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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ABSTRACT

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 set up a working group comprising consultants, academics and representatives from wind farm developers and local authorities. This paper presents an overview of the work carried out to-date including the consultation document and the responses to it. A preferred method is outlined. This uses signal processing to take a Fast Fourier Transform (FFT) of time series (band-limited 100 millisecond L_{Aeq} values) to determine the modulation frequency and the harmonics. The reconstructed time series is then calculated and the modulation depth can then be determined from the reconstructed series.

1 INTRODUCTION

This paper describes a proposed assessment metric for assessing amplitude modulation in wind turbine noise. The assessment metric is proposed by the Institute of Acoustics' Amplitude Modulation Working Group and is the collective work of the following members:

Jeremy Bass	RES Ltd.
Matthew Cand	Hoare Lea Acoustics
David Coles	24 Acoustics
Robert Davis	RD Associates
Gavin Irvine (Chair)	Ion Acoustics
Geoff Leventhall	
Tom Levet	Hayes McKenzie
Sam Miller	Farrat Ltd.
David Sexton	West Devon Borough Council
John Shelton	AcSoft

All wind turbines produce amplitude modulation. Blade swish – a form of amplitude modulation - was described by early researchers and was noted in the guidance document ETSU-R-97[1] with a typical modulation depth (peak to trough) of 3dB. But in 2005, another form of amplitude modulation was reported by Van den Berg[2] and in a Hayes McKenzie study for the DTi[3]. The modulation of this 'other' amplitude modulation was typically greater than blade swish with a modulation depth up to 10 dB peak to trough. This form of amplitude modulation has also been known as 'excess' or 'other' amplitude modulation and an example is shown in Figure 1 below.

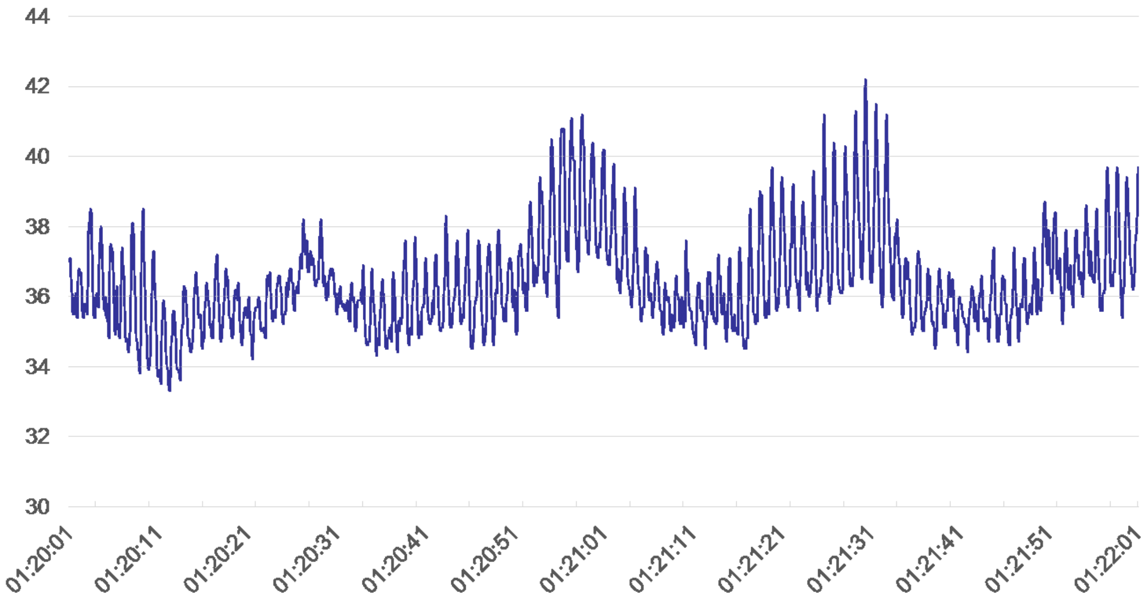

Figure 1 Two Minute Sample of Amplitude Modulation (dB $L_{Aeq,\ 100ms}$)

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.

The DTi /Hayes McKenzie report made the following recommendation:

> *To take account of periods when aerodynamic modulation is a clearly audible feature within the incident noise, it is recommended that a means to assess and apply a correction to the incident noise is developed.*

However, although this type of AM has been well studied in the years since 2005, and various researchers have devised methods of measuring it, the methods available yield different results. There is a clear need for an agreed assessment method. To address this, the IoA AM working group was set up with representatives including academics, consultants, developers, environmental health officers and instrumentation specialists.

1.1 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. A separate Government-funded study is studying how an agreed assessment metric can be used in a planning condition.

1.2 Success Criteria

A number of criteria were considered by the group when assessing the proposed metric:

- Achievability – using the equipment & software typically available to acoustic professionals
- Reality – work with samples of 'noisy', real-world data, not just, artificial simulated data created for testing purposes
- Robustness – minimising the influence of 'noise' in test data, which can make signal detection difficult, to ensure low rates of false positives and negatives
- Location – the chosen methodology will be applicable to measurements in free-field conditions, external to affected premises, so that it can be used in conjunction with current good practice in wind turbine compliance measurements
- Objectivity – providing a unique number which characterises the level of AM in each case
- Repeatability and reproducibility – returning the same unique number for a given sample of test data irrespective of who runs the test, where or when or how
- Specificity – as AM is currently defined as 'the modulation of the broadband noise emission of a wind turbine at the blade passing frequency (BPF)', it is essential that the methodology is specific to the BPF and not sensitive to variation at any other frequencies
- Automation – the ability to process large data sets. This is necessary because AM is typically only present in certain specific conditions, so that it is necessary to screen large amounts of data to identify those periods which contain AM
- Relativity – relatable to the psycho-acoustic, or subjective, response of individuals to AM noise.

1.3 Acknowledgements

I am indebted to my fellow group members. 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, for his role in steering the group and liaising with the IOA Council.

2 INITIAL WORK

The working group have collated over 30 papers on amplitude modulation, many from previous wind turbine noise conferences. The references with subjective studies were particularly useful, including those by Tachibana's group in Japan[4 5], work by Lee[6] and the R-UK research[7].

The group held workshops in London and Newcastle to discuss the issue further. Various trial methods were coded and tested with measured data from several wind farms including Askam Wind Farm in Cumbria which was considered in the Hayes McKenzie report. Some methods were trialled and rejected including the impulsivity criteria considered in BS 4142.

2.1 Definition

Rather than worry about the source mechanism or the 'type' of amplitude modulation, the following broad definition was agreed following the consultation period:

Wind turbine amplitude modulation (AM) can be defined as periodic fluctuations in the level of audible broadband noise from a wind turbine (or wind turbines), the frequency of the fluctuations being the blade passing frequency of the turbine rotor.

The work of the group quickly decided to focus on amplitude modulation measured outdoors and in free-field locations. This would allow amplitude modulation to be measured at the same location as those chosen for noise surveys for planning compliance. While amplitude modulation is also heard indoors, measuring indoor sound can be difficult for a variety of reasons.

3 CONSULTATION DOCUMENT

To consult with the IOA membership, a discussion document was prepared in April 2015[8]. This described three methods which could be used to rate amplitude modulation. These are:

3.1 Tachibana Method

The work of Tachibana's Group in Japan 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, D_{AM}, is then calculated the difference between the 5^{th} and 95^{th} percentile values of the difference values, $\Delta L_{A(t)}$.

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

This method is straightforward and could easily be implemented directly in a sound level meter. However, this method does not account for the periodicity in the signal, 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, typically with the data checked by a visual inspection.

Part 2 of the Japanese research described subjective studies in a listening room with different AM signals which were synthesized. 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. It is interesting to note however, that 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.

From the listening tests, dose-response relationships were derived as a function of the '*AM Index*'. The *AM Index* is a parameter based upon the design values of synthesised stimuli with a constant modulation depth. This parameter can be loosely related to the D_{AM} value, as the Table below.

D_{AM} and *AM Index*		
D_{AM} (35dB) (dB)	**D_{AM} (45dB) (dB)**	**AM Index (dB)**
0.8	0.8	0
1.2	1.1	1
1.7	1.7	2
2.3	2.3	3
3.0	3.0	4
4.3	4.3	6
5.5	5.6	8
6.7	6.9	10

3.2 Frequency Domain Method

The most common approach used by other researchers is to analyse the signal in the frequency domain, to determine if modulation is occurring at a regular rate within the expected range of the Blade Passing Frequency. The Fast Fourier Transform (FFT) is widely used in signal analysis, for example to identify tones. Where AM is present and when the FFT is applied to a time-series of the modulating noise (not the audio waveform), the analysis results in a spectrum exhibiting a peak at the blade passing frequency (BPF) of the turbine(s). The magnitude of the peak can be related to the depth of the modulation. The R-UK analysis method adopted this approach.

The method in the discussion document was similar to the R-UK method but uses 100 millisecond $1/3^{rd}$ octave band L_{Aeq} values to determine a band-limited signal, say 100 Hz to 400 Hz (seven $1/3^{rd}$ 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 a different 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. This is shown in Figure 2 below.

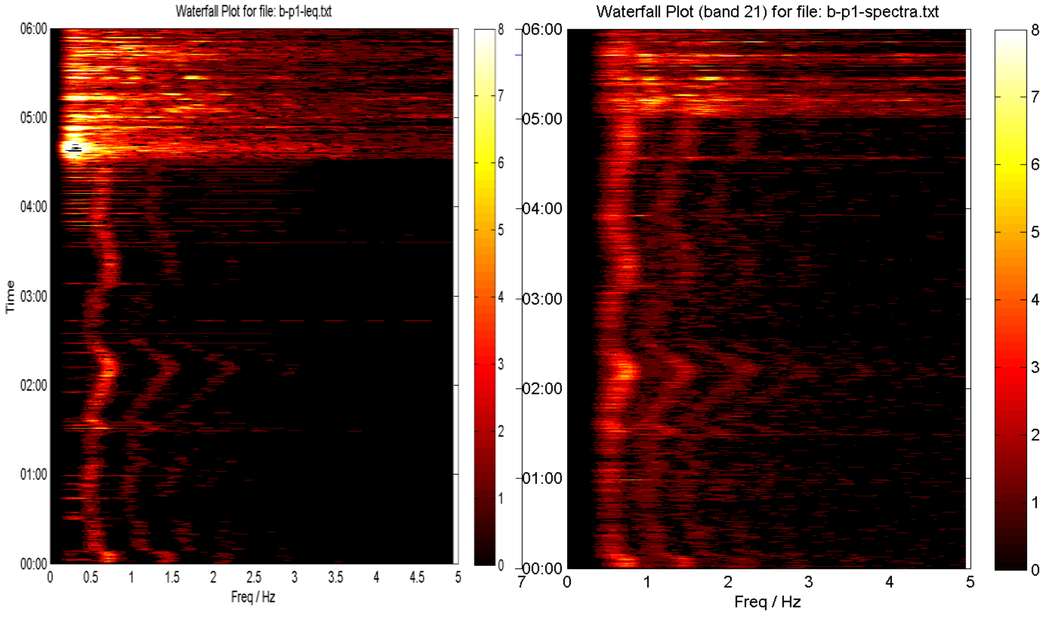

Figure 2 Comparing the long-term FFT analysis of modulation spectra for A-weighted signal (left) with band-filtered signal (right, 100-400 Hz)

This shows that, in this example, a period around 04:30-05:00 in which AM was present was masked by bird-noise in the analysis based on A-weighted signal but becomes apparent when undertaking the analysis on band-limited data. The band-limited FFT method has been used successfully with large data sets to compare AM before and after mitigation[9]. When making comparisons of this nature, it is important that the method is consistent and is robust in terms of handling large data sets.

3.3 Hybrid Method

A hybrid method for the assessment of AM was proposed by Cooper and Evans[10] when carrying out a compliance noise survey for a wind farm in Australia. The method proposed in the consultation document is a hybrid between a frequency domain method and a time-series method.

An FFT is performed to obtain the blade passing frequency, which then forms the basis of 1/3rd octave band filters centred on the fundamental and harmonics implemented in the time-domain. The filtered series is a cleaned version of the time-series, with extraneous noise removed whilst retaining energy at the first 3 harmonics. Because the blade passing frequency is known the peak (and trough) selection can then be done relatively easy and the peak to trough level of modulation can be determined by subtracting the average level of the troughs from the average level of the peaks.

4 RESPONSE TO CONSULTATION

Some 19 responses to the consultation document were received including one from Finland and another from Australia. A summary response to the consultation document has been prepared. Overall there was a clear preference for the frequency domain method, although of those recommended the frequency domain method, a second or equal preference was generally also given to the hybrid method.

The reason for choosing the frequency domain method was that it was less susceptible to background noise. Although not all responses to the consultation document were agreed upon by the Working Group, it seems obvious that where amplitude modulation occurs as periodic fluctuations, then the periodicity of the signal should be taken into account as a detection and analysis technique. Using FFT analysis to detect amplitude modulation is widely used by wind farm researchers and in other fields, for example in detecting propeller noise with Sonar. Nevertheless, four respondents indicated a preference for a time-series method, largely it seems on the basis of its intuitive visual and technical simplicity.

Having studied the consultation responses, the group believes that a time series method is too susceptible to corruption to be used on large data sets and cannot be recommended for the assessment and analysis of amplitude modulation. However the intuitive benefits of retaining a time-series are noted and while the FFT method is invaluable as a detection tool, it is difficult to relate the modulation spectrum to the strength of the modulation if this is to be assessed on the basis of the peak to trough depth. This is where a hybrid time series method is useful. The peaks and troughs can be assessed directly. Following the consultation document, it has been agreed that a hybrid method is the best solution. It is believed that this combines the best of both the time domain and frequency domain methods. Therefore the proposed method reconstitutes the time series using the fundamental and the first two harmonics. A band-limited 100 millisecond L_{Aeq} signal is used as before as confining the analysis to the frequency range of interest also has benefits in determining the signal in relation to the background noise.

5 RECOMMENDED METHOD

Rather than using the method described in the discussion documents, a simpler method is proposed based on that described in a paper by Swinbanks[11]. The method is described below:

- Take a block of 100 ms band-limited data
- Take the FFT (keeping both real and imaginary parts)
- Identify the first three harmonics (ie fundamental, 2nd and 3rd harmonic)
- Create an array with real and imaginary values at the harmonics and zeroes elsewhere
- Carry out an inverse FFT to recreate the time series
- Identify the peaks and troughs which fall into an expected time window governed by the modulation frequency.

The frequency range for the band-limited data should be selected to give the worst case values. Typically 100 to 400 Hz works for many large turbines at normal residential distances.

The reconstituted time series is shown in Figure 3.

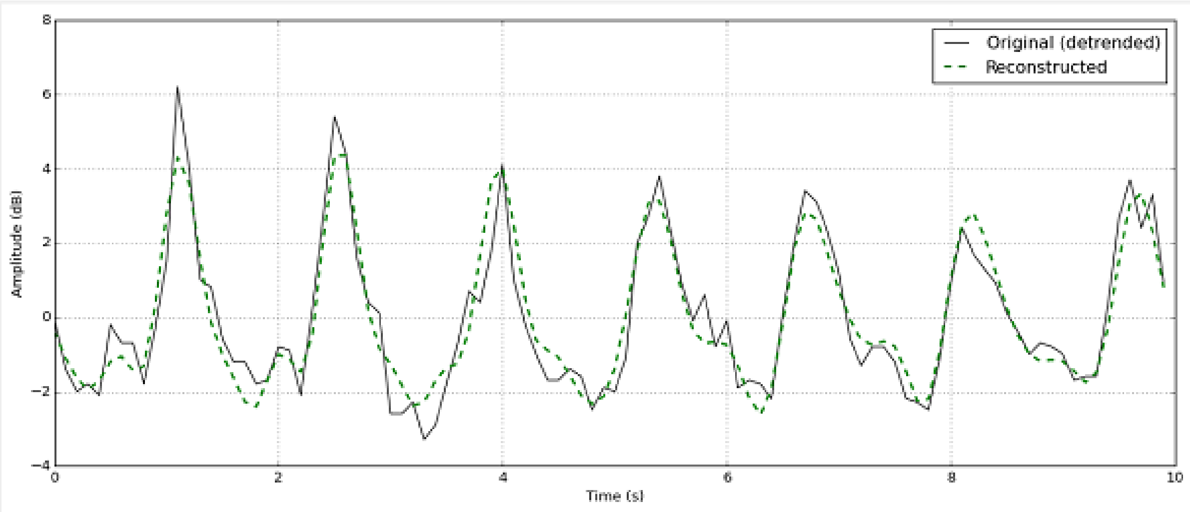

Figure 3 Original (detrended) and reconstructed time series

6 REFERENCES

1 ETSU-R-97 The assessment and rating of wind turbine noise

2 Van den Berg G P. The Beat is Getting Stronger: The Effect of Atmospheric Stability on Low Frequency Modulation Sound of Wind Turbines. Journal of Low Frequency Noise Vibration and Active Control. Vol. 24(1) 2005

3 Hayes McKenzie *The Measurement of Low Frequency Noise at Three UK Wind Farms.* DTi, 2006

4 Fukushima, A., et al. (2013). "Study on the amplitude modulation of wind turbine noise: Part 1 – Physical investigation " Proc Internoise 2013

5 Seong, Y., et al. (2013). "An experimental study on rating scale for annoyance due to wind turbine noise " Proc Internoise 2013

6 Lee, S Kim K. Lee S, Kim H and Lee S An estimation method of the amplitude modulation in wind turbine noise for community response assessment. Third International Meeting on Wind Turbine Noise Aalborg 2009

7 RenewableUK. *Wind Turbine Amplitude Modulation: Research to Improve Understanding as to its Cause and Effects.* 2013

8 IOA AMWG Discussion Document http://www.ioa.org.uk/publications/wind-turbine-noise

9 Cand, M. & Bullmore, A. Measurements demonstrating mitigation of far-field AM from wind turbines. 6th International Meeting on Wind Turbine Noise Glasgow 2015

10 Cooper, J and Evans, T. Automated detection and analysis of amplitude modulation at a residence and wind turbine. Proceedings of Acoustics, Victor Harbor, Australia 2013

11 Swinbanks M.A. Assessment of RES Revised Condition 20 for Evaluating Excessive Amplitude Modulation