurements made in Virginia Tech University’s wind tunnel in 2011. All details about the experiment are found in [11].

4.1 Airfoil aerodynamics

We tested two different airfoils in the anechoic wind tunnel of Virginia Tech University: the NACA64-618 airfoil and a trailing edge noise optimised airfoil based on the previous one, called NACA64-618t. Those two airfoil differ significantly in the stall behaviour. The \( C_l \) vs \( \alpha \)-polars, figure 43, show that the NACA64-618t has a very abrupt and hard stall behavior characterised by a sudden drop in lift while the NACA64-618 stalls gradually. This difference is advantageous for the present analysis, because we can study the effect of stall on the noise emission for two aerodynamically completely different airfoils.

We use the following terminology for this report to describe the different states of the airfoil flow:

- **Pre stall**: AoA range with linear increase of the lift coefficient before maximum lift is reached. In this region the flow is attached to the airfoil.
- **Post stall**: typically the first AoA measured beyond maximum lift. Separation of the flow from the airfoil starts to occur and covers a small part of the chord length.
- **Deep stall**: AoAs far beyond the maximum lift AoA. The flow is separated over large parts of the chord length.

4.2 Far field Sound and Surface Pressure for High AoAs

The acoustic array measurement technique is limited to frequencies higher than 500Hz. Due to background noise in the wind tunnel, the measurements are often limited to even higher frequencies. This frequency is determined by looking into the acoustic map to check if the trailing edge is visible as a noise source. The limit
is typically about 700Hz. The important frequency content of sound emission from stalled airfoils in this configuration is most likely in the range below 500Hz. We can only measure the surface pressure fluctuations in the low frequency range. The model to convert surface pressure fluctuations into far field sound is only valid for attached flow. Hence, we need to analyse the far field sound in stalled flow conditions in the measurable frequency range together with the surface pressure fluctuations. From the result of this analysis we can draw conclusions about the sound emission of stalled airfoils in the high frequency range and try to link qualitatively the surface pressure fluctuations with the far field sound. Then we can try and transfer the results to the low frequency range by means of measured surface pressure fluctuations.

The far field sound pressure spectra of the two airfoils for a pre, post and deep stall AoA are shown in figure 44. Both airfoils show a strong increase in the overall noise level when the airfoil is in deep stall (α > 12°). However, in the mid frequency range the levels are very similar and due to the limitation of the measurements we can draw no conclusion for the low frequency range. Comparing the two airfoils, the NACA64-618t airfoil in deep stall is more noisy than the NACA64-618 airfoil. There is a link to the aerodynamic stall properties. We find a big difference between the two airfoils when looking at AoAs in the stall region, figure 45. The noise level increases gradually for the NACA64-618 airfoil with the AoA. For the NACA64-618t the far field sound pressure level jumps together with the jump in lift. An increase in sound pressure level of about 7dB for a change in the AoA of only 2.1° is observed. The jump in lift is observed...
within a change in AoA of 1°. The sound pressure level is only measured every 2°. As we expect a direct link between the two phenomena, we also expect the gradient of the SPL change to be steeper. This can be checked by refining the AoAs in the measurement matrix.

The effects of stall on airfoil noise in the low frequency range have to be estimated qualitatively by means of the surface pressure. Even though the far field noise models are not valid in stall, we expect the far field noise level to follow the surface pressure level. The surface pressure spectra at chord position $x/c = 0.975$ for the same AoAs as the far field sound in figure 44 are displayed in figure 46. Note

![Surface pressure spectra at chord position $x/c = 0.975$ for several AoAs of the two airfoils measured in the Virginia Tech wind tunnel at Reynolds number $1.9 \cdot 10^6$.](image)

that the wavy shape of the spectra in the low frequency range ($f < 500\text{Hz}$) is due to wave reflections in the tubing system of the surface pressure microphones and the imperfect compensation for temperature shift in the calibration function. The surface pressure level (PL) for pre stall conditions is significantly higher than for post stall conditions in the mid frequency range ($f > 1000\text{Hz}$). This is not reflected in the far field sound pressure spectra, figure 44. For the NACA64-618 the far field SPL is slightly higher for pre stall conditions than for post stall conditions, but the difference is by far less than the difference in the surface PL. For the NACA64-618t the far field SPL for the pre and post stall conditions are almost identical.

In deep stall the far field sound and the surface PL of the NACA64-618t are the highest in the mid frequency range. The far field SPL of the NACA64-618 is the highest in deep stall, but the surface PL is lower than for pre stall conditions. We conclude that the relationship between far field SPL and surface PL in pre and post stall conditions are different. But qualitative estimations of the far field SPL based on surface PL can be done with care.

We then analysed the surface pressure spectra and used the previous findings to conclude about the far field sound in the low frequency range. The surface pressure spectra show clearly a shift of the energy to low frequencies ($f < 600\text{Hz}$) when going from pre to post stall for both airfoils. The difference of the level is more than 10dB at a frequency of 200Hz. Such a large difference must be reflected in the far field SPL. When going from post to deep stall the overall surface PL increases. The increase of the overall surface PL is larger for the NACA64-618t airfoil than for the NACA64-618. The increase in surface PL at a frequency of 200Hz is again in the order of 10dB. If an airfoil operates in or close to the stall region, strong changes in the surface PL in the low frequency range go hand in hand with relatively small changes in the AoA. Hence, we also expect the far field SPL in the low frequency range to change significantly with very small changes in AoA. This mechanism can lead to amplitude modulation in the far field.
4.3 Far field Sound Modelling for high AoA in Pre Stall

With the trailing edge noise models described in [11] one can gain more direct information about the far field sound in the low frequency range. However, the model is restricted to AoAs in pre stall conditions.

In [11] two different models used to estimate the far field SPL by means of the measured surface pressure frequency wave number spectrum were investigated: 1) the model of Howe [12] and 2) Amiet’s model with Roger’s extensions [13].

In the high frequency range both models give almost identical results, but in the low frequency range significant differences can be observed. Amiet’s model with Roger’s extensions takes the finite chord length of the airfoil into account and models the back-scattering effect from the leading edge. Those effects are important in the low frequency range. Hence, we use only this model here.

The measured and predicted far field SPLs of the NACA64-618t airfoil for various pre stall AoAs are depicted in figure 47. Predictions and Measurements are in very good agreement in the mid frequency range (800Hz < f < 2000Hz). For higher frequencies they start to deviate. The model predicts much larger differences in SPL than the measurements show. The model also predicts very big differences in SPL along with only small changes in AoA, especially for high AoAs. The difference of SPL at 200Hz when going from $\alpha = 7.21^\circ$ to $\alpha = 8.16^\circ$ is 2.8dB. Such a difference can cause OAM. But this result has to be considered with care, because it is only based on model predictions without a direct measurement.

4.4 Conclusions

The analysis of the FF sound data of the Virginia Tech experiment identifies 3 possible causes for OAM:

1. An alteration in AoA causing the flow condition to alternate from pre to post stall. In this case a large difference in SPL was observed on both airfoils. It is a condition which should be avoided in every case.

2. For airfoils with very abrupt stall behaviour like the NACA64-618t we found a large jump in SPL when changing AoA by less than 2$^\circ$ in the stall region. It is probably caused by a very sudden change from partial to full separation of the flow.

3. The model of Amiet with Roger’s extensions predicts large differences of FF SPL in the low frequency range for relatively small changes in AoA. This result has to be handled with care, because there are no direct measurements.
to support this observation so far. But if the model results reflect reality, OAM without stalled flow conditions could be possible.
References


A Turbines used in the investigation and influence of turbine size

A.1 The 5MW NREL reference turbine

Data on blade planform (chord and twist as a function of radius) and operational conditions (e.g. rpm and pitch as a function of wind speed) are generally not made publicly available by manufacturers. However, in the research community there is a need to have such data in order to test models, to study wind turbine aerodynamics and aeroelasticity and in general to carry out research on wind turbine rotors. This led to the definition of the 5MW reference wind turbine by National Renewable Energy Laboratory (NREL) in the US [5]. We cite the following from the executive summary of [5]:

"To support concept studies aimed at assessing offshore wind technology, we developed the specifications of a representative utility-scale multimegawatt turbine now known as the NREL offshore 5-MW baseline wind turbine. This wind turbine is a conventional three-bladed upwind variable-speed variable blade-pitch-to-feather-controlled turbine. To create the model, we obtained some broad design information from the published documents of turbine manufacturers, with a heavy emphasis on the REpower 5M machine. Because detailed data was unavailable, however, we also used the publicly available properties from the conceptual models in the WindPACT, RECOFF, and DOWEC projects. We then created a composite from these data, extracting the best available and most representative specifications. This report documents the specifications of the NREL offshore 5-MW baseline wind turbine including the aerodynamic, structural, and control-system properties and the rationale behind its development. The model has been, and likely continues to be, used as a reference by research teams throughout the world to standardise baseline offshore wind turbine specifications and to quantify the benefits of advanced land- and sea-based wind energy technologies."

So the reference turbine is close to the REpower 5M machine. The design data in [5] allow detailed aerodynamic and aeroelastic simulations and is thus well suited to be used in a study like the present. However, as discussed in section 2.2 the turbine operates at an inflow angle range that is in a safe distance from stall and some of the commercial turbines have a more slender blade design causing the operational point on the lift curve to be closer to stall. We demonstrated this change in the design by reducing the chord, figure 18, and showed how this had the effect of pushing the operational point closer to stall, figure 20. Finally, the operational characteristics for the turbine and the power curve are shown in figures 48 and 49, respectively.

A.2 The NM80 turbine

The other turbine involved in the work is the NM80 turbine where we carried out the detailed inflow measurements and surface microphone measurements in the DANAERO MW project. The measurements from this machine were introduced in order to show how the surface pressure spectra changes during operation in extreme shear, where the turbine was forced to approach stall by using a constant speed of operation and by running the turbine at extreme negative pitch. Both the constant rpm and the negative pitch are far from normal operation. In addition, while this turbine is a standard variable speed, pitch-regulated turbine but we were unable to show the turbine characteristics in its normal mode for reasons of confidentiality.
(a) rotational speed  
(b) pitch angle

Figure 48. Variation of rotational speed and pitch as a function of wind speed.

Figure 49. Computed power curve as a function of wind speed for the 5MW reference wind turbine.
**B Difference between angle of attack AoA and inflow angle IA**

The angle AoA for an airfoil section is the angle between the chord of an airfoil section and the direction of the incoming flow described by the streamlines, figure 50. However, as seen on figure 50 the streamlines bend when they approach the airfoil; upwards on the upper side and downwards on the lower side. When measuring the inflow on the blade of a wind turbine rotor with e.g. a five hole pitot tube, figure 51, it will often be made rather close to the airfoil section. We then measure a flow direction called inflow angle IA that is influenced by the airfoil section itself. If it is along the red solid line close to the airfoil in figure 50 we will measure a bigger angle (IA) than the AoA. Based on simulations of the flowfield around the rotor blade it is possible to derive a calibration equation to convert from AoA to IA for the specific blade design and pitot tube.

![Figure 50. Illustration showing definition of AoA and how the streamlines bend when the approach the airfoil.](http://hyperphysics.phy-astr.gsu.edu/hbase/fluids/angatt.html)

![Figure 51. To the left is seen the five hole pitot tube mounted on the leading edge of the blade of the 3.6MW Siemens wind turbine at the Høvsøre test site in Denmark. The pitot tube is about 1m long and measures the direction and magnitude of the incoming flow.](image)
Our vision is for renewable energy to play a leading role in powering the UK.

RenewableUK is the UK’s leading renewable energy trade association, specialising in onshore wind, offshore wind, and wave & tidal energy. Formed in 1978, we have a large established corporate membership, ranging from small independent companies to large international corporations and manufacturers.

Acting as a central point of information and a united, representative voice for our membership, we conduct research, find solutions, organise events, facilitate business development, advocate and promote wind and marine renewables to government, industry, the media and the public.