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Mechanisms of amplitude modulation in wind turbine noise

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The noise produced by wind turbines is inherently time varying. This amplitude modulation is normally due to the directivity of the dominant trailing edge noise sources combined with the changing position and orientation of the rotating blades. In some circumstances the level and character of the amplitude modulation is altered and this paper outlines results from a Renewable UK funded research programme into the possible causes. Besides the variability of the normal trailing edge noise mechanism, other factors investigated include the possibility of blade stall or increased levels of inflow turbulence under some wind conditions combined with various propagation factors such as the effect of wind gradients and atmospheric absorption.

1 Introduction

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), often referred to as "swish", the variation in noise level occurring periodically in time at the blade-passing frequency of the turbine rotor. This effect is audible close to the turbine but is not expected to be significant at distances greater than 500 metres.

This 'Normal' amplitude modulation is caused by the directivity of the dominant trailing edge noise source, discussed in Section 2.2, combined with the time-varying position and orientation of the rotating blades. For typical large wind turbines, it is characterised by a variation of up to 5dB in the level of mid-high frequency noise (400 – 1000Hz) 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.

In some circumstances 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.

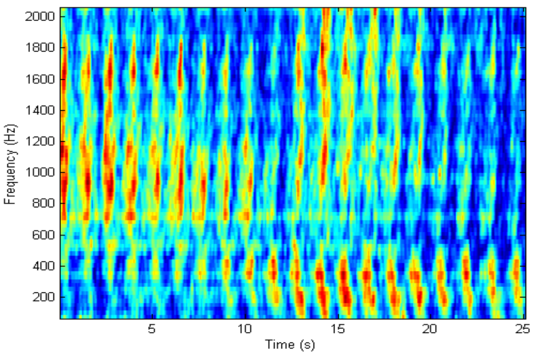

Figure 1: spectrogram of a sample of wind turbine noise.

This paper reviews the factors that could be contributing to the occurance of Other AM. Source effects are considered in Section 2, propagation effects are considered in section 3, and the way in which these may combine to produce the observered features of Other AM are set out in Section 4.

Good quality far-field data showing the spectral characteristics of Other AM are difficult to obtain, but figure 1, shows the spectrogram of a recording made in the nearfield of an 80m diameter wind turbine. This shows 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 and Other AM are plotted in figure 2, showing the shift in the peak of the A-weighted spectrum from 800Hz to 250Hz. It must be borne in mind however that this single piece of data is not necessarily representative of either what would have been measured on this wind turbine in the far-field 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 fully explain Other AM.

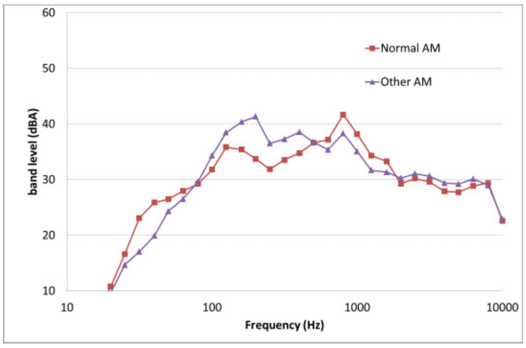

Figure 2: spectra of normal and Other AM for this sample

2 Source effects

There are many aerodynamic noise source mechanisms on wind turbines: self-noise mechanisms that would occur in steady wind; inflow turbulence noise that occurs in unsteady flow. The relative contributions of inflow noise and self-noise is still the subject of some debate [1], but the former tends to dominate at high frequencies and the latter at low frequencies.

2.1 Inflow turbulence noise

Prediction models of inflow turbulence noise based on Amiet [2] have the general form:

$$L_1(f) = 10\log_{10}\left(\frac{\sigma^2 L d U^5}{R^2} A_1(St_1) D_1(\theta,\phi) C(M,\varsigma)\right) \quad (1)$$

Here $L_1(f)$ is the 1/3 octave band spectrum at centre frequency f. The parameters σ^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 $A_1(St_1)$ 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 $St_1=fb/U$, where b is the blade chord. The directivity function is the dipole radiation pattern:

$$D_1(\theta,\phi) = \sin^2(\theta)\sin^2(\phi) \qquad (2)$$

The convective amplification factor C increases the intensity of the sound when the source is moving towards the observer:

$$\mathrm{C}(M,\zeta) = 1/(1-M\cos(\zeta))^4 \qquad (3)$$

Here M is the relative Mach number of the source and receiver, and ζ 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 incidence.

Another important factor that needs to be considered is the 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, then the observer hears the frequency

$$f' = f/(1-M\cos(\varsigma)) \qquad (4)$$

The Doppler effect is an inherent part of the characteristic 'swish' of a wind turbine and might possibly be manifesting itself in the spectrogram of figure 1 through the slight "slope" of the high frequency peaks.

2.2 Self-noise mechanisms

Brooks, Pope and Marcolini [3] (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:

- 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 low frequency AM.
- The turbulent vortex flow existing near the tips of lifting blades. This is also normally a relatively high frequency problem.

For trailing edge noise the BPM model can be written in the form:

$$L_2(f) = 10\log_{10}\left(\frac{\delta^* dU^5}{R^2} A_2(St_2) D_2(\theta,\phi) C(M,\varsigma)\right) \qquad (5)$$

Here δ^* is the thickness of the boundary at the trailing edge of the blade. The source spectrum shape $A_2(St_2)$ is derived from test data and is a function of the Strouhal number of the boundary layer, $St_2 = f\delta^*/U$.

At high frequencies or for large chords (b>>1) the directivity is the cardioid radiation pattern given by:

$$D_2(\theta,\phi) = \sin^2(\theta/2)\sin^2(\phi) \qquad (6)$$

At lower frequencies the directivity is a function of the chord to wavelength ratio, as described in [4]

The general form of Eq. (5) also applies to stall noise, but stall noise has the same dipole directivity as inflow turbulence noise, Eq. (2):

During stall, the boundary layer thickness increases considerably, so that the length scale of the turbulence is increased, and the Strouhal number at which the non-dimensional spectrum peaks is also reduced. These effects combine to give the shift to low frequencies that is observed when an aerofoil moves from attached flow to detached flow. Eq. (5) shows that the increased value of δ^* also leads directly to an increase in far-field noise level.

Figure 3 shows the BPM source spectrum for a typical blade segment as a function of angle of incidence, showing how the spectrum shifts to lower frequencies as the blade approaches stall. At angles of incidence beyond stall 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.

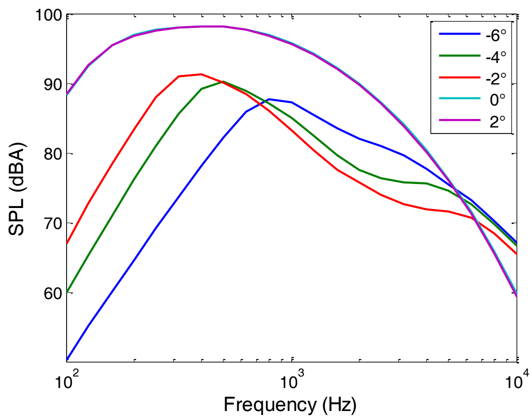

Figure 3: Blade element source spectra as a function of angle of incidence (relattive to the stall angle) used by Oerlemans [5] as derived from the BPM model [3]

2.3 AM mechanisms at source

The wind turbine noise model developed by Oerlemans [4] to explain the characteristics of Normal AM combines three elements: the steady state BPM model of trailing edge noise; the directivity model of Amiet [6]; a model of the time varying geometry and flow conditions of the turbine.

From this 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 combined with the changing position and orientation of the rotating blades.

At large distances downwind however, the directivities of neither inflow turbulence noise nor trailing edge noise vary in time with respect to the observer in the way that occurs in the near-field according to the Oerlemans model. For AM to be generated at source therefore the key factor that needs to be investigated is the assumed uniform inflow condition. 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. This causes time varying source characteristics, especially when local stall occurs.

- The turbulence entering the rotor disk is non-uniform due to upwind obstructions or meteorological conditions. This causes time-varying levels of inflow turbulence noise as each blade enters the region of high turbulence.

One example of a non-uniform wind speed condition is wind shear, where there is an increase in wind speed with increasing height, *z*, according to a shear factor *m*. In Eq. (7) the wind speed profile is generalized to also include variation in the lateral direction, *y*.

$$\frac{U_w(y,z)}{U_w(y_h,z_h)} = \left(\frac{z}{z_h}\right)^m \left(\frac{y}{z_h}\right)^n \qquad (7)$$

In his recent RenewableUK funded study [5], Oerlemans shows that vertical wind shear may give rise to localised stall, which could explain some of the observed characteristics of Other AM. It is 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 incidence α must also vary with height.

Figure 4 then shows the resultant angle of incidence 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 Top-Dead-Centre (TDC). It is assumed here that stall will occur beyond an angle of incidence of about α=10°.

Ref. [5] does now show significant modulation in the downwind/upwind directions when stall occurs, but the predicted modulation depth remains below 5dB in the far-field unless a high stall noise spectrum is assumed

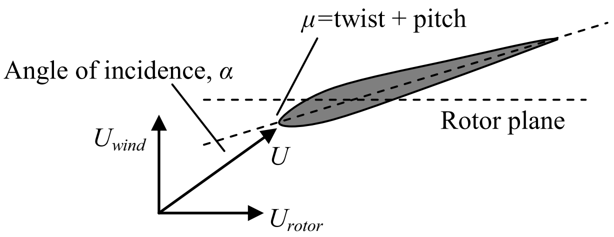

Figure 3: Flow vector geometry showing components due to wind and rotor motion, angle of attack and blade twist

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)
- 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.
- 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.

Considering the possible effect of local gusts of wind, figure 6 shows the effect of 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. This shows how stall could potentially occur in any region of locally increased wind speed.

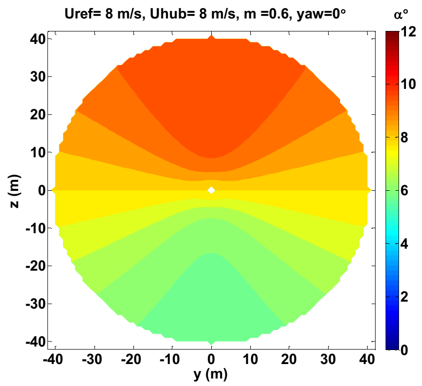

Figure 4: estimated angle of incidence on the rotor disk with a wind shear factor *m*= 0.6

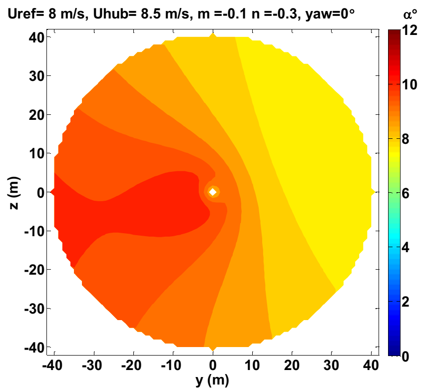

Figure 5: Effect of a local wind gust on the estimated angle of incidence

3 Propagation effects

ISO Standard 9613-1 [7] describes the 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 0.5dB/km at 100 Hz and 5dB/km at 1000 Hz. Applying this to the two near-field spectra presented in figure 2, it is apparent that beyond 1km both spectra would be dominated by frequency components below 630 Hz.

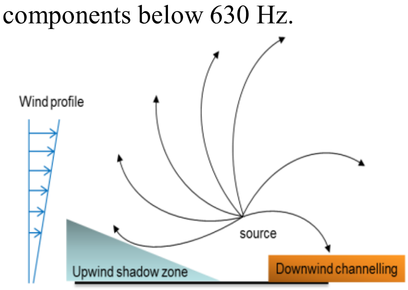

Figure 6: shadow zone due to wind gradients

The creation of an upwind noise shadow is well known, figure 6. The curvature of the sound rays is caused by refraction due to the variation of convected speed of sound 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.

A Parabolic Equation model developed at Hoare Lea was used to predict the transmission loss as a function of source height at 250Hz, figure 7. For an observer at 500m there is a 25dB difference in transmission loss for a source at 120m compared with a source at 80m. Thus, as each blade passes through this 'window' of high sound transmission near TDC, it will be more audible to an observer at this distance. Comparing one source at 120m (high noise condition) with two sources at 100m that occurs 1/6 of a rotation later (low noise condition), results in a calculated variation of more than 10dB at 250Hz at a distance of 500 m in upwind conditions.

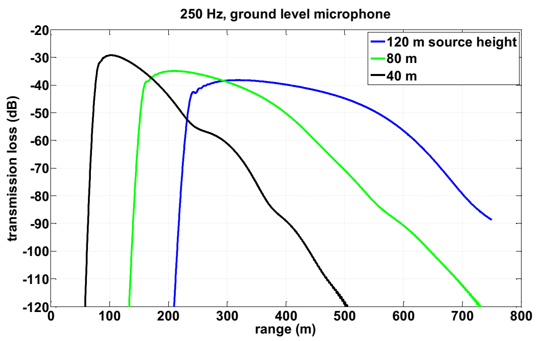

Figure 7 depth of the shadow zone at 250 Hz as a function of source height

The effect of ground reflections is illustrated in figure 8, 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.

A prediction for a range of 500m is presented, 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.

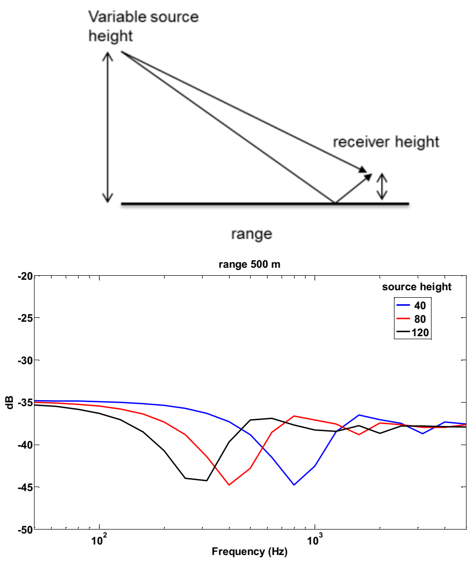

Figure 8: Ground interference dips at 500m range for various source heights

4 Factors contributing to Other AM

4.1 Non-uniform flow

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 3).
- 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. This would lead to increased modulation levels at large distances downwind/upwind.
- Downwind: at large distances the effect of atmospheric attenuation increases the relative importance of low frequencies, and it would strongly attenuate the frequencies above 500Hz 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 data in figure 1, the onset of local blade stall might be used to explain the time sequence of the spectrogram as follows:

- The first six blade passages are Normal AM
- Non-uniform inflow increases leading to four blade passages with the pre-stall condition of a thickened trailing edge boundary layer, an increase in low frequency noise and a decrease in high frequency 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
- Non-uniform inflow decreases returning the blades to the pre-stall Normal AM condition with low levels of high frequency noise.

4.2 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. 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 increased wind shear, there is no change to the position of the shadow zone.

On this basis, inflow turbulence is less satisfactory in explaining the features of the particular data in figure 1:

- The first six blade passages 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.

5 Conclusion

The two key mechanisms identified as potentially playing a part in the generation of Other AM in wind turbines are high levels of inflow turbulence and detached or stalled flow over the turbine blade. 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 incidence, with increased levels of AM being produced upwind/downwind when local stall occurs. The importance of these effects is likely to be dependent on the control algorithms specific to 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 the dominant source on modern turbines in the neafield, 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 modulation at certain frequencies 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 this work.

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