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The Institute of Acoustics' Working Group on Amplitude Modulation in Wind Turbine Noise - Progress towards an agreed rating and assessment metric

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Summary

Amplitude modulation in wind turbine noise has been well documented in recent years in the UK and overseas and various researchers have devised methods of measuring it. However, the methods available yield different results and few are backed up with research on subjective dose response relationships. To address the need for a common rating and assessment metric, the Institute of Acoustics have set up an amplitude modulation working group. The working group includes consultants, academics and representatives from wind farm developers and local authorities. This paper presents an overview of the work carried out to date, includes samples of amplitude modulation compared with different rating metrics and describes the difficulties encountered in discriminating wind turbine amplitude modulation from other modulated environmental noises.

1. Introduction

In response to a request from the Institute of Acoustics Noise Working Group (IOA NWG), and approved by IOA Council, the IOA set up a working group to look at amplitude modulation in wind turbine noise. The aim of the group is to review the available evidence and to produce guidance on the technical aspects for the assessment of AM in wind turbine noise.

1.2 Terms of Reference

The agreed terms of reference are as follows:

- Undertake a literature review of available research and evidence on amplitude modulation and current methods in use, as appropriate; and on psycho-acoustic effects of AM;
- Consider the design parameters for an AM metric and assessment method to be used in the UK;
- Consider the various metrics and methodologies available to describe AM, and develop a preferred option if possible, or identify alternatives for the IOA membership to consider;
- Produce a first draft of a consultation document with explanatory notes / justifications for consultation;
- Consult the IOA membership and where appropriate other relevant technical experts on the draft guidance document;

- Consider the consultation responses and if appropriate, produce a final Guidance Note and / or consider the need for further research;
- Provide software, if possible, to allow the analysis of AM data.

It is noted that the group are focussing on technical aspects of the rating mechanism but would wish to select a rating with obvious subjective relevance. Any penalty scheme would be a matter of Government policy and is likely to be the subject of a separate Government-funded study.

1.3 Acknowledgements
I am indebted to my fellow group members: Jeremy Bass, Matthew Cand, Dave Coles, Bob Davis, Geoff Leventhall, Tom Levet, Sam Miller, David Sexton, and John Shelton. Their work is presented in this paper. In particular, I would like to thank Matthew Cand, Dave Coles and Tom Levet and their respective companies (Hoare Lea, 24 Acoustics and the Hayes McKenzie Partnership) for their invaluable efforts in coding various methods so that they can be used to process wind farm noise data. I would also like to thank Dr Jeremy Bass for keeping track of the complex discussions and taking the minutes of our meetings and organising the group's extranet system. Last, but not least, I would like to thank Richard Perkins, Chair of the IOA Noise Working Group for his role in steering the group and liaising with the IOA Council.

1.2 The Problem
In the context of wind turbine noise, amplitude modulation (AM) means the regular fluctuations in the level of the perceived noise from wind turbines, the periodicity of the fluctuations being determined by the blade-passing frequency of the turbine rotor (BPF) – the frequency at which a blade passes a fixed point on its arc. The phenomenon can be described as a regular 'swish', 'whoosh' or 'thump'. The frequency of the fluctuations is typically in the range 0.5 – 1 Hz for wind turbines in the 500 kW – 3 MW range with 3- bladed rotors, but can be higher for smaller turbines. Figure 1 shows the extent of the problem.

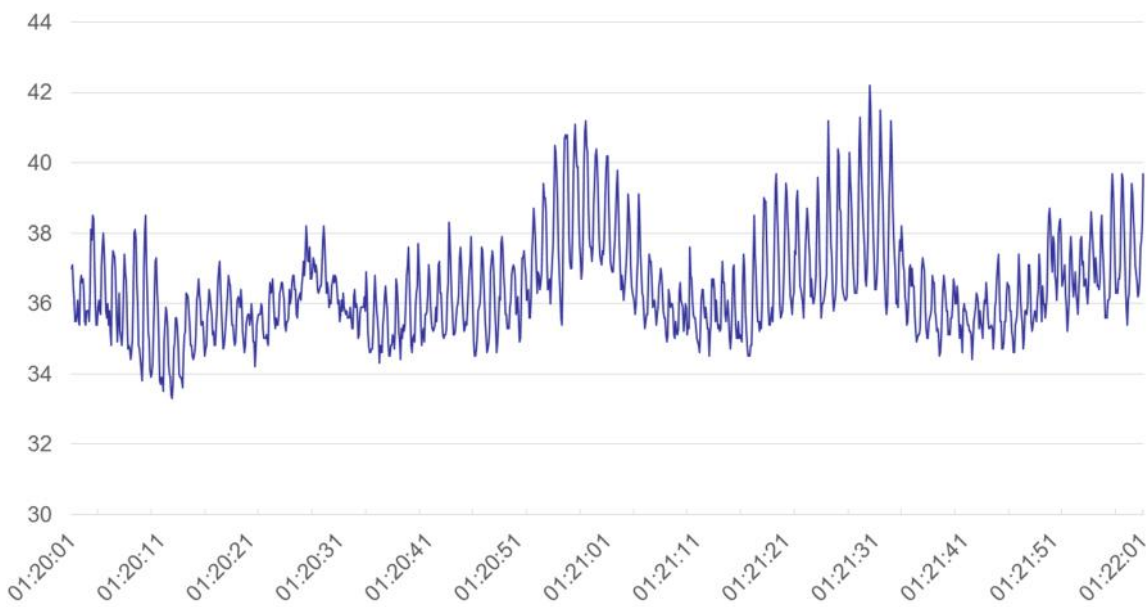

Figure 1 – Typical Amplitude Modulation Time History 100 millisecond L_{Aeq} samples

For the two minute period shown above, the amplitude modulation is variable and not consistent except for the frequency of modulation. At 01:20:30 there is some extraneous noise which may influence the results.

2. Definition of Amplitude Modulation

One of the first tasks of the group was to define amplitude modulation.

Amplitude modulation in wind turbine noise was identified in 2004 / 2005 by Van Den Berg (1) and in the Defra study on low frequency noise from wind farms in 2005 (2). Various terms have been adopted by researchers including Excess or Enhanced Amplitude Modulation (EAM) or Other Amplitude Modulation. A planning condition imposed on Denbrook wind farm deemed AM to be 'greater than expected' where there was a rise and fall in the $L_{Aeq\ 125\ msec}$ level by more than 3 dB in any two second period, subject to certain other qualifications.

The term amplitude modulation needs some clarification as all wind turbines produce amplitude modulation in the form of blade swish. The work of Oerlemans (3) identified that blade swish is a result of the directivity of the trailing edge noise and the rotating blade. This can result in amplitude modulation of 5 dB for crosswind directions but is typically characterised by mid to high frequency noise. This has been referred to as 'normal' AM. However the RenewableUK (4) study identified an entirely separate mechanism for the low frequency 'thumping' or 'whoomphing' sound that was more prevalent in downwind directions. The mechanism was transient stall on the rotor blades occurring at the blade passage frequency. The term 'other' AM (OAM) has been used to describe this, to emphasise the different mechanism. However it is accepted that both mechanisms might occur and the work of the group should not necessarily limit itself to one or the other. The following definition of wind turbine amplitude modulation was agreed with the group:

In the context of the objectives of the Working Group, wind turbine AM (WTAM) is defined as periodic fluctuations in the level of broadband noise from wind turbines; the frequency of the fluctuations being the blade-passing frequency of the turbine rotor, as observed outdoors at residential distances in free-field locations.

For the purposes of the Working Group, there is no need at this stage to adopt separate definitions for 'normal' or 'other' AM, and there is no agreed basis for defining any particular level or character of AM as 'enhanced' or 'excessive' or 'greater than expected'. The objective is to define a measurement protocol and associated metric which is technically robust and correlates with subjective response to AM.

The group decided to confine itself to measurements outdoors. It is recognized that AM can be a problem indoors, but indoor measurements in occupied buildings present many difficulties, and in the UK, noise limits set in planning conditions relate to the outdoor sound level.

It is recognised that smaller turbines would have higher blade passing frequencies and that some micro-turbines have rattle/flap problems, which might show up as amplitude modulation. The applicability of the metric to smaller turbines will be reviewed when considering alternative metrics.

3. Literature Review

The working group have collated over 30 papers on amplitude modulation, not least from those presented at previous wind turbine noise conferences. Researchers have proposed different ways of rating amplitude modulation. Many (5), (6), (7) have taken a Fast-Fourier Transform (FFT) of the time series as represented by short L_{Aeq} or L_{pA} values, eg in 100 millisecond samples. By using the FFT, the modulation frequency appears as a spectral peak in the frequency domain and the periodicity of the amplitude modulation can clearly be seen. The power spectral density of the fundamental can be related to the peak to trough value of the amplitude modulation. One of the advantages of this approach is that false positives can be reduced as modulated sounds with a modulation frequency outside of the expected range can be ignored.

RenewableUK proposed a planning condition on this basis. The method has been adopted but it has been shown by Levet (8) that the R-UK methodology under-estimated the Salford definition of the peak to trough level and therefore the method needs some refinement.

In Australia, Cooper and Evans (9) proposed a hybrid method where they used the FFT method only to find the modulation frequency and then used this to select peaks and troughs within a time window defined by the modulation frequency. This again reduces the influence of the spurious results. The outcome is the depth of the modulation, albeit with some averaging depending on the chosen time period.

Other methods used included impulsiveness, fluctuation strength (after Zwicker and Fastl) and the D_{AM} index proposed by Tachibana's group in Japan (10). The work of Tachibana and other researchers who also carried out subjective research was deemed to be more valuable to the group because of the subjective relevance.

The group have rejected the fluctuation strength metric; although it is noted that it is the one rating system that accounts for the frequency of modulation and some researchers, eg Legarth (11) noted a correlation between fluctuation strength and annoyance due to blade swish. The modulation frequency is known to be a factor in the annoyance as noted in the RenewableUK study (Op.Cit) with a peak in the annoyance occurring at a modulation frequency of 4 Hz. Seong and Lee (12) compared this rating to various others and backed this up with subjective tests. However the fluctuation strength metric was not better than the other metrics considered. The simple L_{AMax} value was the best metric identified in the work of Seong and Lee, perhaps not surprisingly as the RenewableUK study also highlighted the fact that the overall level of sound (irrespective of any modulation) was an important factor in the subjective response.

Similarly, rating AM in terms of the impulsiveness was rejected. Impulsiveness can be rated according to DIN 45645-1 and is featured in the new British Standard BS4142, but compared with other banging type noises, wind turbine AM does not have very short rise-times and therefore this method would only identify the very worst examples of AM.

The work of Tachibana et al is perhaps the most comprehensive study as data was gathered from several wind farms and their metric was supported with subjective studies in a listening room. As part of their paper, the authors propose a simple metric for the rating of AM. This first de-trends the data calculating the difference between L_{AF} (fast) and L_{AS} (slow) samples to obtain a series of $\Delta L_{A(t)}$ values. An estimate of the magnitude of amplitude modulation is then determined through the difference between the 95th and 5th percentile values of the $\Delta L_{A(t)}$ values.

$$D_{AM} = \Delta L_{A5} - \Delta L_{A95}$$

The period of analysis is specified as 3 minutes. This method is straightforward and could easily be implemented directly in a sound level meter. This method does not account for the periodicity in the signal however, and is therefore susceptible to corruption by extraneous noise. In particular, an impulse can corrupt the L_{AS} slow signal significantly and therefore the metric would only be effective with clean AM signals.

Part 2 of the Japanese research described subjective studies in a listening room with different AM signals which were synthesised. This included tests of the 'noisiness' of sounds with varying modulation depth. To do this, the participants adjusted the level of modulation sounds with a volume controller to obtain the equivalent noisiness of an unmodulated stimulus. The research revealed that the apparent 'noisiness' increased as the modulation depth increased. However the relative noisiness of the modulated sound was no more than 2.5dB on average for sounds with a modulation depth of up to 10 dB.

4.0 Methods Chosen for Further Consideration

Following the literature review, three methods were chosen for further consideration. These will be included in a consultation document.

- An enhanced FFT-based method based on band-limited data.
- A hybrid method based on filtering the data to reconstitute a time series.
- A time-based method, such as Tachibana et al.

Common Assessment Parameters

With all methods some common parameters need to be assumed. This will simplify the analysis and allow the methods to be compared. The choice of these is somewhat arbitrary as there is no subjective research which states, for example, that the use of the short-term L_{eq} samples, eg 100 milliseconds is better than the sampled fast sound pressure $L_{p100\ msecs}$.

The common assessment parameters include the following:

- The use of the short-term L_{eq} in 100 millisconds
- Wind farm noise to be analysed in 10 second periods (a shorter time may capture some short-lived AM but there are signal analysis issues with using too short samples). Therefore an AM rating will be determined for each 10 second block. Within these 10-second periods the modulation is averaged.

- Since most planning noise assessments use 10-minute samples, the 60 AM ratings (one for each 10-second period) will be processed to find the 90th percentile representing the highest samples.

These assumptions can be applied to any of the ratings. It is acknowledged that Tachibana used 3-minute samples, but his method can be applied to any time period in principle.

The three methods are described in more detail below.

4.1 Enhanced FFT Method

From Figure 1, it could be seen that the only consistent part of the signal was the periodicity. Therefore a method which uses this will be advantageous because most of the peaks and troughs from other environmental noise sources will be less regular. This allows spurious results to be rejected. For example, any results with a modulation frequency outside of the expected blade passage frequency can be rejected. The expected blade passage frequency can be inputted from SCADA data or can be readily observed using a Waterfall plot. See Figure 2.

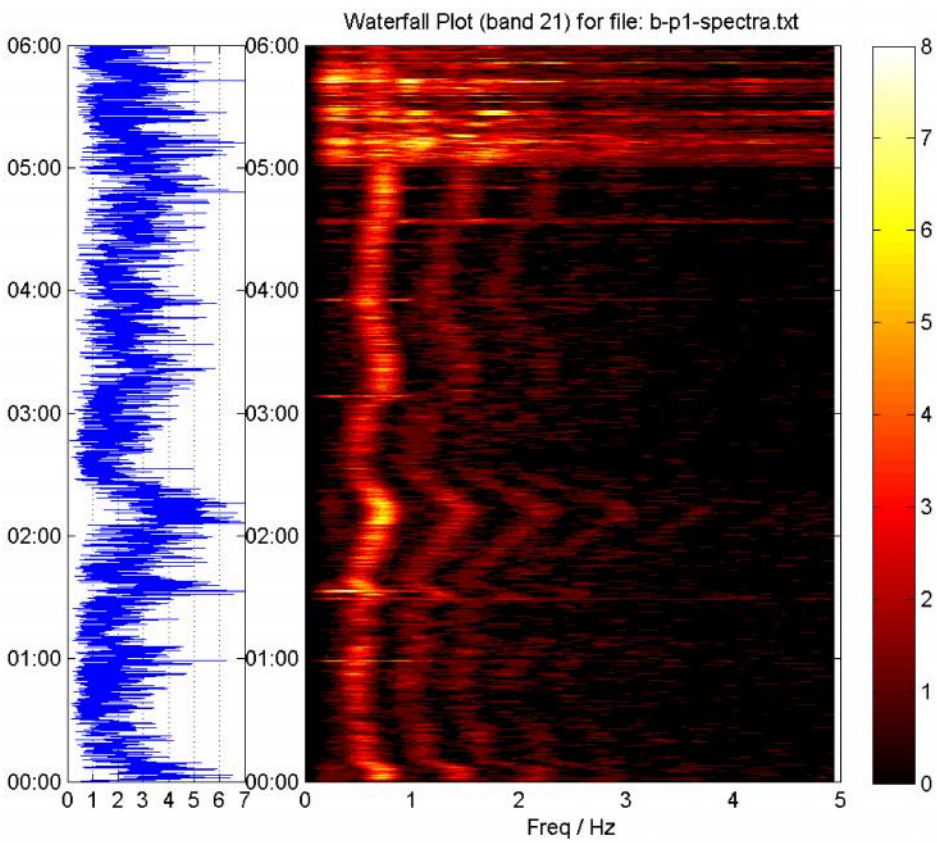

Figure 2 – Waterfall Plot (Analysis by Hoare Lea)

The enhanced FFT method will be similar to the R-UK method but will use 100 millisecond 1/3rd octave band values to determine a band-limited signal, say 100 Hz to 400 Hz (7 1/3rd octave bands). The advantage of using a band-limited signal is that the modulation is located in this frequency range and higher frequencies, which

in effect are noise, are eliminated. The 100 Hz to 400 Hz frequency range will cover the typical sound of large turbines at residential distances but there may be other examples where an extended frequency is required – the frequency range should always cover the frequencies where modulation is present and could be extended downwards or upwards.

A band-limited signal will always result in a higher modulation rating than A-weighted levels because the noisy part of the signal, which masks the modulation, is reduced. Some consideration has been given to adding the second harmonic of the signal, but it is considered that this is not necessary and it results in more noise and an increased likelihood of spurious results.

The band-limited FFT method has been used successfully with large data sets to compare AM before and after mitigation (13). When making comparisons of this nature, it is important that the method is consistent and is robust in terms of handling large data sets.

4.2 Hybrid Method

An alternative to the FFT method is to apply 1/3rd octave band filters to the time series to in effect filter the time series. Once filtered, the time series can be re-constituted and a clean signal is obtained where it is relatively easy to select the peaks and the troughs. This method has been devised by Dave Coles of 24 Acoustics.

The reconstruction method is a hybrid between an FFT-based method and a time-series method. An FFT is performed to obtain the blade-passing frequency, which then forms the basis of digital filters implemented in the time-domain. The result is a cleaned version of the time-series, with extraneous noise removed whilst retaining energy at the first 3 harmonics. The amplitudes of the peaks and troughs are then identified, which provide a means of calculating the peak to trough level of modulation, typically by taking the average level of the troughs from the average level of the peaks.

The method has a greater number of calculation steps and in fact an FFT of the signal is taken to first determine the expected modulation frequency, so that a 1/3rd octave band filter can be centred on the appropriate frequency. Nevertheless the method results in a time series that allows peaks and troughs to be compared such that it should relate fairly well to the Salford subjective tests.

4.3 Tachibana Method

The Tachibana method has some advantages in that it can be readily assessed with a sound level meter (albeit one with parallel fast and slow time weightings) without specialist software. It also has some subjective significance since the additional “noisiness” of the amplitude modulation signal can be determined. Therefore the consultation document has also included this rating. It is noted however that the slow response of a sound level meter can easily be disrupted by impulses and this method is only suitable with relatively clean signals.

5.0 Consultation

The consultation document will propose these three methods for discussion. Comments are welcome. In particular anyone holding any data is welcome to compare the methods.

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