UNIVERSITY OF Southampton
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Consultancy Report
Ref: 8630-R01

Submitted to:

RenewableUK

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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

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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 demonstrated 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 μ so as to give an angle of incidence or attack α 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, θ and ϕ, 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:

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

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:

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

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:

$$C(M,\zeta) = \frac{1}{(1-M\cos(\zeta))^4} \quad (3)$$

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 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:

$$L_2(f) = 10\log_{10}\left(\frac{\delta^* d U^5}{R^2} A_2(St_2) D_2(\theta,\phi) C(M,\varsigma)\right) \tag{4}$$

Here δ^* is the thickness of the boundary layer at the trailing edge of the blade. The spectrum shape $A_2(St_2)$ 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 $St_2 = f\delta^* / U$.

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

$$D_2(\theta,\phi) = \sin^2(\theta/2)\sin^2(\phi) \tag{5}$$

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/λ = 1, for example if b= 0.5m then λ = 0.5m 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:

$$L_3(f) = 10\log_{10}\left(\frac{\delta^* dU^5}{R^2} A_3(St_3) D_3(\theta,\phi) C(M,\varsigma)\right) \tag{6}$$

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):

$$D_3(\theta,\phi) = \sin^2(\theta)\sin^2(\phi) \tag{7}$$

During stall, the boundary layer thickness δ^* increases considerably, so that the length scale of the turbulence is increased, and the Strouhal number at which the non-dimensional spectrum $A_3(St_3)$ 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 δ^* also leads directly to an increase in far-field noise level, and the level of the BPM source spectrum $A_3(St_3)$ also changes compared with the trailing edge source spectrum $A_2(St_2)$.

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 ζ is the angle between relative to the direction of motion, then the observer hears the frequency:

$$f' = \frac{f}{(1 - M\cos(\varsigma))} \tag{8}$$

For example with a Mach number $M = 0.21$ (71m/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 500Hz 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 630Hz 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 0.5dB/km at 100 Hz and 5dB/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 1km 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:

$$\frac{U_w(z)}{U_w(z_h)} = \left(\frac{z}{z_h}\right)^m \qquad (9)$$

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 α must also vary with height.

Figure 7b) plots the flow distribution over the rotor, with U_w=8m/s at the hub and U_w=10m/s at top-dead-centre (TDC). In any specific wind turbine, the angle α 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 α=8° 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 α=10°. 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 (ξ=0° or 180° 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

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Table 1. Sources of Normal AM in Uniform Steady Flow

Mechanism	Frequency	Directivity	Level / character of AM	Tests / measurements	Expected occurrence and other comments
Standard trailing-edge noise	Broadband noise, spectrum controlled by boundary layer thickness. Dominated by 1 kHz "swish" in the past, suggestions that this has reduced to ~350-700 Hz ("swoosh") for larger turbines.	Peaks at about 30deg to blade angle: i.e. Near the rotor plane, crosswind after blade twist is included.	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.	Decreases with distance, thus measurable in the nearfield but not in the far-field.	Part of normal wind farm noise.
Ground interference for receivers at standard height	Spectrum dip at 200-600 Hz depending on time varying geometry and distance from WT.		Ruled out as significant, could provide 'colouring' of the spectrum.	Simultaneous measurement at height and at ground level.	Would be present at every wind farm.
Atmospheric attenuation	Spectrum shifts to lower frequencies as high frequencies are attenuated more.	Shift in spectrum increases with distance. Otherwise the same in all directions.	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 "swish" or "swoosh" more than "thump".	Use ground plane measurements at various distances. Record humidity and temperature.	Intrinsic to all wind farms in far-field situations.
Background noise masking	Would be present at every wind farm to varying extent.		Limits the level of AM due to source characteristics.	Will limit any depth of modulation at large distances: measure at increasing distances in quiet conditions.	

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

Mechanism	Frequency	Directivity	level / character of am	Tests / measurements	Expected occurrence/ other comments
Standard TE noise	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.	Source directivity unchanged. Could show up on axis as blades are now different, but effect is small according to Oerlemans [13].	Predicted increase in level and change of spectrum is marginal compared with standard swish, according to Oerlemans [13], unless detached flow occurs.	Detailed measurements at different locations around the turbine.	Shear amount is site-specific and will vary with time of day and atmospheric conditions.
Partial stall noise	Stronger shift to lower frequencies.	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.	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.	Ideally: stall flag, torque and RPM measurement, manually change blade pitch to trigger stall. Otherwise: measure changes in directivity.	Stall-regulated turbines are designed to go into full stall at high wind speeds. Stall should not normall occur for pitch-regulated turbines in design conditions. Effects of atmospheric absorption would emphasise any shift to lower frequencies.

Table 2 (continued)

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

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

Mechanism	**Frequency**	**directivity**	**level / character of AM**	**tests / measurements**	**Expected occurrence/ other comments**
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).	Increased levels of low frequency noise, whilst high frequency TE noise remains the same.	Similar to the Oerlemans assumed dipole directivity for stall noise: peaks orthogonal to blades.	Would explain a particular type of impulsive 'thump' noise, similar to helicopter “blade slap” noise. Would appear as a high level of AM, but is actually harmonics of blade passing frequency noise. Would be highly irregular.	Ground plane measurements at various azimuthal postions 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.	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.
Large scale structure of fast moving air such as a local wind gust.	Same as above, except that it could lead to stall noise.	Same as above.	Would be short duration.	LIDAR measurements, acoustic camera, distribution of microphones.	Same as above.
Smaller scale turbulence (inflow turbulence noise).	Increase in low frequency noise.	Same as above.	Only leads to AM if the distribution of spatial turbulence is non-uniform.	Measures of turbine inflow turbulence with a high resolution if possible.	Could be dependent upon meteorology, topography and location of nearby wind turbines.

Figures

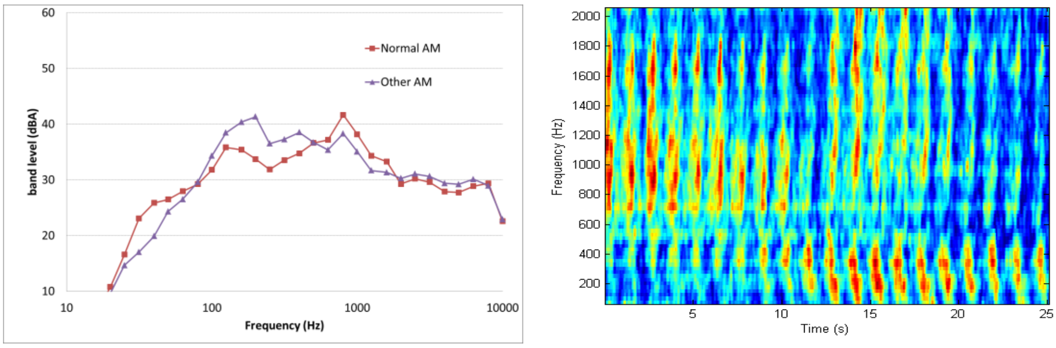

Figure 1 - a) Change in spectrum shape between 'Normal AM' and 'Other AM' as recorded by Bowdler [1] close to a turbine b) spectrogram of the complete time history.

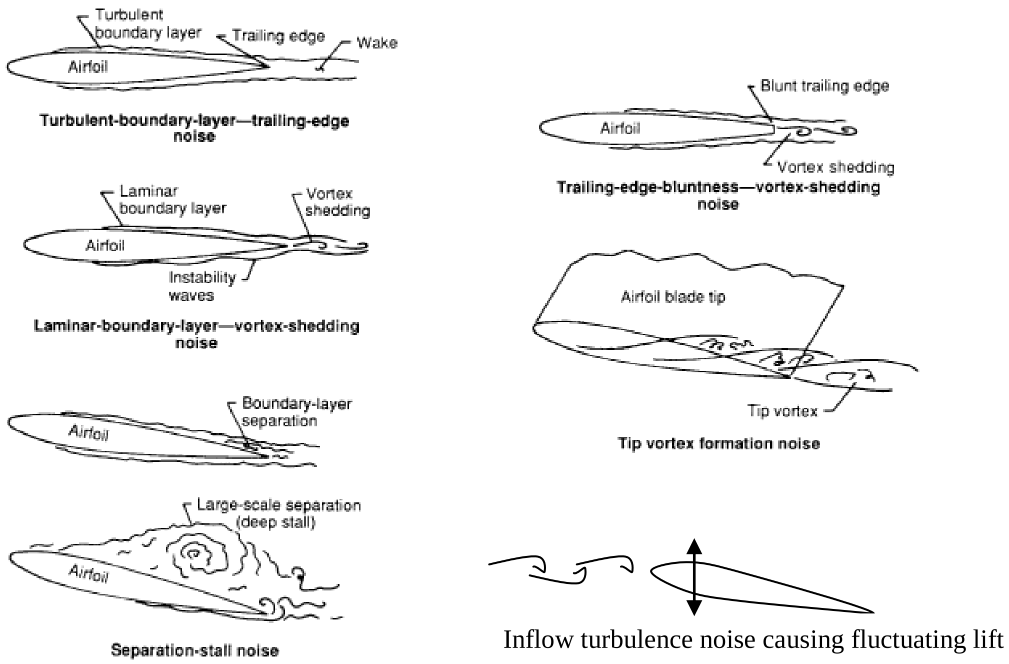

Figure 2 - Aerofoil self-noise source mechanisms identified by Brooks Pope and Marcolini [8], and illustration of the inflow turbulence mechanism.

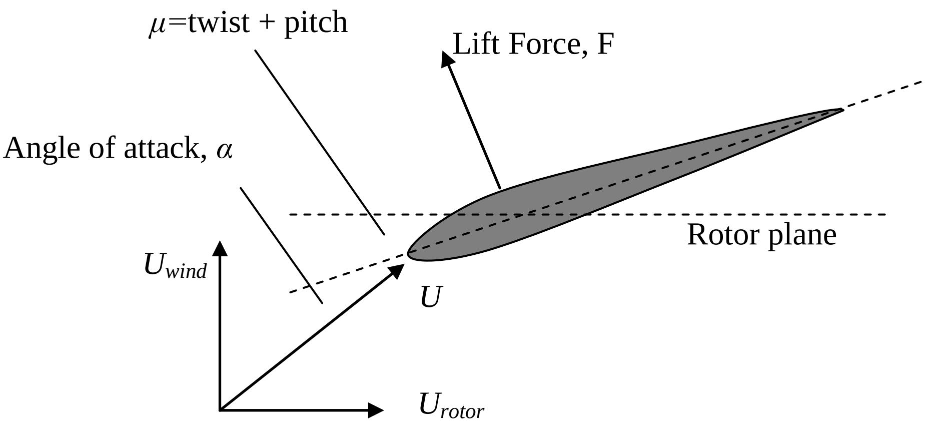

Figure 3 - flow vector geometry showing the components due to the wind speed and rotor motion, the angle of attack, and the blade twist and pitch angles

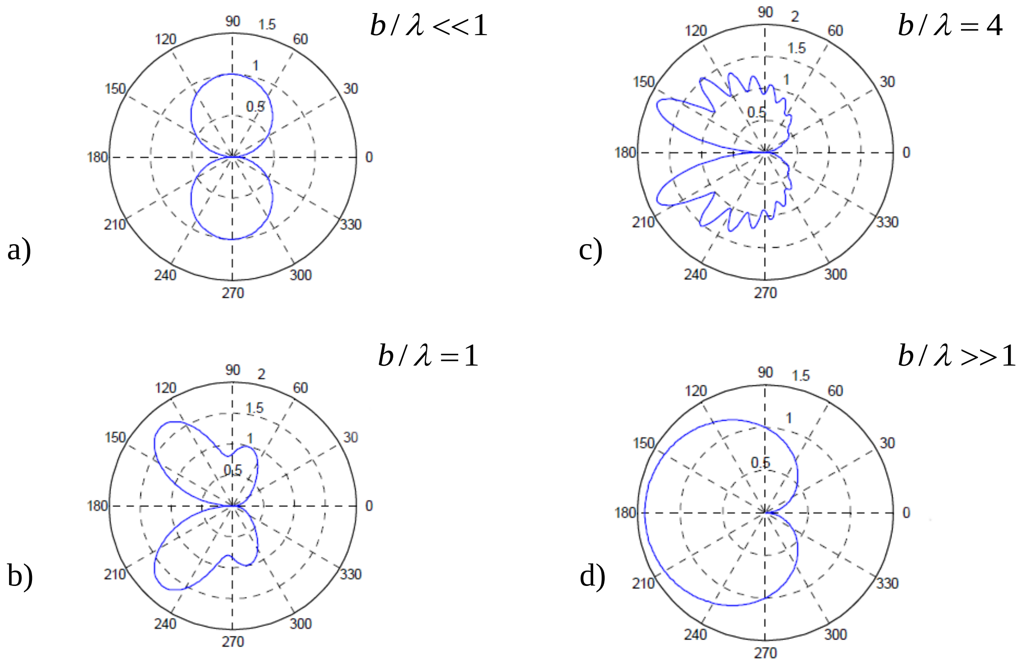

Figure 4 - Polar directivity of sources on an aerofoil: a) dipole directivity generally associated with low frequency inflow turbulence noise where the wavelength is large compared with the chord. b) –c) directivity for frequencies typical of trailing edge noise, d) cardioid directivity of trailing edge noise for a semi-infinite plate. From Oerlemans [17]

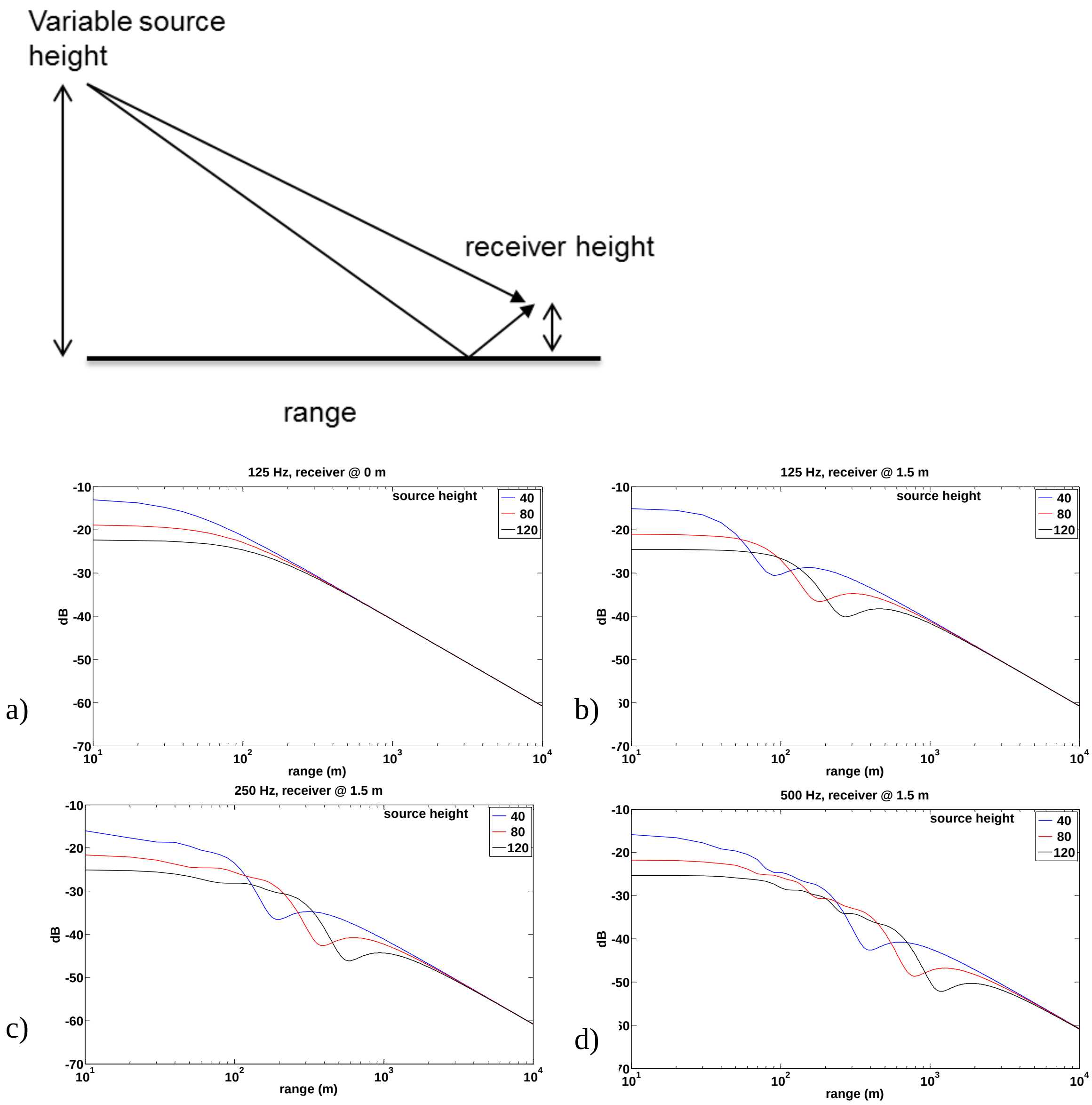

Figure 5 - predicted 1/3 octave band ground interference effect as a function of varying source height and range at different 1/3 octave band frequencies

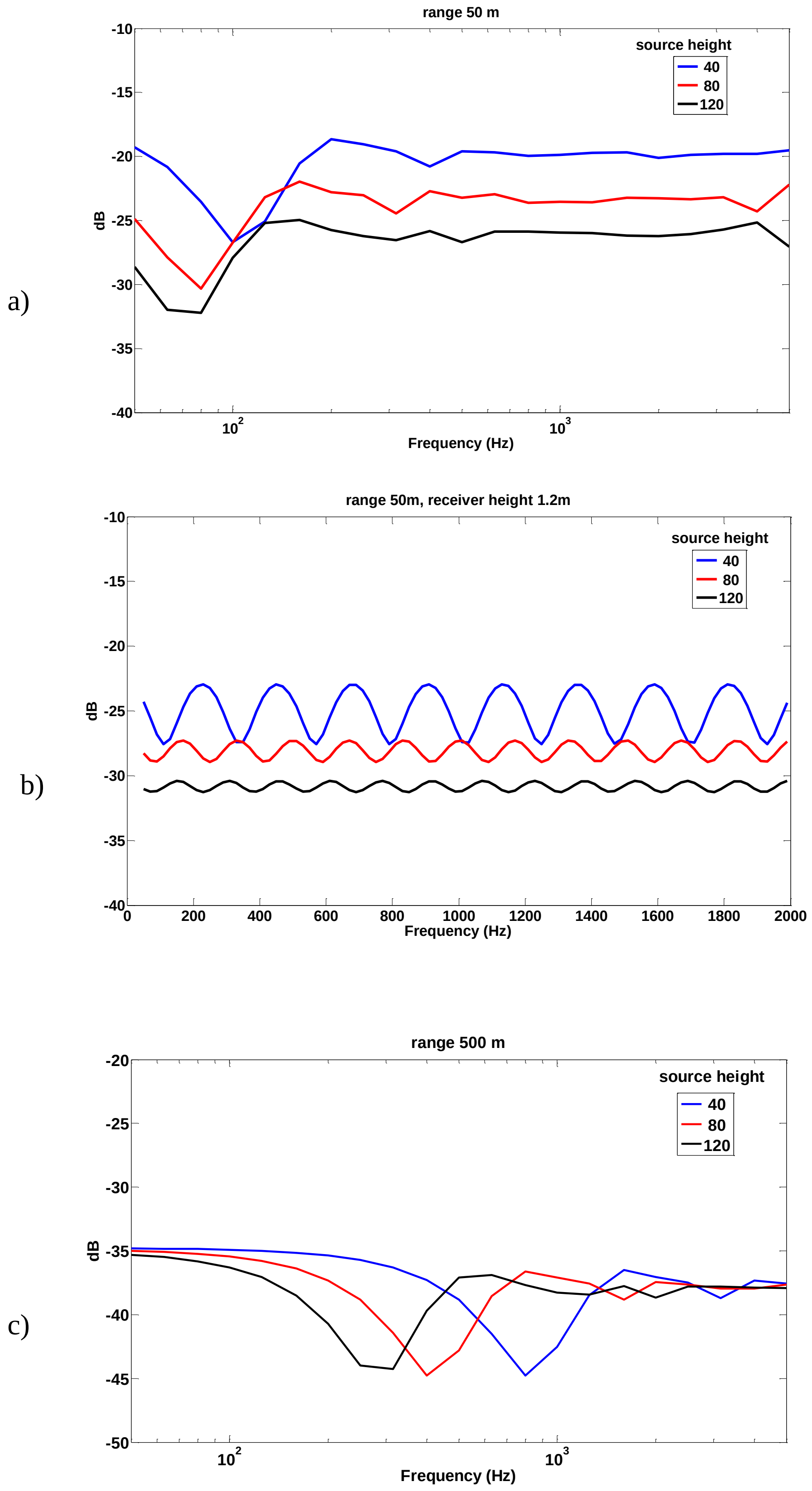

Figure 6 - predicted ground interference effect as a function of varying source height a) 1/3 octave band averaging at 50m range b) averaging in constant 100Hz bandwidths (plotted every 20Hz) c) 1/3 octave band averaging at 500m range

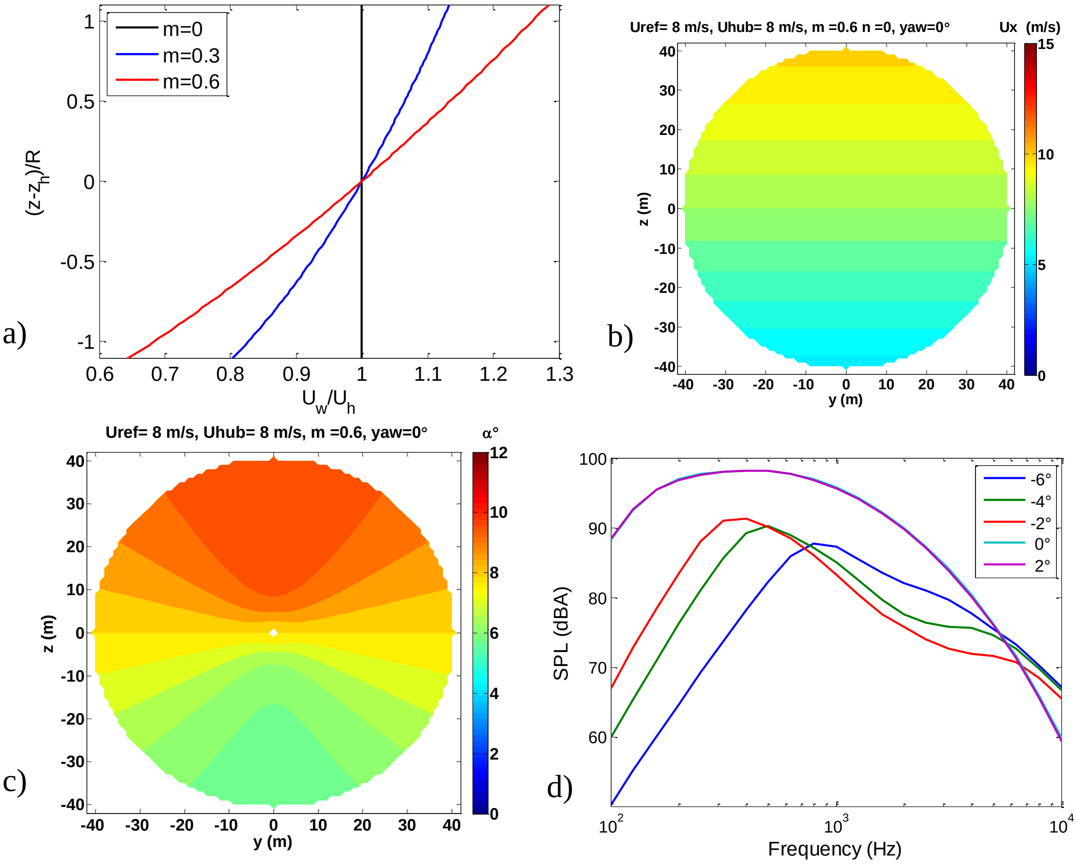

Figure 7 - effect of wind shear, adapted from Oerlemans [13]: a) incident flow profile as a function of windshear factor m; b) wind speed distribution over the rotor disk; c) angle of attack assuming U_0=8 m/s and m=0.6; d) change in the blade segment source spectrum as a function of angle of attack close to stall.

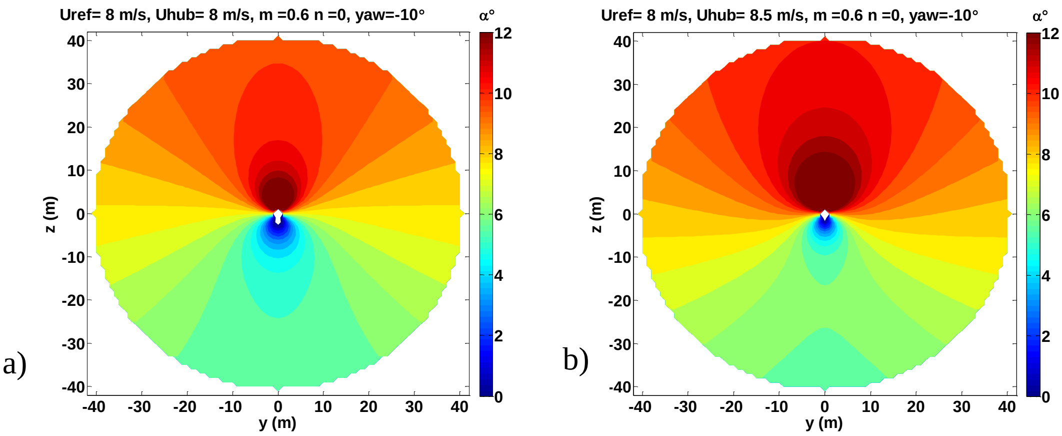

Figure 8 - a) Effect of combined m=0.6 wind shear and -10° yaw on blade angle of attack. b) Additional effect of a 6% error in estimated wind speed at hub height

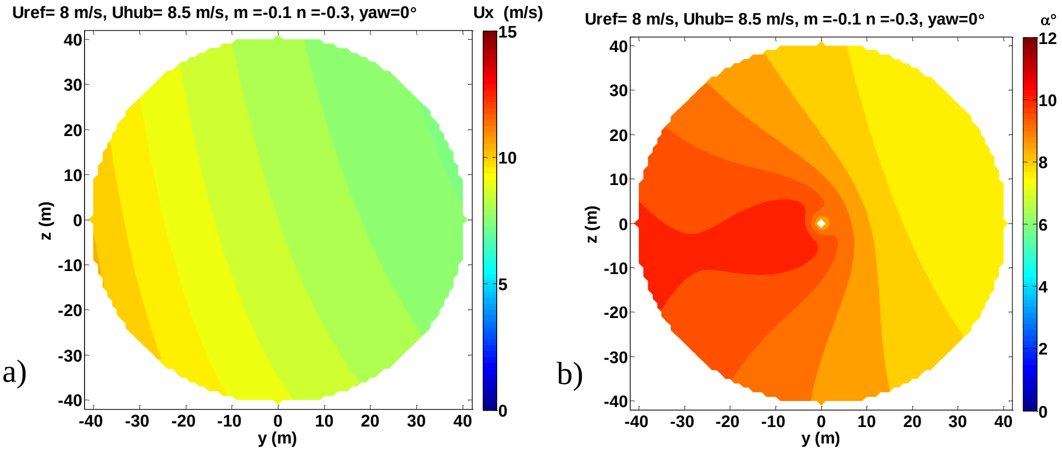

Figure 9 - Effect of a local gust of wind affecting one area of a turbine a) assumed flow distribution; b) angle of attack of the blade during the gust

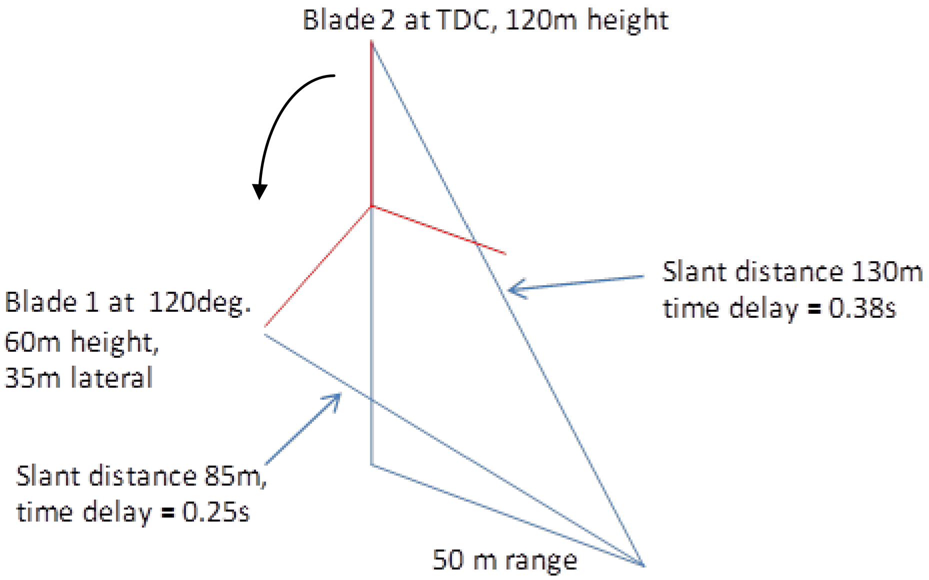

Figure 10 - Geometry for a measurement in the nearfield of a turbine showing time of flight delays. Time delay for Blade 3 is the same as for Blade 1, but directivity effects mean that its noise contribution is lower. A rotor diameter of 80m and a hub height of 60 m were assumed.

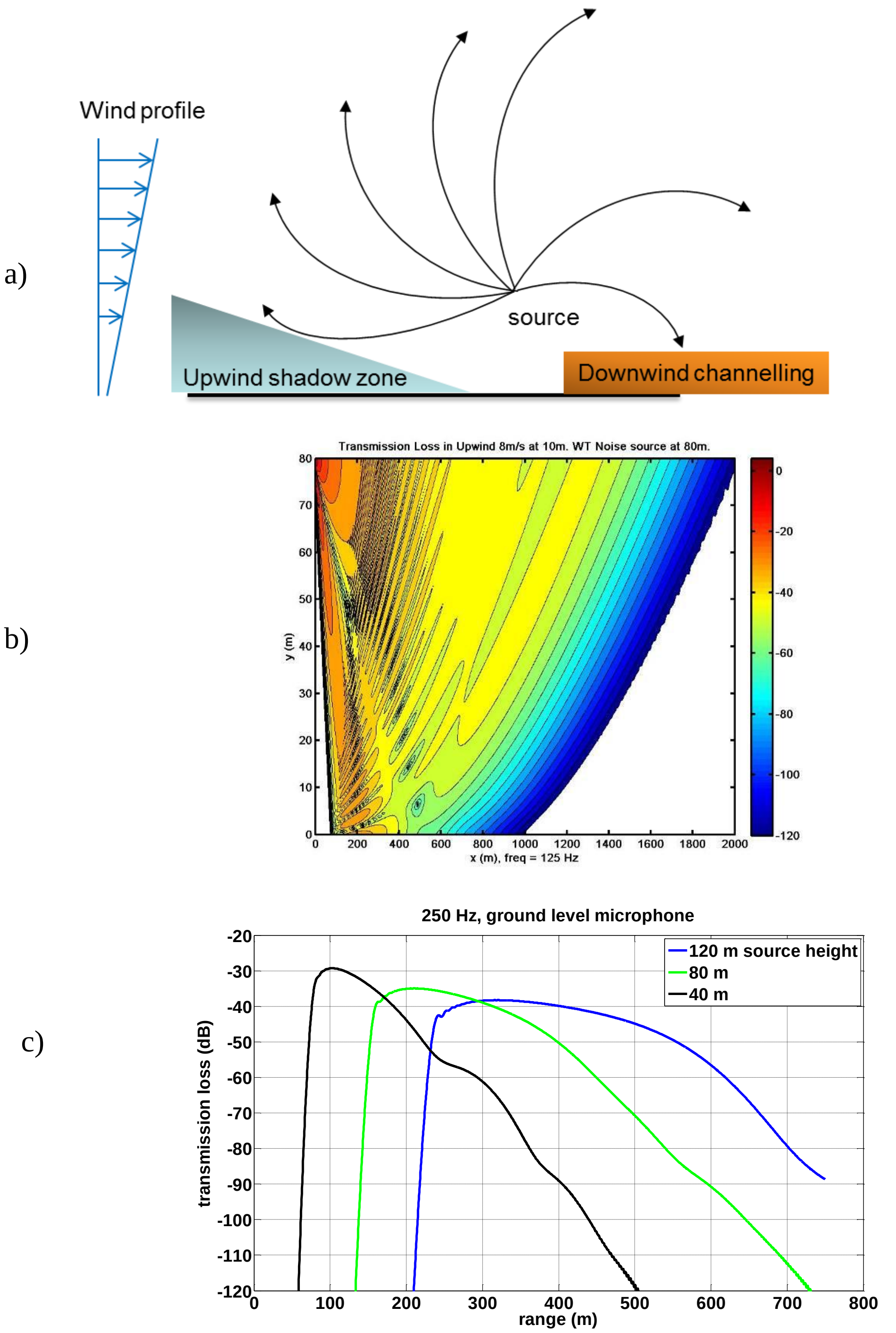

Figure 11 - effect of wind shear on sound propagation from an elevated source: a) schematic 'ray acoustics' diagram showing the upwind noise shadow and downwind channelling of sound. b) example prediction of transmission loss at 125 Hz using the Parabolic Equation method, showing the upwind noise shadow 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)