Independent Noise Working Group

Wind Turbine Amplitude Modulation &

Planning Control Study

Work Package 1 – The Fundamentals of Amplitude Modulation of Wind Turbine Noise

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Contents

Note: footnotes are superscripted; bibliographic references are within square brackets.

1 Introduction

The wind industry, and successive Governments much in thrall of it, after years of suffering of noise nuisance by many wind farm neighbours, and under pressure from those neighbours and concerned acousticians, physicists, medical consultants and engineers, have finally acknowledged the seriousness of the issue of Excessive Amplitude Modulation (EAM).

Normally amplitude modulation is a relatively benign characteristic of wind turbine noise. It is the periodic 2 - 3 dB(A) variation[1] in the level of the audible noise emitted by the turbine blades, modulated at the blade pass frequency (BPF) by a quasi-sinusoidal envelope. Its cause is well understood and its characteristics are quantitatively consistent with that understanding.

Unfortunately increasing numbers of wind farm neighbours in many countries now suffer from a rather different wind turbine noise characteristic which is far from benign, which has come to be called "excessive amplitude modulation" (EAM). Now that this has been acknowledged as a problem both by Governments and by the wind industry it is essential that its causes and effects are correctly and objectively determined. A group of acousticians with long experience in working with and for the wind industry (the IOA AMWG) is leading a consultation exercise on AM; its outcome is awaited with interest. The acousticians of the Independent Noise Working Group (INWG) are concerned by the narrowly defined terms of reference of the IOA AMWG consultation, which appear to have impeded the exposure of important evidence concerning the true spectrum of EAM, and thus of wind turbine noise as now frequently experienced by many wind farm neighbours.

This paper explores aspects of AM and EAM relating to their definition, causes and measurement. The high incidence and harmful effects of EAM are reported in other INWG papers.

2 The Characteristics of AM and EAM

2.1 Amplitude Modulation is Always Present

The principal source of audible noise from an ideal wind turbine is aerodynamic noise from the blades. As they rotate the distance between them and a static observer varies at the frequency at which the blades pass the turbine tower. This variation causes a quasi-sinusoidal modulation of the aerodynamic noise in both frequency and amplitude, usually referred to respectively as the Doppler effect and convective amplification, and creates the

[1] When dB differences are quoted the descriptor (A) is redundant, but its retention can serve as a reminder that measurements in question are A-weighted. This is important because an unweighted sound pressure level (SPL) relates to true sound power, whereas an A-weighted SPL relates only to its perceived audibility. Whilst these two quantities are very similar at frequencies around 1 kHz the unweighted SPL at 20 Hz, for example, is 50 dB higher than the A-weighted SPL at 20 Hz.

characteristic "swish" of wind turbine blade noise. The modulation depth varies as a function of the observer's orientation to and distance from the turbine; indeed if the observer were, rather unrealistically, on the rotor axis of a turbine, with no wind shear, no ground reflection and a wind-transparent turbine tower, there would be no modulation. Off the rotor axis, at realistic positions for noise sensitive receptors, operational turbines always emit noise that is modulated in both amplitude and frequency.

ETSU R 97 [1] (ETSU) described AM long ago (in 1997), ascribing to it a modulation depth of 2 - 3 dB. This is consistent with the predictions of the well-established BPM [2] aerofoil noise model. Such "normal" AM is thus an intrinsic property of the noise emitted by operational wind turbines and is always present.

2.2 Excessive Amplitude Modulation – when Swish Turns to Thump

Amplitude modulation is excessive when the "modulation depth" of the time series envelope exceeds the maximum of the 2 – 3 dB range reported in ETSU; compared with normal AM the peaks of EAM are narrower, with modulation depths up to 30 dB(A) reported. The trough amplitudes show no change at the onset of AM. The waveform thus changes radically, but over a relatively small part of the blade pass period. An example of a high (25 dB(A)) modulation depth time series chart from Huson [3] is shown in Figure 1.

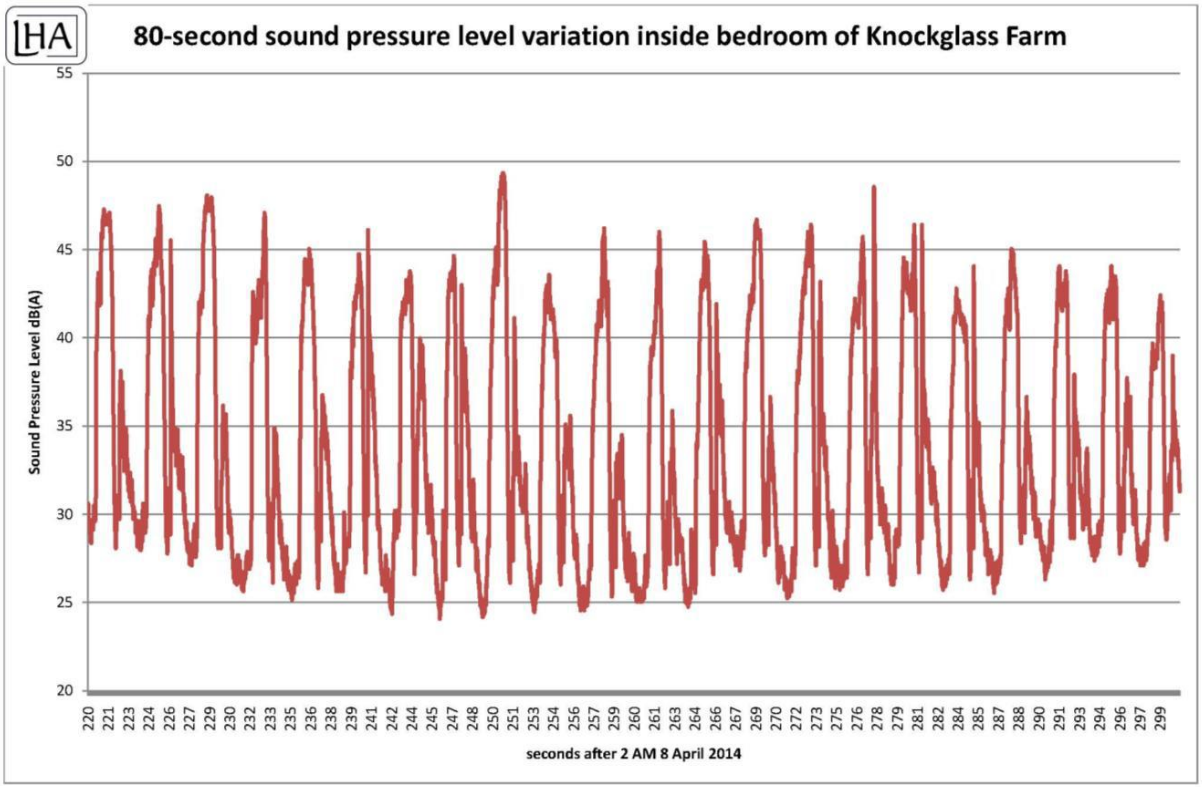

Figure 1: High levels of EAM (up to 25 dB(A)) at Knockglass Farm. Credit: Huson [1].

This is an interesting example as the AM frequency is relatively low, corresponding to the rotor frequency rather that the BPF. Much of the increase in modulation "depth" may well be due not to modulation of aerodynamic noise frequencies but to tones at turbine blade or tower resonant frequencies.

True AM as defined in other engineering disciplines would have the troughs descending as much as the peaks ascending; in the present case, where the trough level does not descend when the peak level ascends, it is more logical to refer to modulation height than modulation depth, as I do in all that follows.

The use of the term "modulation" in the acronym EAM was unfortunate as it pre-judged the spectral content of EAM at a time when it was little understood. In signal processing terms a modulated waveform is typically the product of a carrier frequency signal multiplied by a normally much lower modulation frequency or band of frequencies. EAM however is the sum of incoherent noise, modulated both in frequency and in amplitude, together with high levels of very low frequency tones. "Modulation" should therefore be understood in its lay definition rather than in any technical definition; use of the term does not suppress the very low frequencies from wind turbine noise, although it does appear to have suppressed serious consideration thereof by the wind industry or its acousticians.

The RenewableUK AM research report [4] ("the RUK report") states that EAM is entirely due to increased aerodynamic noise from the turbines blades which can stall at blade zenith ("12 o'clock") in high wind shear. I will show below that this can explain only a small part of the greater observed modulation heights; the major contribution comes from noise well below 100 Hz. I will also show that the RUK report and the IOA AMWG discussion document [5] largely derived from it repeatedly exclude any consideration of acoustic emissions at frequencies below 100 Hz. The RUK report includes no measurements below 100 Hz to support the exclusion however. In truth the greatest observed modulation heights are fairly easily explained by consideration of the very low frequency emissions which are a consequence of the structural dynamics of large modern wind turbines rather than aerodynamic noise from the blades. These very low frequency emissions are well known [6,7,8,9,10] to turbine manufacturers, but by reason of mechanical fatigue issues rather than noise nuisance.

2.3 The Normal Wind Turbine Noise Spectrum

The major part of the aurally perceived (i.e. A-weighted) acoustic emissions from normally operating turbines falls within the frequency range 100 Hz to 4 kHz, as seen in the logarithmic A-weighted trace (blue) of Figure 2, which is plotted from data in an independent test report [11] by Windtest gmbh for a typical modern turbine, the RePower (now Senvion) MM92. The major part of the acoustic power however falls below 4 Hz, as seen in the unweighted traces (linear, green and logarithmic, red) of figure 2; 4 Hz is well below the threshold of hearing. The A-weighted trace reflects the perceived loudness of the turbine, and thus its annoyance value to a listener, whereas the two unweighted traces reflect the true power level of the sound, and therefore give an indication of the likelyhood of any potential health hazard. This distinction is highly significant because the nature of complaints about wind turbine noise clearly indicate that wind turbine noise disturbs the human vestibular function rather than the human auditory function. See the report of INWG Work Package 3.2 [12] and the many referenced documents therein for further information.

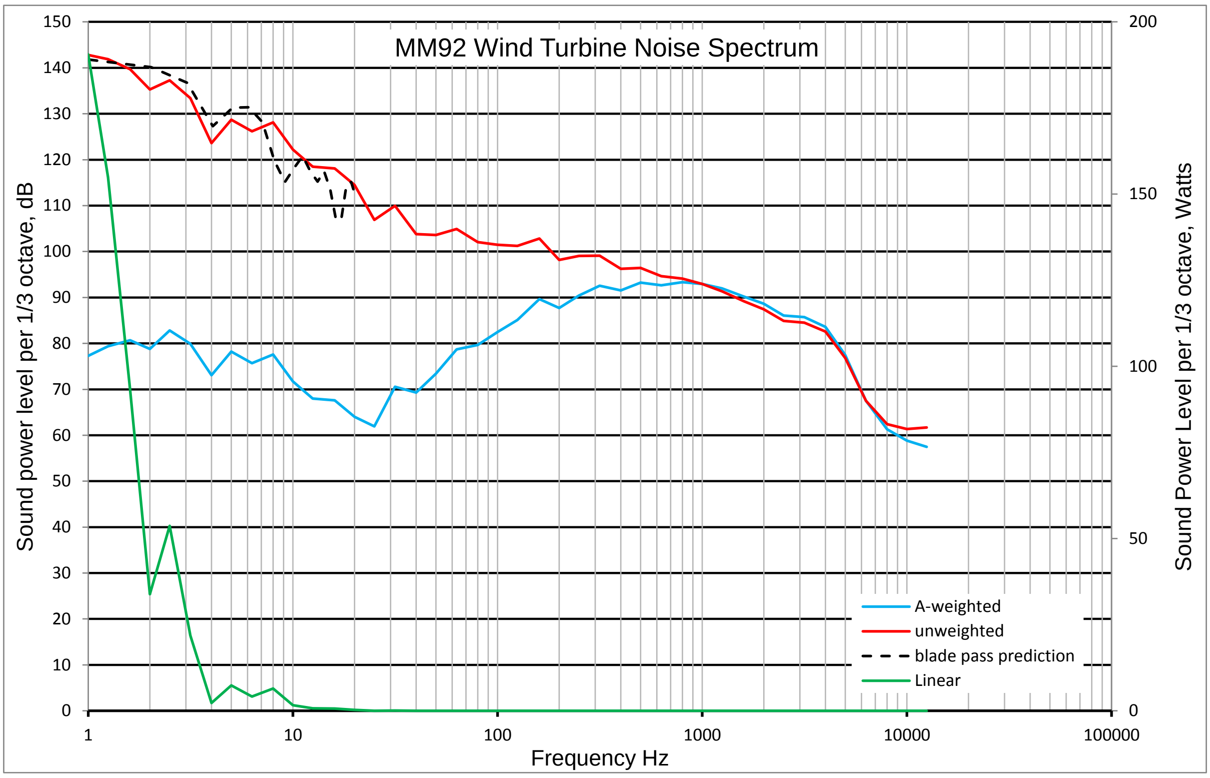

Figure 2: Noise emission power data to IEC 61400-11 from measurements on a RePower MM92 wind turbine, 1 Hz to 12.5 kHz, by Windtest gmbh.

Examining figure 2 in detail it is seen that the A-weighted spectrum appears to have a gradient discontinuity at around 20 Hz. This is because the because the data provided below 20 Hz does not state what weighting curve (if any) was used, so I have assumed no weighting. The standard A-weighting curve is defined down to 10 Hz, so this assumption may be incorrect, and may therefore have caused understatement of the unweighted noise power level below 10 Hz. The essential point to grasp is just how much power, rather than how much perceived loudness, is in the 1 - 20 Hz frequency band compared with that in the 20 Hz to 12,500 Hz frequency band; to illustrate this the linear green trace is plotted on the linear scale to the right of the chart. The answers are 99.94% and 0.06% respectively, of a total of 572 W. The total noise power below 20 Hz is. Irrespective of the mounting evidence of damage to both human and non human species, the magnitude of this ratio, 1,726, suggests that it is most unwise to ignore the existence of the acoustic energy below 20 Hz just because that frequency defines a nominal lower limit of human hearing.

The reason offered in ETSU for setting the night time noise limit at 43 dB(A), as opposed to the outdoor limit of 35 dB(A), is the assumption of 8 dB sound attenuation in passage through an open window. This assumption is valid at normal audio frequencies but certainly does not apply at very low frequencies; even with windows closed there is usually little or no attenuation from outdoors to indoors, and sometimes amplification due to room resonances. It is therefore not surprising that the majority of noise complaints relate to sleep deprivation indoors, and not to annoying noise levels outdoors.

2.4 Aerodynamic Blade Noise

The cause of aerodynamic blade noise is turbulence towards the trailing edges of the blades; noise and turbulence are closely related. If the blades are "free-wheeling", i.e. rotating at an angle of attack of 0^o without generating any torque on the rotor or therefore any electrical power, turbulence, and thus noise generation, is confined to the trailing edge of the blade and is relatively low. But maximum power generation is normally sought whenever the wind speed is not sufficient for the turbine to generate its installed power output, which is typically for about 90 % of the operating time.

For maximum power the angle of attack of the blades is adjusted close to maximum torque (equivalent to maximum lift from an aircraft's wing), at which point the airflow on the leeward side of the blade has started to detach as shown in Figure 3; this is close to stall. The emission noise power levels at integer wind speeds should then be those given in a turbine's test report, and the modulation height will indeed be around the 2 – 3 dB reported in ETSU.

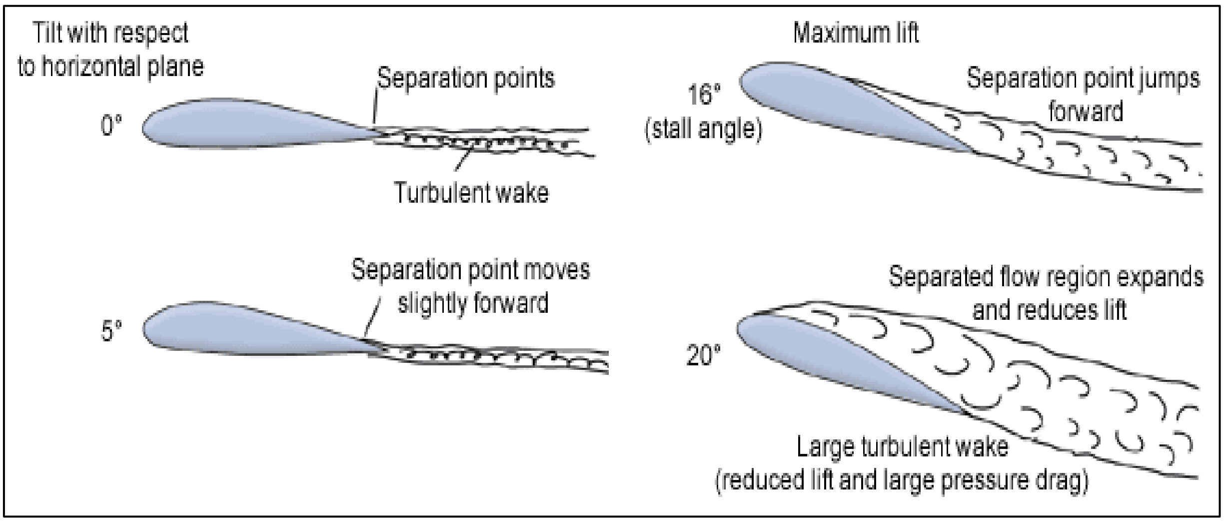

Figure 3: Aerofoils at increasing angles of attack (credit: NASA).

The turbine operational regime described above is assumed to prevail by ETSU, by the IOA Good Practice Guide [13] ("IOAGPG") thereto and until recently by the entire wind industry. Indeed it does usually prevail during daytime hours, but during evenings and at night time, because wind shear is greater, the higher noise levels of EAM are commonplace, as is explained in the following paragraphs.

As turbulence occurs on the trailing edge and adjacent leeward side of the blade the aero-dynamic noise is directional, and more downwind propagation exceeds upwind propagation.

3 The Causes of EAM

3.1 Wind Shear

In order to understand one of the causes of EAM it is necessary to understand wind shear, which is the change of wind velocity with height above ground. The long established equation for wind shear, as given in ETSU, is:

$$\frac{V_1}{V_2} = \frac{log_e\left(\frac{h_1}{z_0}\right)}{log_e\left(\frac{h_2}{z_0}\right)}$$

where V_1 and V_2 are the heights above ground of two different wind velocities at corresponding different heights above ground level h_1 and h_2; z_0 is the "roughness length" of the ground, and varies from a millimetre for smooth water to 0.3 m for forest.

The chart in Figure 4 shows average daytime values of wind shear for terrains of different roughness length, all normalised to a wind speed of 10 m/s at 10 m reference height. Wind shear is considerably greater in the evening and at night because of nocturnal temperature inversion. During the daytime the sun heats the land, which in turn heats the air in direct contact with it. This reduces the air density, so it rises over the colder air above it. The local turbulence disrupts laminar air flow. In contrast, the ground cools at night as it radiates heat instead of receiving it. Thus it cools the air in immediate contact with it, which stays low, and in turn cools the air above it, etc. This establishes a positive temperature gradient and a stable atmosphere. This encourages laminar air flow, and therefore greater wind shear, as there is no vertical turbulence to provide horizontal friction between layers.

Greater wind shear also results in greater atmospheric refraction, which "steers" (i.e. curves the propagation path of) the turbine noise downwards in the downwind direction, thus increasing downwind immission noise levels. Furthermore in higher than normal wind shear the ratio between hub height wind speed and receptor height wind speed, and therefore the ratio of turbine noise to background noise, will also be higher than normal. Thus wind turbine noise, even without any consideration of EAM, is a more serious problem during evenings and at night time than during the day-time. Again it is no surprise that most wind turbine noise complaints are about

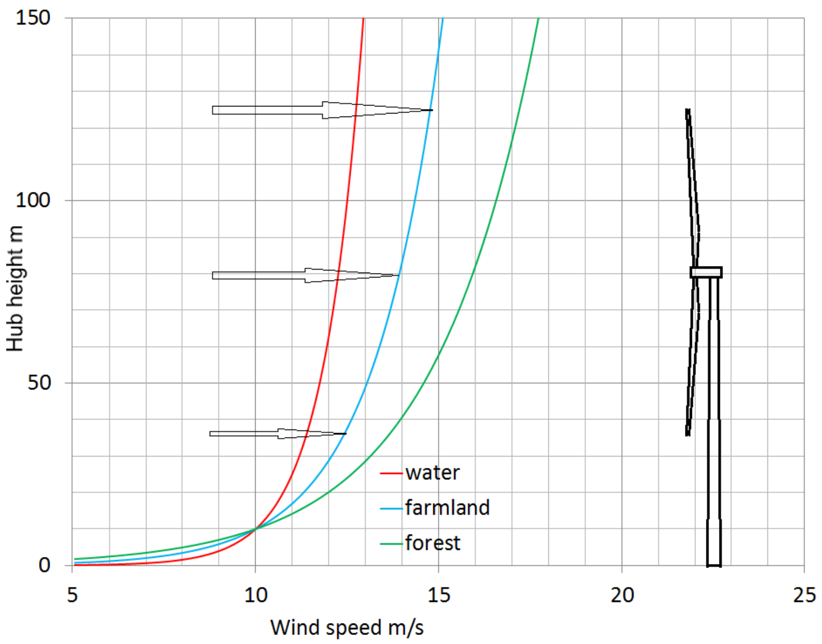

Figure 4: Wind shear; 125 m turbine on various terrains.

Figure 5: Noise contours; range of colour scale is 12 dB.

sleep disturbance at night, and rarely about excessive noise during the daytime.

3.2 Transient Stall at Blade Zenith

As stated above the blade pitch of a turbine is normally adjusted for optimum energy conversion at the hub height wind speed. High wind shear creates EAM because, in the higher wind speed that pertains at blade zenith for a given hub height wind speed, the blade may not move fast enough to "keep up with" the wind; it therefore stalls. Figure 5 (from Oerlemans, pdf page 21 in the RUK report) shows the measured noise source distribution of a modern large wind turbine. It is seen that nearly all the noise comes from each downward sweep of a blade (the noise level increases by 12 dB from blue to red). The noise measurement however is A-weighted, which greatly understates any very low frequency noise power content. Nevertheless there is still some evidence of both blade/tower interaction at blade nadir and near stall at, or just after, blade zenith.

In deep stall the air flow is detached and turbulent over the whole of the leeward side of the blade. As the average wavelength of the noise is related to the extent to which the turbulence spreads across the blade this lowers the peak noise frequency by several octaves as well as considerably increasing its amplitude; see Figure 9.

Blade stall at zenith can quantitatively explain a 3 dB increase in the aerodynamic noise on stall, and the downwards frequency shift, but, notwithstanding repeated claims to the contrary in the RUK report, it cannot explain modulation heights up to 30 dB in measured noise level, also cited by Oerlemans in the RUK report.

The errors in the RUK report in this respect are explained in detail in §4.2 below.

3.3 Transient Stall Pressure Pulses at Blade Zenith

When a blade stalls and loses the force of the wind it also rebounds due to its elasticity (see Figures 6 and 7), generating a sound pressure pulse at the BPF. Because of the impulsive nature of the rebound its harmonics reach up into the lower part of the audio spectrum, i.e. above 20 Hz. When the BPF is close to a blade resonance frequency, or a subharmonic thereof, the blade oscillation can build in amplitude. Thus transient stall generates very low frequency noise as well as increasing the level of aerodynamic noise. Because of the vast area of a modern turbine blade the acoustic power of the very low frequency noise can be considerable. Its directivity differs from that of the aerodynamic noise; the blade acts as a dipole source, propagating equally upwind and downwind, although the wind shear still enhances the downwind propagation.

The higher nocturnal wind shear can thus increase peak wind turbine noise at night by three different mechanisms. In addition to the higher aerodynamic noise emission levels from the turbines from transient blade stall and higher noise immission levels at homes due to wind shear enhanced noise propagation there will also be very low frequency noise due to blade rebound and possible resonance.

Although blade stall has been described as transient most aerofoils have a hysteresis loop in their stall characteristic, in the case of turbine blades exacerbated by their considerable elasticity. The duration of stall is therefore a significant part of the blade passing period, as at zenith the vertical velocity component of the blade motion obviously passes through a minimum of zero.

Figure 6: Unstressed but considerably curved blades awaiting shipment.

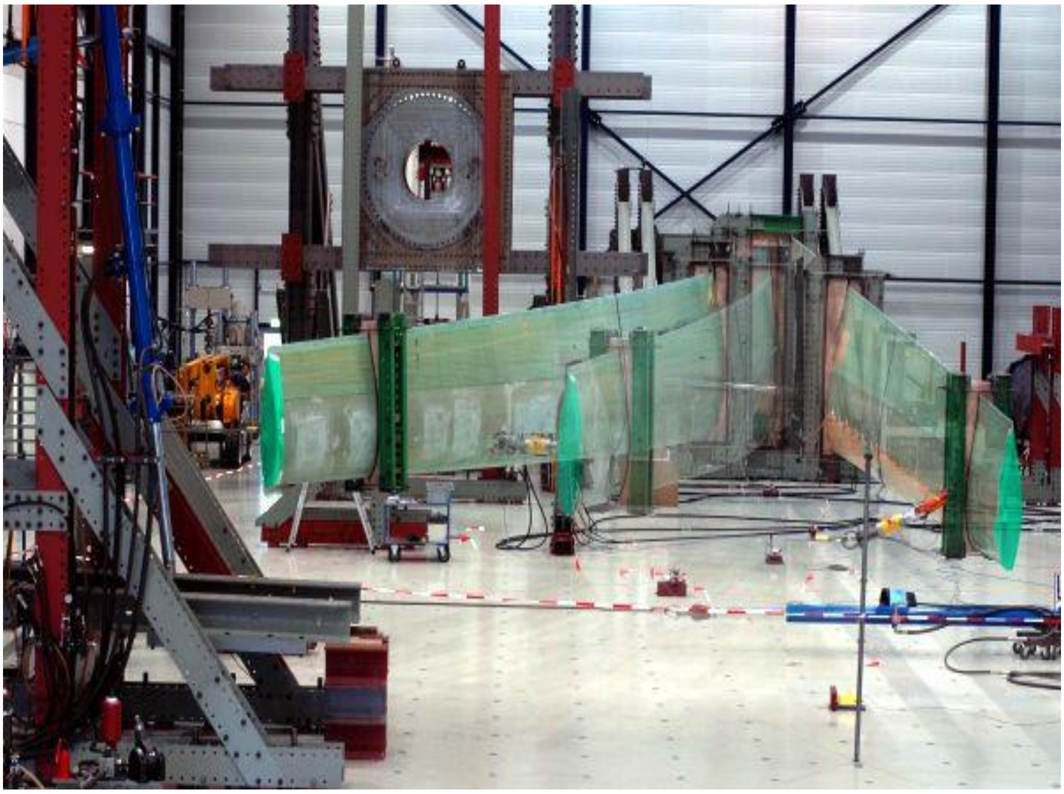

Figure 7: Triple exposure of a blade undergoing bending test.

3.4 Wind Turbine Evolution – from Large to Very Large, from Stiff to Soft

The smaller wind turbines of the 1990s were designed with sufficient rigidity not to vibrate; today's turbines are designed with less material and more subtlety in order to control and survive resonant vibration rather than to eliminate it by rigidity.

The relevant variables are the several resonant mode frequencies of the turbine components (the blades and the tower) and the frequencies of the periodic forces that risk exciting those resonant modes. Of the latter there are five:

- The rotational frequency of the rotor, f_r. Any static or dynamic imbalance in the blade weight or weight distribution will result in a rotating radial force at the hub, which can excite tower resonances.
- The BPF ($3f_r$ for a three bladed turbine, which is now almost universally the case, particularly for the larger AM prone turbines which have given rise to noise complaints). The reduction in the wind force on the tower when a blade is passing it can excite tower resonances.
- Again at the BPF, but at blade zenith, the blade rebound impulse on stall as described above in §3.3.
- The Kármán vortex shedding frequency of the tower, which is proportional to the wind speed and inversely proportional to the tower diameter.
- Similarly, the vortex shedding frequency of the blades, as acknowledged for example by Oerlemans in the RUK report [4].

Towers with a fundamental resonance frequency f_t higher than the BPF are referred to as "stiff", whilst those with f_t between the f_r and the $3f_r$ are referred to as "soft-stiff" or just "soft". If f_t is lower than f_r the tower is referred to as "soft-soft". Burton et al. comment [14] (on page 379 of the referenced book): "*The principal benefits of stiff towers are modest – they allow the turbine to run up to speed without passing through resonance,* ***and tend to radiate less sound***" (my emphasis).

Simply scaling a turbine design by a factor of two would increase the rotor swept **area**, and therefore the power generation capacity, by a factor of four. The **volume**, and therefore the mass and much of the cost of materials used in the construction of the turbine, would increase by a factor of eight. Thus a simple scaling by two would, perhaps surprisingly, approximately double the materials cost per MW generation capacity. As the major purpose of increased turbine size is cost reduction per MW generation capacity modern wind turbines are, in relative terms, much more lightly built than their earlier brethren and therefore much more prone to resonance and vibration.

Turning again to Figure 2, a most unusual feature of the chart (perhaps unique for published data) is its coverage of a bandwidth down to 1 Hz. The blue trace is the usual 1/3 octave A-weighted noise emission power from SPL measurements at the rated turbine output power. The red trace is the same data with the A-weighting removed. The dashed black trace is the Fourier transform of a tower pass pressure impulse of arbitrary amplitude, that I have modelled at the BPF with a rise, dwell and fall time consistent with the manufacturer's published turbine dimensions. The BPF of the turbine is less than 1 Hz, so the fundamental at the BPF is not visible, but its amplitude is probably higher than that of any of its harmonics. It can be seen that the spectrum shape matches the measured values below 20 Hz reasonably well. Although the MM92 is an upwind turbine the nacelle overhang is relatively small, and at full power the wind-strained blades pass fairly close to the tower, so there is significant interaction therewith.

The green trace shows exactly the same unweighted data as the red trace, but plotted on a linear scale rather than a logarithmic (dB) scale. This provides a pictorial representation of where the noise power is at its highest level: below 10 Hz. The two ordinate values at which the logarithmic and linear plots coincide are 0 dB and 140 dB. The measurements were made in daytime wind shear so relate to turbines noise with normal AM, but without EAM.

3.5 Vortex Shedding from Wind Turbine Towers

Wind blowing past a cylinder (not necessarily a circular cylinder, but any bluff object) can create vortices which are shed alternately on each side of the cylinder. A common small scale experience of this is the whistling of overhead wires in a strong breeze; the alternating shedding of vortices applies an alternating force to the wire along its length, causing it to oscillate. The same applies to a tall factory chimney, where the effect can be more serious. The tower of a large modern wind turbine has resonant frequencies typically around 1 Hz or less.

Vortex-induced vibration (VIV) is well understood and well documented in journals of fluid dynamics and structural mechanics. If the vortex shedding frequency matches the resonant frequency of a structure the oscillations can destroy it. Wind turbine manufacturers are well aware of VIV; their concerns until recently have related only to fatigue and the structural integrity of the turbines rather than their noise emissions. A purely illustrative example of the power of VIV can be found here [15].

A frequently seen solution to VIV is the fitting of a helical "spoiler" around the outside of a chimney. This deflects the airflow upwards on one side of the chimney and downwards on the other side, thus avoiding the formation of vertical cylindrical vortices. Spoilers are not fitted to wind turbine towers, possibly for aesthetic reasons, but the towers do often have damping devices fitted internally to control resonance [13].

The unplanned shutdown from full power of Macarthur wind farm (140 x 3 MW Vestas V112 turbines) provided Huson [16] with clear evidence of wind turbine resonances by vortex shedding. When recording infrasound and low frequency noise from the turbines, the rapid shutdown caused the total loss of the aerodynamic noise signal from the turbines, but the tower/blade infrasound tones decreased by only a few dB. In such a case tower and/or blade structural resonances would seem to be the only plausible explanation of the tones.

3.6 Blade – Tower Interaction

The regular passing of the tower by the turbine blades can also cause a tower to oscillate at one of its resonant frequencies. Dwelling at any resonant frequencies of modern turbines is avoided when increasing or decreasing the rotor rotation rate, so whilst this mechanism can be a powerful source of infrasound it could in principle be mitigated, for the benefit of the turbine operator and the wind farm neighbour alike.

Much has been made by the wind industry of the reduction in turbine noise that was achieved by the transition from downwind designs to the now almost universal upwind designs. The problem with downwind turbines was that the blades passed through the wind shadow of the tower, producing an infrasound or very low frequency pulse at the BPF. This did cause the relatively small early downwind turbines to be very noisy for their size. Replacing the blade-passing-through-wind-shadow-of-tower event by the tower-passing-through-wind-shadow-of-blade event of upwind turbines whilst solving one problem created another; the latter event can and does cause tower oscillation. I have observed this myself on several occasions when half way up the inside of the Ecotricity 1.5 MW Enercon turbine at Swaffham, Norfolk, at amplitudes I estimated to be up to about 40 cm. On other similarly windy occasions the amplitude of the swaying was only a few cm, presumably because the vortex shedding frequency was less close to a tower resonance frequency. I saw no internal damping devices in the tower of this turbine.

3.7 Vortex Shedding from Blades

Finally turbine blades, like turbine towers, can be caused to resonate by vortex shedding; as they are usually made of glass fibre composites they are highly elastic, as is seen in Figures 5 and 6. Blade vortex shedding causing a 30 dB EAM modulation height is reported in the AIAA paper cited by Oerlemans as his ref. [21] in the RUK report.

4 The RUK Report

4.1 A Note on the Academic Status of Authors and Publications

When decision makers are not specialists in the science on which their decisions should be based it is essential that they are aware of the academic status and any beneficial interests of the people and publications from which they take their guidance. This is particularly relevant when the technology is complex and the potential financial gains of its promoters are high, as in the present case. The RUK report was commissioned by the wind industry lobby organisation RenewableUK, which in its own words is the "*leading renewable energy trade association working to grow your business*", so makes no claim to be an impartial academic institution. My own opinion of the RUK report is that it is technically unsound and highly misleading. Its authors work in or largely for the wind industry. I have found no evidence that the report has been peer reviewed, in spite of its statement (page 372) that "*it will be peer-reviewed by other specialists working in the field.*" The three work package reports by Bullmore and Cand of Hoare Lea state on their audit sheets that the authors have reviewed each other's papers; this is not peer review. Cand in particular is identified as an author of four of the six UK produced work packages listed on pdf page 2 of the RUK report and his "*considerable contribution*" is gratefully acknowledged in one of the remaining two.

Conference papers are frequently referenced in the RUK report; these are rarely peer-reviewed. It is only for the learned journals that independent peer reviews are required; the review process is managed by the journal and is usually anonymous. By way of example, a leading peer-reviewed international journal in acoustics is that of the Acoustical Society of America (JASA). According to the American Institute of Physics "*Since 1929 The Journal of the Acoustical Society of America has been the leading source of theoretical and experimental research results in the broad interdisciplinary study of sound*."

The claim of "peer reviews" by an author's colleagues who rely on the same customer base and belong to the same professional institution as the author is worthless and serves only to demean the author and the institution.

4.2 "WP A1 - An explanation for enhanced amplitude modulation of wind turbine noise"

In the following three sections I question the validity or relevance of three of the papers in the RUK report. The first carries the logo of the Dutch NRL which, though a commercial concern, not a government laboratory, is well respected and long established in aerospace research. I understand that Oerlemans, the paper's lead author, works for Siemens Wind Power, a major wind turbine manufacturer.

The paper is concerned with transient aerodynamic stall at blade zenith, which occurs when wind shear is high and the angle of attack of the blades is optimised for the wind speed pertaining at hub height, as explained in §3.2 above. It seeks to demonstrate that EAM can be quantitatively explained by blade stall at zenith; it appears to me that the demonstration, whilst plausible in principle, is arithmetically flawed.

Oerlemans states (on pdf page 4):

"*The simulation results* [using the BPM model] *show that, as long as the flow over the blades is attached* [meaning laminar]*, wind shear has practically no effect on amplitude modulation. However, strong wind shear can lead to local stall during the upper part of the revolution. This can yield noise characteristics which are very similar to those of EAM. Thus, it can be concluded that local stall is a* ***plausible explanation*** *for EAM."*

On pdf page 19 Oerlemans reviews three reports of measured stall induced noise increases:

"*In Ref. [19] stall was found to result in a 10 dB increase in broadband noise. In Ref. [18] the noise increase due to stall appeared to be* ***somewhat lower*** *than 10 dB, but in Ref. [21] noise increases up to 20 dB (light stall) or 30 dB (deep stall) were found in a certain frequency range. All in all, it seems reasonable to assume an increase of 10 dB in overall sound level, although the actual value may depend on the airfoil. Thus, the prediction method should exhibit a sudden noise increase of about 10 dB when stall occurs."*

I do not agree that it is *"reasonable to assume an increase of 10 dB"* based on reported EAM heights of 10, 20 and 30 dB. In terms of SPL 30 dB is one hundred times greater than 10 dB.

I was unable to find in Oerlemans' ref. [19] any reference to a 10 dB increase in broadband noise on stall, or indeed any measurement data that I felt was relevant to the matter in hand.

Oerlemans' ref. [18] is about rotor noise from hovering helicopters, which does have something in common with wind turbine noise. From page 35 of the referenced document, "*The tip vortex generated by the upstream airfoil at an angle of attack, au = 8°, caused the 30 and 70% chord fluctuating surface pressures to increase on the order of* ***20 to 30 db at low frequencies with smaller increases obtained at high frequencies. These large increases were associated with airfoil leading edge-stall*** *as confirmed by flow visualization with tufts."* This is considerably higher than 10 dB, not *"somewhat low*er"; furthermore the quoted figures are surface pressure measurements, not far field SPL measurements, so of little quantitative relevance.

The device under test was NACA 0012 aerofoil with a 23 cm chord. The objective of the referenced document was to:

"...define the noise characteristics associated with the interaction of a stationary tip vortex and a downstream stationary airfoil. This model test geometry simulated, in its simplest form, the tip vortex-blade interaction which occurs on single rotor helicopters during hover".

This is a different cause of stall from wind shear, but I see no obvious reason why the noise increase on stall should differ markedly. The authors state that *"The stall noise was qualitatively of a* ***buffeting low-frequency*** *nature"*. Scaling the frequency to fit the chord length of a typical turbine blade will scale the frequency proportionally lower

Oerlemans' Ref. [21] (my reference [17]) are to a paper given at the 30th American Institute of Aeronautics and Astronautics conference in 2009; it reports wind tunnel measurements, again on NACA 0012 aerofoils. The high levels of EAM (30 dB) to which Oerlemans refers occurred at frequencies around 100 Hz and are ascribed by the authors to vortex shedding. The aerofoil chord lengths in this case were around 10 cm, so scaling the 100 Hz frequency to current wind turbine blade dimensions would scale the stall noise frequencies down to a few Hz, which eliminates aerodynamic noise as a source of the 30 dB of EAM.

Having read Oerlemans' references [18, 19 and 21] I consider that, to merit the adjective *"plausible"*, a quantitative explanation of EAM should account for his highest quoted stall noise increase of 30 dB, not just his lowest quoted increase of 10 dB. Reference to noise measurements of wind turbines rather than of scaled down aerofoils in wind tunnels would perhaps be useful; I refer again to figure 1, where the maximum EAM height is 25 dB.

Oerlemans shows (pdf page 20) that typical measured AM heights of 2 – 3 dB, as described in ETSU, are indeed comparable with those predicted by the referenced BPM model. He then observes that the BPM model includes a module for stalled air flow, from which he predicts a noise increase on stall of about 3 dB. The waveform provided by Bowdler to Oerlemans (figure 4, pdf page 30 of the RUK report) shows such an increase, and this is moreover an increase in the peak level without any associated decrease in trough levels, as would be expected from an event which only occurs at blade zenith. It does not however explain even the reported EAM heights of 10 dB, let alone 25 or 30 dB. Oerlemans continues (pdf page 20):

"…7 dB is added to the spectral levels calculated using the BPM code, in order to obtain the desired 10 dB overall noise increase."

Yet he later (on pdf page 25) repeats his initial conclusion that:

"…if local stall occurs, the resulting noise characteristics can be very similar to the EAM characteristics mentioned above, depending on the size of the stall region. Thus, it can be concluded that local stall is a ***plausible explanation*** *for EAM."*

In summary, the objective was to demonstrate that the proven and well established BPM model supports the hypothesis that stall-at-blade-zenith can account for observed levels of EAM. But in truth the model predicts only a doubling of the modulation height on stall (from 3 dB to 6 dB), not an increase to 30 dB. So the target was lowered from 30 dB to 10 dB and the BPM prediction of 3 dB was increased by a declared but nevertheless arbitrary unjustified 7dB to achieve even that lowered target. Thus the paper offers no "*plausible explanation"*, even though it purports to do so, for the levels of EAM measured and reported in Oerlemans' references or indeed those measured and reported for example by Cooper, Huson, Stigwood and many others at wind farms around the world.

4.3 "WP B1 - The measurement and definition of amplitude modulation(s)"

This paper addresses a problem which in my view does not exist: the search for an automated process to determine whether or not the amplitude modulation height of a time series waveform is of acceptable magnitude. Taking figure 1 as a sample of EAM, albeit a fairly extreme example, it is abundantly clear that there is a typical modulation height of around 20 dB, peaking to 25 dB. All that is required to determine the modulation height is the eye and a ruler; all that is required to verify that the signal is indeed from a wind turbine and not some other source is the ear, for which purpose sound is recorded along with the LAeq.

There is no legitimate benefit to be derived from the use of complex and opaque signal processing techniques to derive a "metric" from a time series signal with clear and stable periodicity. It is noticeable that all the methods proposed by the IOA AMWG understate the modulation height when compared with the simple observation of the time series signal, as is demonstrated by Large in INWG Work Package 7 [18]. Whatever method is used transparency is essential, and must include independent evaluation of the final method chosen by the IOA INWG and the release of the source code for the MatLab software proposed by the IOA AMWG for the signal processing, not forgetting that the latter is in fact entirely redundant.

4.4 "WP B2 - Development of an AM dose-response relationship"

This paper describes the Salford listening room test commissioned by RUK. The listening room has a surprising inclusion in its sound reproduction system: **a high pass filter with a corner frequency of 140 Hz and 20 dB attenuation at 100 Hz** (see figure 8 reproduced from the RUK report, pdf page 229). The filtering out of all frequencies below 100 Hz in the measurement of EAM will completely remove any and all of the turbine noise signals from the sources described above in §3.3 to §3.7, along with some of the downward shifted frequency content of the aerodynamic noise in stall. This equipment was used to replay real wind farm noise recordings for volunteers to rate the degree of annoyance they caused. The RUK report, wind industry developers and their IOA AMWG acousticians repeatedly assert that the noise of EAM is all aerodynamic and has little content below 100 Hz; this would seem to make the 100 Hz filter redundant. No spectral measurements have been published in the RUK report to support this assertion; indeed independent measurements, such as reproduced in figure 1 above, demonstrate the contrary. I must therefore conclude that this paper, whatever its intention, serves to obfuscate rather than to illuminate the matter that the RUK report purports to address.

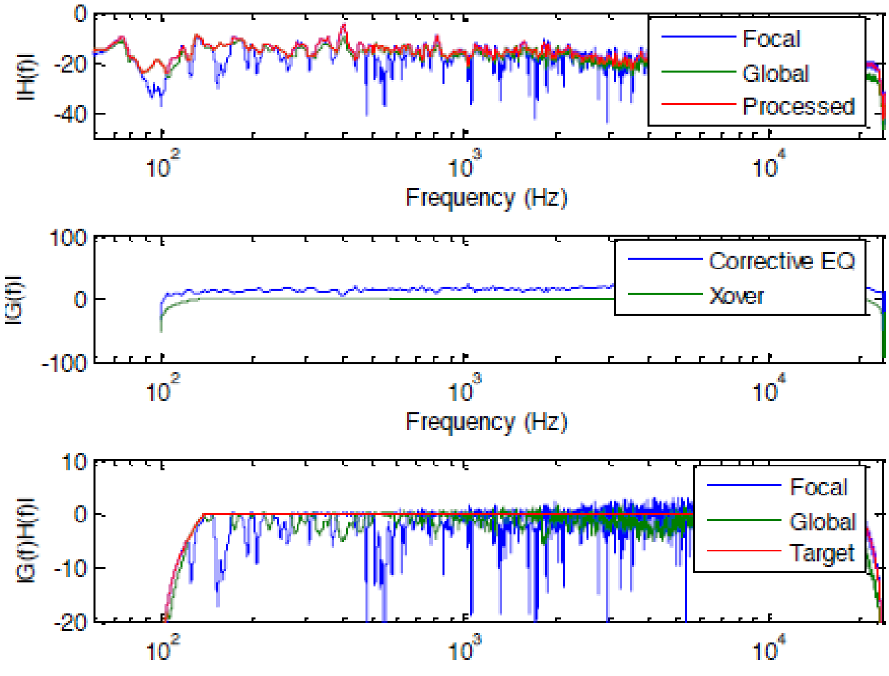

Figure 8: Salford listening test progressively filters out frequencies below 140 Hz.

The three traces in figure 8 are respectively the raw recorded signal IH(f), the response function of the filter IG(f) which the authors refer to as "the correction applied", and the resulting spectrum, the product of IH(f) and IG(f), which has clearly been stripped of any signal below 100 Hz.

4.5 "WP C - Collation and analysis of existing acoustic recordings - Hoare Lea Acoustics"

It was noted in §3.6 above that much effort has been expended by the wind industry to downplay the significance of wind turbine low frequency and infrasound emissions. For example in WP C, §2.1.5 on page 272 of the RUK report [4] Cand states:

"These considerations are complicated to a degree by the historical presence of infrasound in downwind turbine designs due to blade flow/tower interaction effects, which have now been effectively designed out of modern turbines through the use of upwind designs. The above-referenced studies, as well as more recent research [4] presented in 2011, have confirmed that there is no significant level of infrasound emitted from modern wind turbines."

Cand's reference [4] (and my reference [19]) is to a paper by commissioned and co-authored by Australian wind energy developer Pacific Hydro. It is based on wind turbine noise measurements using G-weighting, a rarely used weighting curve which, like A weighting, purports to model the frequency response curve of the ear, only at infrasound rather than audio frequencies. At 10 Hz its weighting is zero, but the ear's sensitivity and therefore the G-weighting curve, descend rapidly below 10 Hz,; at a typical blade pass frequencies around 0.6 Hz the Z-weighting curve is close to - 50 dB, which is the same as the A-weighting curve at 20 Hz. At 0.25 Hz, the corresponding rotor rotation frequency, the G-weighting curve is not even defined, but extrapolates to – 96 dB. G-weighting is scarcely more relevant than A-weighting, as both assume that the human auditory response is the only relevant criterion.

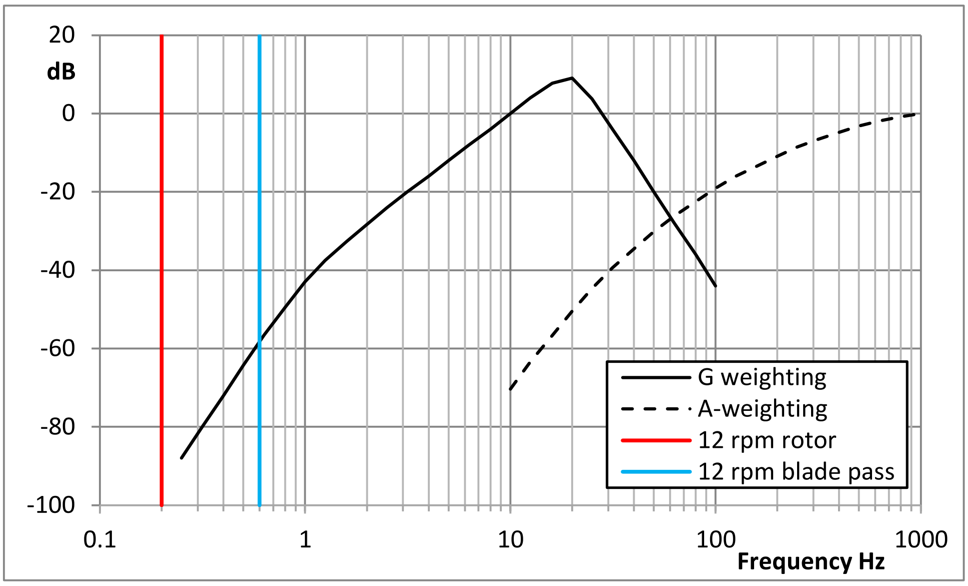

Figure 3: G-weighting and A-weighting curves with 12 rpm rotor and blade pass frequencies.

5 Measurement Problems

5.1 Why Always Use A-weighting Even When the Problem may not be Audible Sound?

The precise mechanism of the potential health hazards presented by turbine noise is outside the scope of this paper, but it should be understood here that, whilst the sound of normal AM turbine noise, with its normal 2 – 3 dB of AM, can cause annoyance, EAM differs from AM it that it can present a health hazard. This is a fundamental distinction between the effects of AM and EAM, and a fundamental reason why the appropriate measure of EAM is given by the true sound pressure level measured as dB re 20 µPa. By way of illustration, for the ear to perceive sound at 20 Hz and sound at 2 kHz to be of equal loudness the sound pressure level at 20 Hz needs to be 50 dB higher than the sound pressure level at 2 kHz. Below 10 Hz the A-weighting function is not even defined.

The common objective is, or should be, the determination of the levels at which wind turbine noise becomes:

(a) annoying to an extent that should be considered in the planning balance, or
(b) a potential health hazard, in which case the application/appeal should fail notwithstanding any other planning considerations.

It is important to use tools appropriate to each task. One tool which is clearly unsuitable for (b) is the A-weighting curve, which over rather more than 50 years has become entrenched, and often mandated, in environmental and industrial noise regulation. The original objective of the A-weighting curve was to reproduce the sensitivity of the average human ear over the audible frequency spectrum (defined as 20 Hz to 20 kHz) at low sound levels. It achieves that function well, but only at low sound levels; it is not suitable for, and was never intended for, the present purpose, where unacceptable levels of low and very low frequency sound may be present at high levels. The fundamental frequencies involved are the turbine rotation frequency, the blade pass frequency, and blade and tower resonant frequencies. All of these, and many harmonics thereof, fall below 20 Hz, where the A-weighting curve is not even defined.

The use of A-weighting reduces the sound level measurement – but not of course the sound level - by 50 dB at 20 Hz. At these low frequencies G-weighting is equally inappropriate as it too reduces measurements, by 50 to 100 dB at blade pass frequencies. Any weighting is inappropriate. As even the straightforward unweighted measurement of sound power level is referred to as “Z-weighting” the concept of weighting is obviously well entrenched in the acoustic mind set; inaudible pulsing pressure waves around 1 Hz however are far better understood in terms of physics rather than acoustics.

5.2 Use of a 100 Hz High Pass Filter Causes Understatement of EAM

The IOA AMWG Discussion Document [20], in order to *“filter out noise in the ambient environment occurring at frequencies below 100 Hz (which tends to be influenced by wind noise mainly)”* proposes the use of a 100 Hz high pass filter for AM compliance measurements. Inspection of the source spectra of Figure 9, all three of which are from wind energy industry publications, shows stall noise frequencies peaking at around 100Hz, compared with about 400 to 800 Hz in laminar flow. Thus, notwithstanding the contribution from very low frequencies due to blade rebound or resonance, the measured peak amplitude of EAM in stall will understate the true amplitude by around 3 dB, or even if (inappropriately) using A-weighting, by around a dB. The trough amplitude however will lose very little in the high pass filter (HPF), so the use of the 100 Hz HPF will cause significant understatement of the modulation height.

ETSU (page 31) considers frequencies down to 20 Hz in contemplation of the noise from the far smaller turbines current at the time of its drafting:

"It should be noted that low frequency noise, for example, from ventilation systems, can disturb rest and sleep even at low intensity. Where noise is continuous, the equivalent noise level should not exceed 30dB(A) indoors, if negative effects on sleep are to be avoided. In the presence of a large proportion of low frequency noise a still lower guideline value is recommended. It should be noted that adverse effect of noise partly depends on the nature of the source." [WHO]

The comments with respect to low frequency noise reflect the effect of using an A-weighted sound pressure level. If most of the acoustic energy was concentrated at a very low frequency, then high levels of acoustic energy might exist but an A-weighted level may still only be 30dB(A). As an example, the A-weighting network applies a correction of 50dB at a frequency of 20Hz. Therefore, a level of 80dB at 20Hz would meet this 30dB(A) requirement.

The IOAGPG endorses the use of ISO 9613-2 for wind farm immission noise level prediction and of IEC 61400-11 for turbine noise measurement. Both these standards require measurements only down to 45 Hz, a seemingly perverse movement upwards in frequency from 20 Hz over a 16 year period during which turbine noise emissions decreased considerably in frequency due to the increase in turbine dimensions. That the lower frequency limit should be raised even further to 100 Hz for EAM noise measurements, which clearly have a significant content below 100 Hz, seems yet more perverse.

5.3 The Den Brook Amplitude Modulation Measurement Methodology

Bass [21], of international wind farm developer Renewable Energy Systems (RES), claims that the Den Brook EAM measurement methodology is *"not fit for purpose"*:

"The above analysis has clearly demonstrated that the AM Test Method is not a good indicator of the presence of 'greater than expected' AM in samples of acoustic data, having a false positive rate of 67 - 83 %. Given that the sole purpose of such a test is to discriminate between those samples which do, and those which do not, contain 'greater than expected' AM, this high rate of false positives demonstrates that the test is not 'fit for purpose'."

§4.3.2 and §4.5.2 of the IOA AM consultation document [5] echo Bass, referring to a high rate of false positives in the Den Brook time series methodology for measurement of EAM, and to Bass's report of the measurement of a large number of "false positives" at two typical wind farm sites – typical except that they were in fact rural locations devoid of wind turbines. This, he considers, is evidence of a failure of the Den Brook methodology. A simple argument; if you have all those false positives indicating excessive AM even without any turbines present then how can one possibly rely on the data with turbines present? But this argument has a fundamental and elementary flaw. It is easier to explain the flaw by starting at the beginning rather than working backwards from Bass's erroneous conclusion.

Suppose there is a constant background noise level of B = 25 dB(A) and wind turbine noise of 40 dB(A) with 3 dB of AM: T = (40 ± 1.5) dB(A). Because dB scales are logarithmic the sum S of B and T is not given by S = B + T, but instead by

$$S = 10 \log (10^{B/10} + 10^{T/10}) = 40.14 \pm 1.45 \text{ dB(A)}$$

as should be well known to all acousticians. Thus the addition of the constant 25 dB(A) background noise marginally increases the average and noise level and actually **reduces** the AM index. Now let us add ± 1.5 dB of AM to the background noise:

$$S = 10 \log (10^{B/10} + 10^{T/10}) = 40.14 \pm 1.50000 \text{ dB(A)}.$$

That the total AM is again ± 1.5 dB should be no surprise, as both signals had the same ± 1.5 dB level of AM. That adding 25 dB(A) of background noise only adds 0.14 dB to the total noise level should be no surprise either. In summary the background noise has little effect on the turbine noise when it is 15 dB below it, which is likely to be the case, especially when compliance measurements are made indoors rather than outdoors and in high wind shear conditions, which is after all where and when the noise levels that give rise to the majority of complaints are experienced – in homes at night.

The ear's AGC (automatic gain control) system, one of the reasons for measuring sound levels in dB, has a gain compression mechanism which allows the ear to accommodate a huge range of sound power levels. It also enables the well-known property of sound masking. Very simply, a dB change in SPL at 40 dB(A) is far greater than a dB change in SPL at 25 dB(A). At the turbine-free wind farms surveyed by Bass there is no wind turbine noise to mask the background noise, so of course a 3 dB change in background noise will be detected without turbine noise, but it would have masked if there was turbine noise. By its variable nature background noise will always produce "false positives" in the absence of turbine noise – more accurately, they are real, but irrelevant positives.

The argument proposed and published by Bass fails because linear arithmetic and logarithmic arithmetic are different.

5.4 Loss of Frequency Information

I have shown in §4.2 above that stall at blade zenith can only explain increased aerodynamic noise on stall for EAM heights up to about 6 dB; it is also clear that further increases in EAM heights up to 30 dB can only be explained by the presence of much lower frequency acoustic emissions due to the structural dynamics of the turbine components. The IOA AMWG state that all EAM of any height is fully explained by increased blade aerodynamic noise above 100 Hz. This question is easily resolved by measurement, and it is most extraordinary that the IOA AMWG has not reported, and therefore presumably has not made, any such measurements. The word “infrasound” appears 15 times in the RUK report, but always in the context of asserting its non-existence in wind turbine noise.

The measurement system used by the IOA AMWG, because any standard SLM (sound level meter) rectifies and integrates the signal from the microphone, destroys all the original frequency information in the microphone signal. The INWG is therefore undertaking a series of measurements of turbine noise spectra at sites notorious for troublesome EAM heights, as theory should always be proved by measurement, in part to give confidence to those unable to understand the theory. Representatives of the IOA AMWG will be invited to participate in those measurements.

5.5 Indoors or Outdoors

I address here the question of whether EAM compliance measurements should be made indoors or outdoors. The IOA AMWG discussion document proposes outdoors, and justifies this proposal (§3.3 of [5]) by the statement:

“...measurements are made outdoors for consistency with other procedures for measuring wind turbine noise (such as ETSU-R-97).”

In truth AM compliance measurements have little relationship to ETSU background noise measurements. The descriptor proposed by the AMWG is LA_{eq}, whereas ETSU refers exclusively to LA_{90}. Furthermore EAM is an area where ETSU offers no guidance; there is therefore nothing to be consistent with.

It has also been suggested that access indoors may be refused by residents; it is however most unlikely that residents suffering from a serious wind turbine noise problem would not cooperate with attempts to resolve that problem.

The advantages of indoor measurement are threefold:

(a) Wind noise is significantly reduced, particularly at low frequencies, making the turbine noise measurements less contaminated and therefore more reliable. The higher outdoor background noise would of course raise the troughs in the EAM trace far more than it raised the peaks, thus understating the EAM modulation index.
(b) The 8 dB attenuation from outdoors to indoors through an open window assumed by ETSU when setting the 43 dB(A) night time limit does not apply at low frequencies; as discussed in §2.3 above it is certain to be reduced at frequencies below 100 Hz and at lower frequencies is often replaced by amplification due to room resonances.
(c) The resident can be provided with a pushbutton to timestamp the sound recording on occasions when the noise is considered unacceptable, which greatly reduces the

subsequent labour of data analysis by directing the person analysing the data to its relevant high EAM content.

Finally what good reason can there possibly be for measuring the noise level in a very different place from that where the noise level is giving rise to complaints?

It is puzzling that the IOA AMWG has changed its Terms of Reference by adding to the definition of AM the words ***"as observed outdoors".*** Referring to (b) above it is seen that this could allow indoor noise levels 8 dB above the ETSU 35 dB(A) limit on which the ETSU night time 43 dB(A) limit is based.

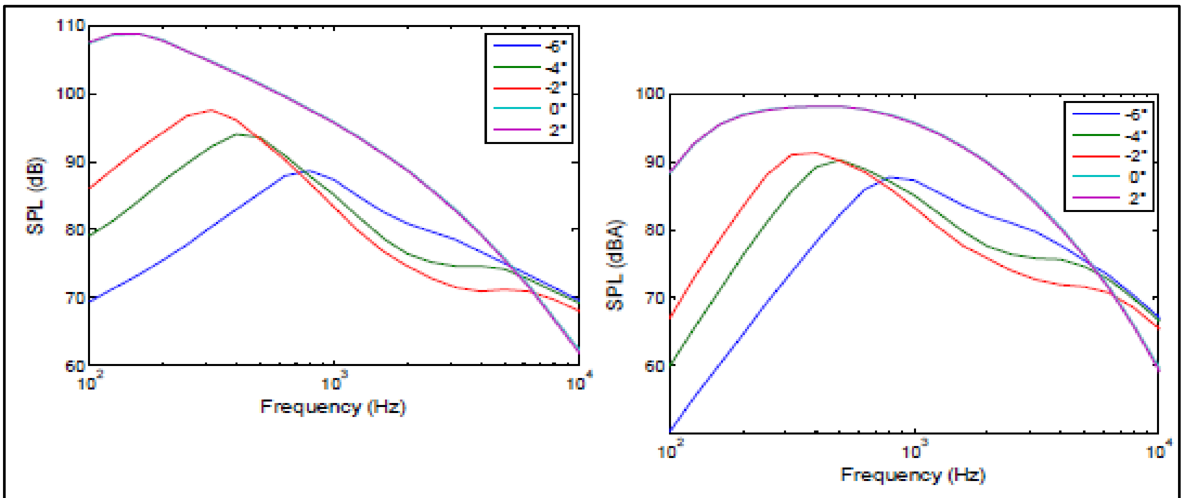

Figure 13: Source spectra for blade section in dB (left) and dBA (right) as a function of relative angle of attack (0° corresponds to the stall angle). The lines for 0° and 2° are practically on top of each other.

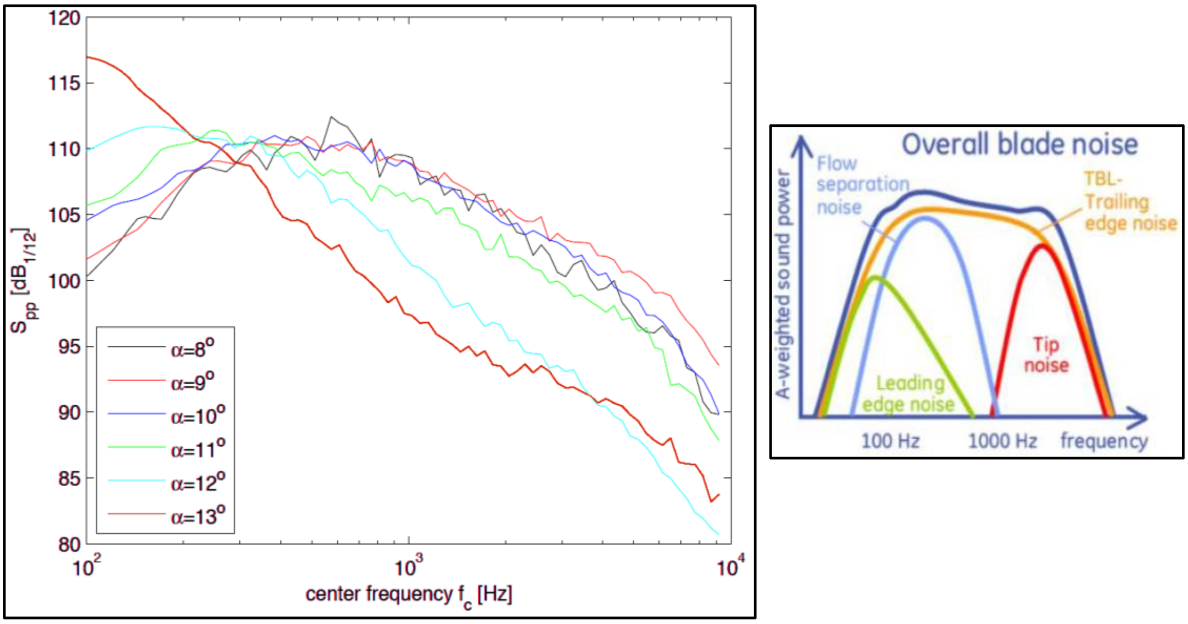

Figure 10: Change of aerodynamic noise spectrum with angle of attack; top, from the RUK report, Oerlemans, page 34; left, from the RUK report, H A Madsen et al., p. 492; right, from presentation by J Bass to EWEA Noise Meeting December 2012.

6 Conclusion

6.1 Understatement of the Modulation Index

Figure 9 shows, from three different wind industry publications, how blade stall at zenith increases the level of aerodynamic noise whilst reducing its frequency. All the charts have what appears to be the IOA INWG's rigid lower frequency limit of 100 Hz. The purple trace in the top left-hand chart is Oerlemans' predicted spectrum of aerodynamic noise in stall. Compare this with the red trace of my figure 2 for a similar turbine; it is seen that the SPL increases by 20 dB per decade as the frequency decreases from 100 Hz to 1 Hz. The comparison permits two observations.

- It cannot reasonably be assumed that the four stall traces of figure 9 all drop suddenly to an insignificant level at and below 100 Hz, yet the IOA AMWG effectively make that assumption by filtering out all noise below 100 Hz. This will cause a significant understatement of the EAM height. The increase in noise amplitude on stall will indeed show as an increase in EAM height, but cutting off all that part of the spectrum shifted below 100 Hz will spuriously and significantly reduce the EAM height.
- Aerodynamic noise from the blades is clearly not the only source of noise in play, as it does not explain the much higher energy part of the turbine spectrum, with or without EAM, below 100 Hz, as shown in figure 2 above but not shown or discussed in the RUK report [4] or in the IOA AMWG discussion document [5] derived from it.

6.2 The Increasing Inadequacy of ETSU

Turbines emit significant audible noise, against which current planning guidance (ETSU and the IOAGPG) provides a limited degree of protection to wind farm neighbours, and claims no better. ETSU opens thus (page iii):

"This document describes a framework for the measurement of wind farm noise and gives indicative noise levels thought to offer a reasonable degree of protection to wind farm neighbours, without placing unreasonable restrictions on wind farm development or adding unduly to the costs and administrative burdens on wind farm developers or local authorities."

I have observed that it is ETSU that is the primary constraint on the design of most commercial wind farms, the for which the NIAs usually predict noise immission levels within a small fraction of a dB of ETSU maximum noise limits; indeed if more turbines could be accommodated on a given site without exceeding those limits it would be commercially inept not to accommodate them. But it is now clear, from increasing numbers of noise complaints, that in many cases either the protection provided by the guidance is inadequate or compliance with the guidance is inadequate. The latter can only be due to questions of conscience and/or competence on the part of both developers and LPAs. I have represented many potential wind farm neighbours in appeals where I have exposed developers' NIAs as, in the words of one of the Inspectors, "deeply flawed" [22], and I have also seen gross but genuine errors due to the inadequate expertise of authors. One of the *"administrative burdens"* which many LPAs have failed to discharge is the verification of the competence of developers' NIAs, either by consulting their environmental health officers who lack the necessary education and experience or by using external consultants who largely work for the wind industry.

The adequacy and scientific rigour of ETSU has been questioned ever since its publication in 1997, not least by ETSU itself (page 2):

"The report was drafted in the light of the best information available at the time. However it is acknowledged that as more experience and information become available and as circumstances develop it may become necessary to revise and improve the contents of this report. The Noise Working Group therefore suggests this report and its recommendations are ***reviewed in two years' time****."*

That review is now 16 years overdue, and in the 18 years since the publication of ETSU wind turbines have considerably increased size and power. An inevitable consequence of this is the increase in amplitude and the decrease in frequency of turbine noise emissions. It is no longer credible for wind industry acousticians to claim that there is no noise problem from wind turbines, and in particular it is no longer credible to deny the emission of low frequencies noise and infrasound from today's wind turbines.

6.3 Annoyance or Health Impairment?

There are two rather different concerns raised by the IOA AMWG discussion document and the RUK report on which it is based. The boundary between the concerns is not abrupt, and is also uncertain because of the paucity of spectral measurements, but the dividing parameter is frequency, with the division probably somewhere near 20 Hz; it is the effect of turbine noise on the human species that changes with frequency.

Very low frequency noise can impair health without the hearer necessarily being aware of an annoying level of audibility, whereas the aerodynamic noise principally causes annoyance – although this too, if of sufficient degree, can ultimately impair health. Very low frequency noise, unless perceived as audible noise, cannot directly cause annoyance.

6.4 The Nocebo Effect

The wind industry response to the rapidly increasing numbers of noise complaints has been to invoke the "nocebo effect", which rhymes convincingly with placebo, and is in a sense its converse. According to the OED a placebo is "A substance that has no therapeutic effect, used as a control in testing new drugs". It also describes harmless but ineffective therapies used to placate patients whose problem is psychological rather than physiological. My OED has no entry for "nocebo"; the Journal *"Nature Medicine"* reports 16,579 titles which include the word placebo but only 35 which include "nocebo". Nevertheless the industry's nocebo-based claim is that negative propaganda about wind turbine noise causes many wind farm neighbours to think the noise is adversely affecting their health and disturbing their sleep when it is in fact innocuous. The industry also invokes psycho-acoustics to suggest that a dislike of the appearance of turbines translates to a dislike of their noise.

The reality is that all the information the general public have had from the wind industry and, until the summer of 2015, from Government, has been extremely positive. The printed and broadcast media, and particularly the BBC, still remain largely supportive of wind energy. When criticisms are made they relate to visual effects, damage to the economy and to security of supply, threat to endangered species, etc. Only rarely does the technically more complex topic of noise receive media attention; it is however usually the wind farm neighbours primary concern, but they do not often object to wind farm noise until they hear or otherwise perceive it. As the density of wind farms increases many potential wind farm neighbours will have heard noise, and the testimonies of neighbours, from other wind farms before they become involved in resistance to a planning application in their own immediate locality but even this does not fit the definition of nocebo unless the neighbours' testimonies are deemed to be false.

Figure 11: Some of the 1,600 aborted mink pups. Credit: Mark Duchamp, WCFN.

There are several species besides man that appear to have suffered adverse health effects from wind turbine noise. It is unlikely that a non-human species would be aware of any propaganda from either side of the wind energy debate, and unlikely that it would take exception to the appearance of wind turbines, and then translate that exception to a dislike of turbine noise.

A 2013 Polish study [23] in the Polish Journal of Veterinary Sciences Vol. 16, No. 4 (2013), 679–686 of the effect of a single 2 MW turbine on domestic geese farming concluded with:

"Geese from the gaggle which was kept at a distance of 50 m from the turbine, grew slower, gained less body weight (by 10 %) and had a higher concentration of cortisol in blood, compared to birds reared 500 meters away from the wind plant. It was also noted that even the distance of 500 meters cannot be considered a safe one; this was confirmed by the results of infrasound measurement and cortisol concentration in blood, which exceeded the control values."

As this peer-reviewed study was done in the interest of commercial goose farming by veterinary science researchers it cannot be portrayed as scaremongering by wind farm opponents.

An equally compelling case is Kaj Bank Olesen's mink farm in Denmark. At the end of 2013 four 140 m high Vestas turbines, the nearest 320 m from the mink sheds, became operational. Overnight the mink became highly aggressive and fought amongst themselves, with some females even killing their own pups. The farmer complained, and the operators terminated the turbine test run. The behaviour of the mink immediately returned to normal. The operators then declared that the problem was not of their making and operated the turbines again; the problem returned immediately, and was accompanied by an extremely high rate of deformities, stillbirths and abortions (see figure 10). The most common deformity was the absence of eyeballs. The Danish Government are holding what seems to be a very lengthy enquiry into the case, but it is of interest that there seems to have been an unofficial moratorium for onshore turbines in Denmark in throughout 2015.

A third, more recent case[24] is that of Yann Joly, a French dairy farmer, who has instructed Me Philippe Bodereau of Cabinet Bodereau Avocats, Arras to take legal action against GDF (Gaz de France) because an adjacent 24 turbine wind farm has caused a 50% reduction in the milk yield of his herd.

There are other cases: a goat farmer in Taiwan, who has gradually lost the majority of his herd since turbines became operational; eggs without yolks in Australia. The wind industry may dismiss all these examples as anecdotal, but when many anecdotes tell the same story the anecdotes become evidence. It would be most unwise to assume that man can cope with an unnatural noise spectrum that many other species evidently cannot cope with.

6.5 The Need for Objective Research and Evaluation

I reproduce below the abstract of the opening paper, "Some pitfalls to be avoided in a wind turbine noise research program", by the internationally renowned acoustician Prof. Paul Schomer, chair of the wind turbine noise session at the 169th Meeting of the Acoustical Society of America in May 2015:

"The Acoustical Society of America has created a public policy position relative to the acoustic emissions from wind turbines. This position calls for research that definitively will show if problems exist, and if so, who is affected, how are they affected, and why. ***Much of the research to date is based on assumptions, frequently contrary to fact or unproven****. That is not the kind of research that the ASA desires. The money spent on this questionable research should have been directed towards definitive research such as that envisioned by ASA. This paper talks about some of the previous research and elucidates on their assumptions with the purpose of preventing mistaken test designs like these in the future, and with the purpose of improving the research program to be developed by ASA."*

Prof. Schomer is a Fellow of and the Standards Director of the ASA. The wind energy industry is global, not national, and his comments apply at least equally to the UK, where most of the "research" has been done by the industry itself or by acousticians predominantly if not exclusively contracted to it. The resulting conflicts of interest, even when declared, have been ignored by the UK Government, as also are papers and reports by highly competent and appropriately qualified "interested parties" whose interest lies not in financial reward but in the welfare of wind farm neighbours.

Wind industry acousticians state on the one hand that:

"This paper outlines a research project [the RUK report] *designed to improve our under-standing of the phenomenon known as 'amplitude modulation' (AM).* ***There is little peer-reviewed, published research into the causes of AM…****"*

And on the other hand that:

"RenewableUK are ***strongly of the view that the frequency*** *and severity of AM are such that there is no need for a planning condition to control its emission…"*

These two comments might reasonably be supposed to have been made respectively before and after the successful execution of the proposed and much needed research project. They are however **consecutive paragraphs** in the wind industry paper (Bass et al., [25]) announcing the commencement of the RUK research project. It is therefore difficult to see the second quotation as anything other than a declaration of bias at the outset of the "research project" to which the first quotation refers.

6.6 Enough is Enough; Early Resolution of the EAM Problem is Essential

The design of most commercial wind farms is constrained by the ETSU noise limits; indeed if more turbines could be accommodated without exceeding those limits it would be commercially inept not to accommodate them. Provided that only normal levels of amplitude modulation are present, and that the noise prediction is fully compliant with planning guidance and best practice, noise nuisance should be minimal and health hazard zero. But when modulation heights are over 3 dB very low frequency noise may be (and, at heights over 6 dB, will be) implicated. The wind industry assumption that "*what you cannot hear cannot harm you*" is then no more valid than an assumption that the inability of the human eye to detect ultraviolet radiation somehow provides immunity to sunburn from it.

Wind industry developers and their acousticians have long asserted that wind turbines produce no significant levels of infrasound. By way of example Leventhall of the IOA NWG is quoted in numerous wind farm NIAs thus:

"I can state quite categorically that there is ***no significant infrasound from current designs of wind turbines****. To say that there is an infrasound problem is one of the hares which objectors to wind farms like to run. There will not be any effects from infrasound from the turbines."*

The UK Government (the Northern Ireland Assembly), like many wind farm victims, expresses a very different view [26]:

*"The Committee therefore recommends that the Department should **review the use of the ETSU-97 guidelines on an urgent basis**, with a view to adopting **more modern and robust guidance** for measurement of wind turbine noise, with particular reference to current guidelines from the World Health Organisation."*

*"The Committee recommends that the Department should bear responsibility for ensuring that arrangements be put in place for on-going long-term monitoring of wind turbine noise. 30. Following on from this, the Committee has heard evidence from local residents who are concerned about potentially **harmful low-frequency noise** emitting from wind turbines.*

*The Committee therefore recommends that the Department, working with local universities, should commission **independent research to measure and determine the impact of low-frequency noise** on those residents living in close proximity to individual turbines and wind farms in Northern Ireland."*

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