THE FUNDAMENTALS OF "AMPLITUDE MODULATION" OF WIND TURBINE NOISE

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1 INTRODUCTION

Amplitude modulation (AM) is a relatively benign characteristic of wind turbine noise. It is the periodic 2 - 3 dB variation in the amplitude 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 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, which appear to have impeded the exposure of important evidence concerning the true spectrum of EAM, and thus of wind turbine noise as frequently experienced by 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 elsewhere in other INWG papers.

2 THE CHARACTERISTICS OF AM AND EAM

2.1 Amplitude Modulation is Always Present

The principal source of 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 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 the positions of real noise sensitive receptors, when turbines are operational there will always be modulation, of 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 operational wind turbine noise and always present.

2.2 Excessive Amplitude Modulation – when Swish turns to Thump

Amplitude modulation is considered excessive when the "modulation depth" of the time series envelope exceeds the 2 – 3 dB range reported in ETSU; modulation depths up to 30 dB have been reported. EAM peaks are narrower; the troughs show no decrease. The waveform thus changes radically, but over a relatively small part of the blade pass period. An example of high (25 dB) modulation depth time series chart from Huson [3] is shown in figure 1. Most of the "depth" is due not to modulation at all but to infrasound tones at 0.3 Hz and harmonics thereof, as was confirmed by simultaneous pressure measurement with a microbarometer. True modulation would have the troughs descending as much as the peaks ascending; in the present case, where the troughs do not descend, it is more logical to refer to modulation height than modulation depth, as I do in all that follows.

The wind industry and the IOA AMWG claim 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 greatest observed modulation heights. The major contribution comes from noise well below 100 Hz. I will also show that the RenewableUK AM research report [4] ("the RUK report") and the IOA AMWG discussion document [5] derived from it systematically exclude any consideration of acoustic emissions at frequencies below 100 Hz. The RUK report includes no measurements below 100 Hz to support the claim however. In truth the greatest observed modulation heights are rather easily explained by consideration of the low frequency emissions which are a consequence of the structural dynamics of large modern wind turbines, not aerodynamic noise from the blades.

The major part of the audible acoustic emissions from 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 from an independent test report by Windtest gmbh for a typical modern turbine, the RePower MM92. The major part of the acoustic power however falls below 4 Hz, as seen in the unweighted traces (linear, black and logarithmic, red) of figure 2; 4 Hz is well below the threshold of hearing.

The A-weighted trace reflects the annoyance value of audible wind turbine noise, whereas the two unweighted traces reflect the sound pressure of, and therefore potential health hazards from, wind turbine acoustic emissions. When only normal levels of amplitude modulation are present, and provided separation distances between turbines and homes are adequate, the health hazard is minimal. When modulation heights exceed 6 dB however infrasound and very low frequency noise are implicated and 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.

2.3 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 0º 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 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 for 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 against 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. This is the wind turbine operational regime assumed to prevail by ETSU, by the IOA Good Practice Guide [6] ("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.

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. High wind shear is one of the known causes of EAM. 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. This local turbulence disrupts streamline 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 daytime. It is therefore no surprise that most wind turbine noise complaints are about 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 presumably 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 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 noise frequency peak by several octaves; see figure 8. Blade stall at zenith can quantitatively explain 3 dB (i.e. a factor of 2) 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 reported modulation heights up to 30 dB (i.e. a factor of 1,000) in measured noise level.

3.3 Transient Stall also Produces Pressure Pulses at the Blade Pass Frequency

When a blade stalls and loses the force of the wind it also rebounds due to its elasticity (see figures 5 and 6), 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 oscillate 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.

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.

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

Two obviously significant aspects of wind turbine design evolution since the early 1990's are the increase in turbine size and generating capacity, and the decrease in the ratio of cost to generating capacity. The latter has been achieved in large part by the reduction of material costs, as can be seen by comparing the power to weight ratio of today's large turbines with those available in the early 1990's. Early turbines were massive enough and therefore rigid enough 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.

The relevant variables are the several resonant mode frequencies of the 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 imbalance in the blade weight or weight distribution will result in a rotating radial force at the hub.
- The blade pass frequency $3f_r$ (for a three bladed turbine, which is now almost universally the case); the wind force on the tower will be reduced when a blade is passing the tower.
- Again at blade pass frequency, but at blade zenith, blade rebound impulse as described above.
- 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 reported in [10].

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 ([7], 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 throughout).

Turning again to figure 2, a most unusual feature of the chart (perhaps unique for published data) is that it covers a bandwidth down to 1 Hz. The blue trace is the usual 1/3 octave A-weighted noise emission power from 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 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. 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 blades pass fairly close to the tower, so there is some interaction therewith, as figure 5 suggests.

The black 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 indication of where the noise power is at its highest level: below 10 Hz. The logarithmic and linear scales coincide in value at 0 dB and 140 dB. The measurements were made in daytime wind shear so relates to turbines noise with normal AM, and without EAM.

3.5 Vortex Shedding from Towers

Wind blowing past a cylinder (not necessarily a circular cylinder) 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 have resonate frequencies typically around 1 Hz or less.

Vortex-induced vibration (VIV) is well understood and 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: [8].

A frequently seen solution to VIV is the fitting of a helical “spoiler” around the outside of a chimney, sometimes referred to as an “NPL helix”. 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.

The unplanned shutdown from full power of Macarthur wind farm (140 x 3 MW Vestas V112 turbines) provided Huson [9] with clear evidence of turbine tower resonance. 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 tones decreased by only a few dB. In such a case tower resonance 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 resonant frequencies is now avoided when increasing or decreasing the rotor rotation rate, so whilst this mechanism can be a powerful source of infrasound it is also easily 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. 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.

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 ref. [21] in the RUK report.

4 THE RUK REPORT

4.1 A Note on the Academic Status of 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 of the people and publications from which they take their guidance. This is particularly relevant when the science is complex and the potential financial gains of its promoters are high. 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 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; 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 has 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, and usually anonymous, peer reviews are required. The leading international journal in acoustics is that of the Acoustical Society of America (the 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."*

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

In the following two sections I question the validity of two 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 however 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; I will show that the demonstration is deeply 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, 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 could not find in Oerlemans' ref. [19] any reference to a 10 dB increase in broadband noise on stall, or indeed any measurement data of great relevance 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 lower".*

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 there is no reason why the noise increase on stall should differ. 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] (also my reference [10]) is a paper given at the 30th American Institute of Aero-nautics 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.

Having read Oerlemans references [18, 19 and 21] I would consider that, to merit the adjective *"plausible"*, a quantitative explanation of EAM should account for the reported stall noise increases up to 30 dB, not just the lowest reported increase of 10 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 asso-ciated 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 30 dB. Astonishingly Oerlemans continues (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 accounts 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 by

a factor of 500 (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 totally unjustified 7dB to achieve even that lowered target. Thus the RUK report offers no plausible explanation for the modulation heights 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.
It seems that the wind industry has prejudged the spectrum of blade stall noise with considerable determination but no measurement.

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

I have commented above that the filtering out of all frequencies in the measurement of EAM will assuredly remove all of the turbine noise signal from blade rebound on stall and from blade and tower resonance or VIV, along with some of the downward shifted frequency content of the aerodynamic noise in stall. The WP B2 report on the Salford listening room experience has a surprising inclusion in its sound reproduction equipment: **a high pass filter with a corner frequency of 140 Hz and 20 dB attenuation at 100 Hz** (see figure 9). This equipment is used to replay sound recordings from turbines for volunteers to rate their degree of annoyance. The RUK report and indeed the wind industry developers and IOA AMWG acousticians repeatedly state 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 – **unless there is in fact something hidden below 100 Hz.**

5 MEASUREMENT PROBLEMS

5.1 Why use A-weighting when the Real Problem is not 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 turbine noise, with its normal 2 – 3 dB of AM, can cause annoyance, EAM 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). 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 (a factor of 100,000) higher than the sound pressure level at 2 kHz. Below 20 Hz the A-weighting function is not even defined.

Our objectives are, or should be, to determine at what levels wind turbine noise becomes (a) unacceptably annoying and (b) a potential health hazard; it is important that we 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 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 levels of very low frequency sound may be present to an injurious extent. 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, and the A-weighting curve is not even defined below 20 Hz.

The effect of turbine noise under consideration is harm, not annoyance, so the relevant parameter is sound power, not sound audibility. A-weighting reduces the sound level measurement – but not of course the sound level - by 50 dB at 20 Hz. G-weighting is equally inappropriate as it reduces measurements by 50 to 100 dB at relevant (sub 1 Hz) frequencies. Indeed any weighting is inappropriate, but as even the straightforward measurement of SPL is referred to as "Z-weighting" (zero weighting) weighting is obviously well entrenched in the acoustic mind set.

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

The IOA AMWG Discussion Document [5], 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 8, all three of which are from wind energy industry sources, shows SPL(dB) stall noise frequencies peaking at around 100Hz, compared with about 400-800 Hz in streamline 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.

5.3 Loss of Frequency Information

I state that stall at blade zenith can only explain increased aerodynamic noise for EAM heights up to about 6 dB; I also claim 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 extraordinary that the IOA AMWG has not reported, and therefore presumably not made, such measurements.

The measurement system used by the IOA AMWG, because the SLM rectifies and integrates the signal from the microphone, destroys all the original frequency information in the microphone signal. I believe that §5.2 above proves my case and discredits the IOA AMWG's case. The INWG has nevertheless embarked on a series of measurements of turbine noise spectra at sites notorious for troublesome EAM heights, as theory should always be proved by measurement if only to give confidence to those unable to understand the theory. Representatives of the AMWG will be invited to attend and observe those measurements.

6 CONCLUSION

6.1 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.

6.2 Summary

Wind industry developers and their acousticians have long asserted that wind turbines produce no significant levels of infrasound. Leventhall is quoted in innumerable wind farm noise impact assessments 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."

This ill-informed and unashamedly partisan statement is negated by the measurements of many reputable and competent acousticians. I and many other appropriately qualified and experienced scientists believe that there is in reality a potential health hazard associated with infrasound and low frequency noise emissions from large modern wind turbines.

7 REFERENCES

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8 http://www.dailymail.co.uk/news/article-2931551/Horrifying-video-shows-motorway-lampposts-shaking-violently-snowstorm-phenomenon-experts-call-vortex-shedding.html.
9 L Huson, "Stationary wind turbine infrasound emissions and propagation loss measurements", 6th International Conference on Wind Turbine Noise Glasgow, 20-23 April 2015.
10 S Moreau, M Roger, J Christophe, "Flow Features and Self-Noise of Airfoils Near Stall or in Stall", AIAA 2009-3198 15th AIAA/CEAS Aeroacoustics Conference (30th AIAA Aeroacoustics Conference) 11 - 13 May 2009, Miami, Florida.

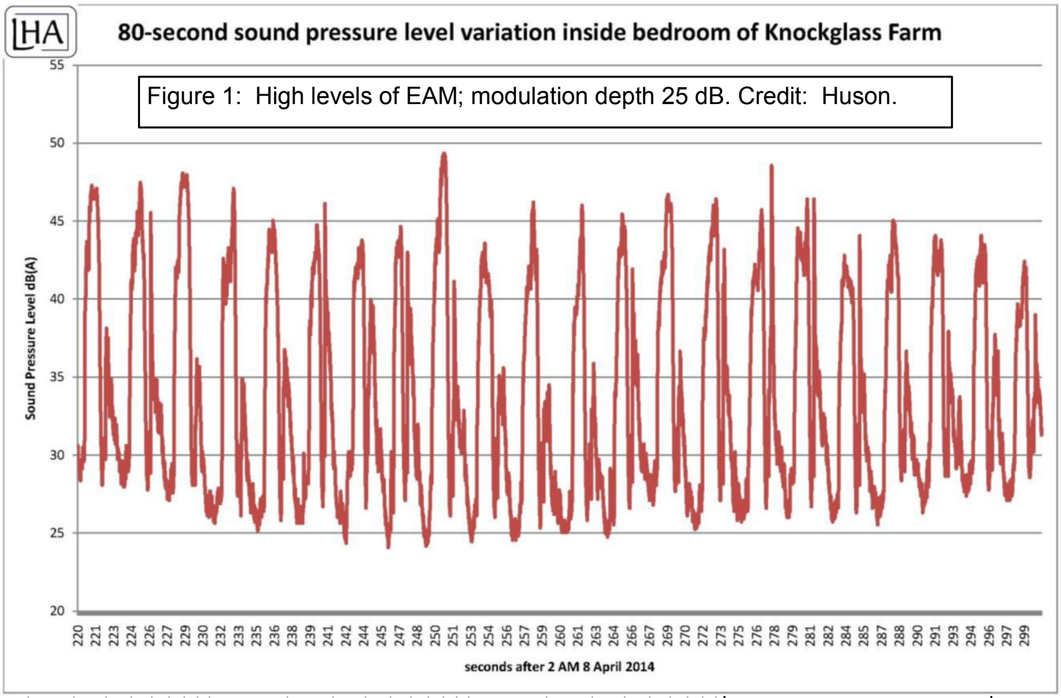


Figure 1: High levels of EAM; modulation depth 25 dB. Credit: Huson.

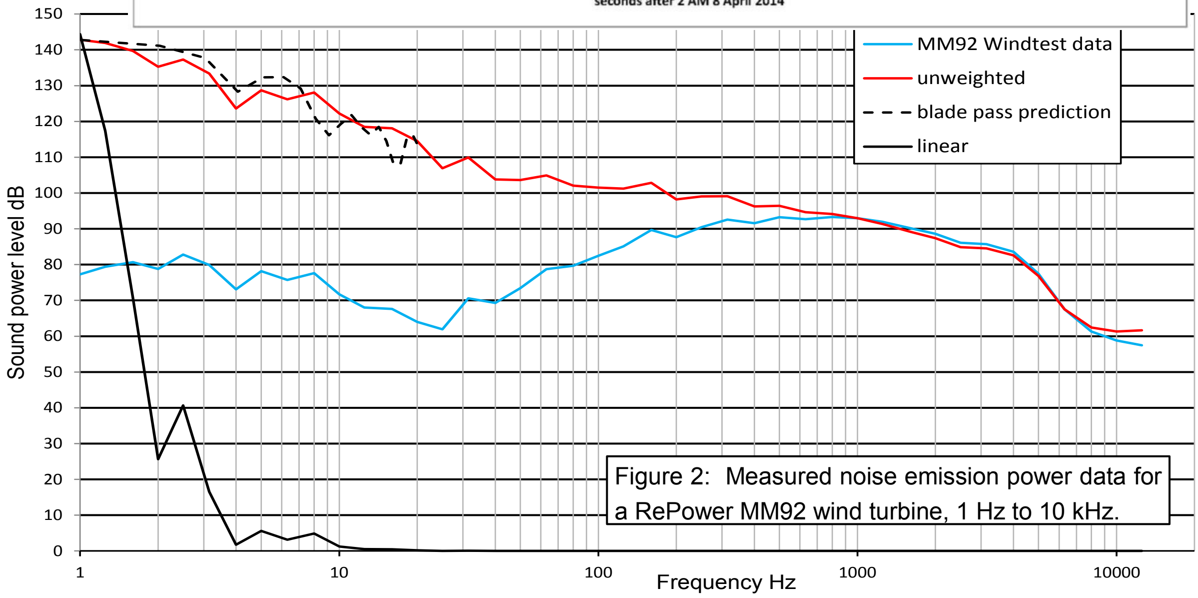


Figure 2: Measured noise emission power data for a RePower MM92 wind turbine, 1 Hz to 10 kHz.

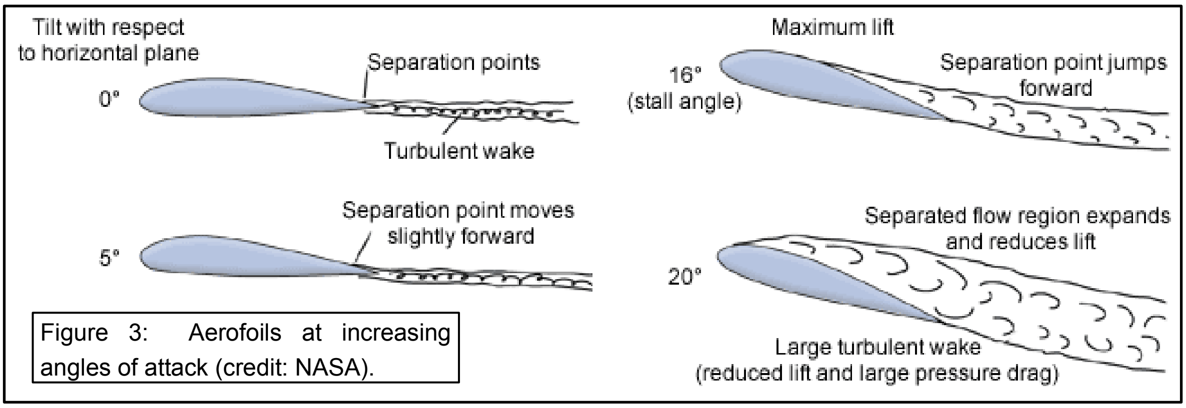


Figure 3: Aerofoils at increasing angles of attack (credit: NASA).

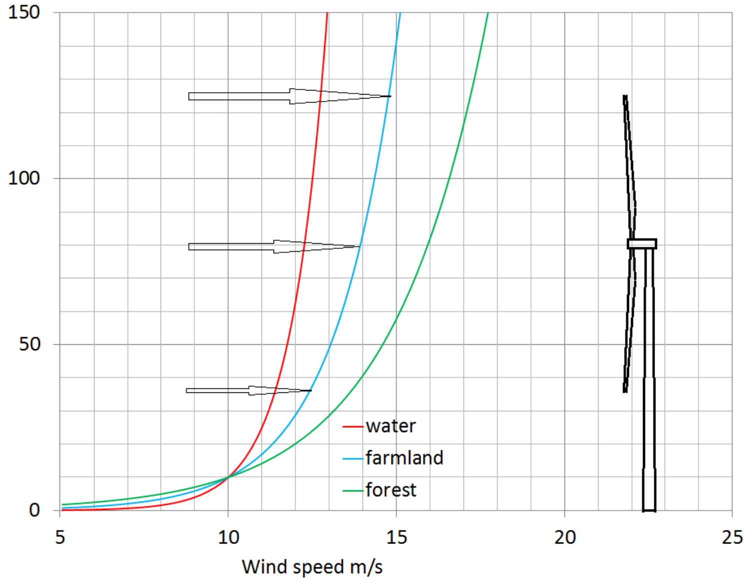


Figure 4: Wind shear;125 m turbine on various terrains.

Figure 5: Noise contours; noise level increases by 12 dB from blue to red.

Figure 6: Unstressed but considerably curved blades awaiting shipment.

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

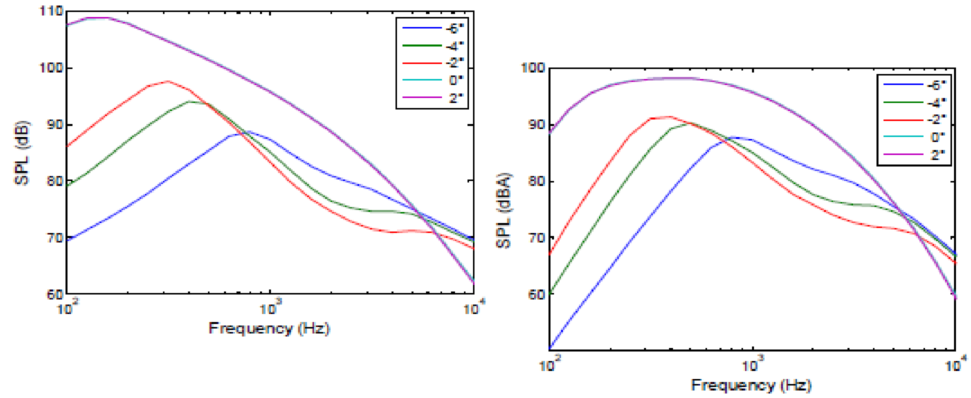
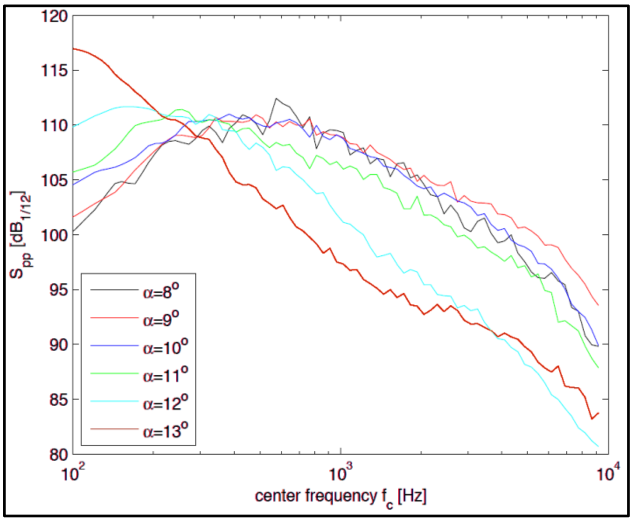


Figure 13: Source spectra for blade section in dB (left) and dBA (right) as a function of relative angle of attack (0° corresponds to the stall angle). The lines for 0° and 2° are practically on top of each other.



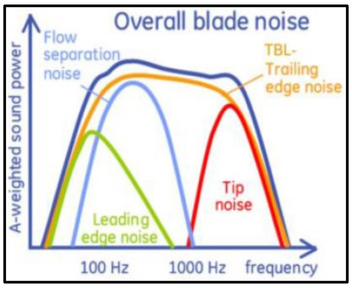


Figure 8: Change of aerodynamic noise spectrum with angle of attack; top, from the RUK report, S Oerlemans, page 34; left, from the RUK report, H A Madsen et al., p. 492; above from presentation by J Bass to EWEA Noise Meeting December 2012.

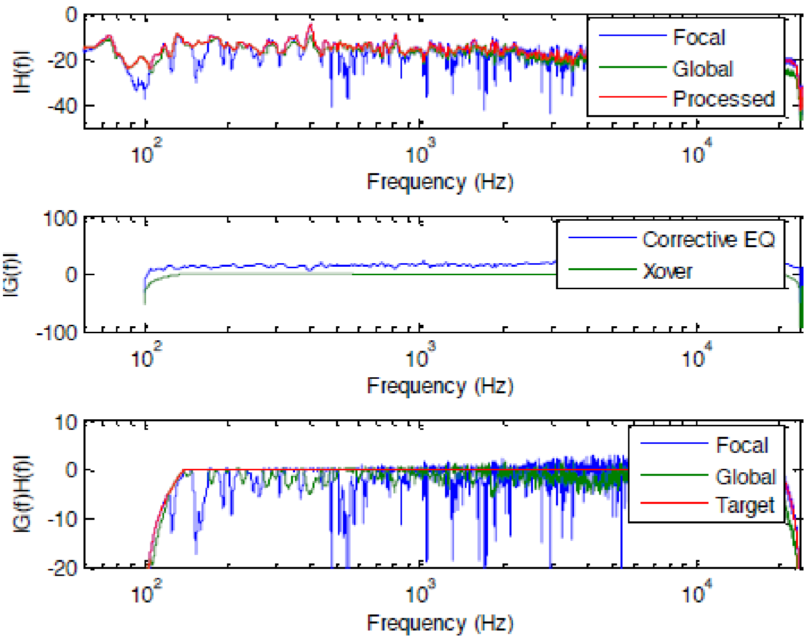


Figure 9: Salford listening test filters out frequencies below 140 Hz.