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Analysis of modulating tones in wind farm noise

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ABSTRACT

The overall level of the noise from wind turbines generally remains the main regulatory driver for control of this source at neighbouring sensitive receptors. In addition, features sometimes present in the noise can increase its subjective disturbance: these are increasingly recognised and sometimes penalised. A fluctuating character in the aerodynamic noise is inherent to some degree, due to the rotation of the blades, but in some cases the Amplitude Modulation (AM) of the sound can become stronger. Tonality is another noise feature which can be detected in some cases due to resonances or emission from specific mechanical/electrical components in the turbine. Objective methods have been developed or adapted over the past years to characterise the magnitude of both features in isolation. This paper considers cases where tones fluctuate, probably as they are emitted from a rotating component of the turbine. Different numerical quantification methods are compared and investigated and the implications on subjective response are considered.

1. INTRODUCTION

In the UK, wind turbine noise is controlled according to the ETSU-R-97 [1] methodology. In common with many other similar guidelines in other countries, noise limits are defined at wind farm neighbours principally based on the overall A-weighted noise levels produced by the turbines. In addition, ETSU-R-97 considers other elements of the character of the noise from the turbines:

- Tonality
- Blade swish or Amplitude Modulation (AM)

1.1 ETSU-R-97 tonality analysis method

With regards to the former aspect, ETSU-R-97 sets out (pages 104-109) a prescriptive tonality assessment method, which was a modified version of the first Joint Nordic Method (JNM) [2] but applied for non-stationary tones (see further discussion in section 2). The method is based on the ratio of the energy in the narrow tonal band compared to the surrounding masking noise energy within a critical hearing band, using narrow-band analysis with a resolution of 2.5 to 3.5 Hz for samples of at least 2 minutes. Once a tone has been identified based on the average spectrum, the non-stationary element of the method is evaluated, by considering short-term spectra with a resolution of 0.3 to 0.4 seconds, and determining the arithmetic average of the top 10% of the energy in these short-term spectra over the tonal bands identified. It is this “typical high” tonality level which is used to calculate the audibility of the tone. The tonal peak is however identified on the basis of the average spectrum and therefore the ETSU-R-97 method uses a hybrid approach between the stationary and non-stationary tonal analysis methods discussed below.

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As the levels of tonal audibility can fluctuate: for different times or wind conditions for example, ETSU-R-97 recommends some form of averaging at different wind speeds. The resulting average audibility determined at each wind speed is used to determine a penalty between 1.5 to 5 dB (defined from available research at the time). The penalty is applied to the A-weighted noise levels from the turbines to reflect the increased audibility of the noise containing this character.

1.2 AM and blade swish

Regarding blade swish, ETSU-R-97 explains that the noise limits already account for "typically encountered" levels of this feature, which is considered inherent for wind turbines. In the last 16 years, this aspect has been the subject of more extensive research, in particular the large project commissioned by RenewableUK published in 2013 [3], specifically aimed at identifying and explaining some of the key features of wind turbine AM noise. The analysis techniques developed in this research were further developed by the Institute of Acoustics (IOA) which published an analysis method [4] for rating the level of modulation at a receptor location. The method provides a decibel level for each 10 minute period, which represents the magnitude of the modulation in the noise and minimises the influence of sources not related to wind turbines.

A review commissioned by the UK Government [5] on the subjective response to AM proposed a rating penalty, similar to that described above to assess tonality in ETSU-R-97. There is however currently no clear guidance from the UK Government or local authorities on whether this scheme should be applied in practice for new UK wind farms. A consensus view of several practitioners [6] is however that, should the AM penalty be applied, this would be added to any tonal penalty (if applicable) to result in a total character penalty added to the wind turbine noise level. This is similar to the approach set out in BS 4142 [7] where penalties for tonality and impulsivity and/or other characteristics can be additive.

2. RESEARCH AND METHODS FOR FLUCTUATING TONES

2.1 ETSU-R-97 and associated research

To support the development of the ETSU-R-97 methodology and specifically the tonality analysis method, specific research was undertaken on behalf of ETSU (the Energy Technology Support Unit). Part 1 of the research [8] included the collation of audio samples from operational wind farms, their objective analysis using an implementation of the JNM [2] and subjective testing through listening tests with a 10-person panel. Nine audio samples were collected between 180 and 550 metres from operational wind farms. The objective tonal analysis was undertaken both using a stationary and a non-stationary version of the JNM; the non-stationary method being based on using an arithmetic average of the 5 highest tonal occurrences, after splitting the sample into 50 individual spectra of 400 ms (*i.e.*, the average of the top 10% as in ETSU-R-97). Results were typically 3.5 dB higher with the non-stationary method. However, the results of the listening tests, which asked participants to describe the tones as inaudible/not prominent/prominent, showed that the stationary JNM method correctly determined the subjective audibility of the tones whereas the non-stationary results tended to over-predict the audibility.

Part 2 of the research [9] used a larger subject and sample size and further developed the analysis method applied. The tonal analysis method was more in line with that of ETSU-R-97: a modified JNM non-stationary tonal method applied over a 2-minute sample cut up in around 300-600 spectra, using the top 10% of the tone levels which is compared to the average masking level. Despite the problems identified with the non-stationary method in part 1, this was chosen because of the analysis of samples highlighting the variability of the tonal levels over a 2-minute period. Different analysis parameters (A-weighting, FFT parameters, etc.) were investigated. The final analysis was made using 16 measured samples, with a wide variation in tonal content. The subjective testing panel comprised 32 participants and showed a good correlation between the method and the subjective ratings, and very little over-rating of the tones (except only in borderline cases). This therefore supported the validity of the method proposed in ETSU-R-97 based on experience at the time.

Although the ETSU-R-97 method and its analysis parameters are clearly set out in the report [1], some of the analysis steps require some degree of interpretation and, compared to some of the more recent tonal analysis methods described below, is arguably less directly amenable for automated analysis in a computer implementation, although this has been achieved in practice [10].

2.2 Other tonal analysis methods

Other tonality methods include non-stationary variants or may include some form of analysis of temporal variability. The second version of the Joint Nordic Method (JNM v2) [11] was implemented as a reference analysis method in BS 4142 [7] as it was included in the 2007 version of the ISO 1996-2 standard. This method is naturally similar to the ETSU-R-97 method which was based on a previous version of the JNM but it is generally a stationary tonality method, as it recommends using a "long-term average" of at least 1 minute. Although it is more algorithmic in nature and amenable to software implementation (with an example code provided in [11]), it still allows some user-defined parameters which can be adjusted in any software implementation.

The JNM v2 method also allows (if the tone *frequency* varies by more than 10% of the critical band width) to "subdivide the long-term average into a number of shorter-term averages", and the tone level is then calculated as the energy average of the tone levels for each of these shorter-term samples. It gives the example of a varying-frequency tone ("example 4" in [7]) where this is used but does not use this for the wind turbine sound ("example 3" in [7]). For tones with clearly fluctuating *levels*, the method does not explicitly allow deviation from the longer-term averaging.

The more recent 2017 edition of the ISO 1996-2 includes a different reference tonality analysis method: ISO/PAS 20065 [12]. This method is arguably more reproducible and amenable for computer implementation than the JMN v2 approach and includes an evaluation of uncertainty. The method requires an averaging time of *at least* 3 seconds but does not prescribe using longer term average as in the JNM v2. It advises against using intervals shorter than 3 s for "signals that have a very high-level dynamic" as this will lead to incorrect results. When considering several spectra, the individual audibilities are averaged logarithmically to provide an overall mean audibility, using a value of -10 dB where no tones are found. The IEC 61400-11-2 method for assessing wind turbine noise at receptor position, which is currently under preparation [13], is likely to adopt the ISO/PAS 20065 method.

The IEC 61400-11 standard is designed for assessing wind turbine noise at source (*i.e.* close to the turbine) but includes a tonality assessment method. In the latest version of the standard [14], tonal evaluation is based on 10-second average spectra which are analysed individually using a prescriptive algorithmic method which is comparable (but different to) the above methods. Tonality is then analysed within wind speed "bins" in line with the overall approach of the standard, but for tones of the same “origin” (*i.e.* similar frequency as defined with a tolerance of 25% of the critical band width) within an individual bin, the audibilities are energy (logarithmically) averaged.

A comparison between analysis by the IEC 61400-11 and ISO/PAS 20065 methods was undertaken [15] based on 24 wind turbine noise recordings of 20 seconds length and some industrial noise samples. This showed that the difference between the two methods was generally very small (less than 1 dB) and that results generally accorded well with additional subjective testing undertaken, although with some outliers. The samples used may however be more representative of noise recordings obtained in proximity of a turbine rather than at receptor locations, where greater changes in tone level may occur.

More complex methods exist which may be more suitable for analysis of complex and time-varying sounds, as discussed by Torjussen in [16]: for example, psycho-acoustics based methods such as the Hearing Model Tonality (HMT) method [17]. The method is however relatively complex compared to the engineering methods described above, with critical band filtering, loudness calculations and block segmentation required, although software implementations exist.

Rather than providing a decibel audibility level as in all other methods, the HMT method provides a “Tonality Units” T_U rating, with values of 0.1 considered tonal, and values of 0.4 and 0.8 representing the threshold of prominent and very prominent tonality respectively. However, the method can powerfully capture temporal variations with a fine resolution (of 50 ms or less) and also takes account of the overall level of the signal, which none of the above methods (which are based on a ratio of tonal energy against a masking level) directly consider.

3. PROBLEM AND EXAMPLE

As noted in [16], when looking at intermittent or time-varying tones, methods based on longer-term averaging may under-rate the audibility of the tone. For wind turbine sources, the above research [9] noted that tonality levels can vary strongly at some distance from the turbines due to complex propagation effects for example. But tones associated with resonances of turbines’ mechanical components can radiate through rotating parts such as the turbine blades in particular. As this tonal radiation can be very directional, with a rotating source the noise level at a receptor will therefore fluctuate in time at the rate at which the blades rotate: even with larger turbines, this variation would occur at a rate of typically around 0.5 to 1.5 Hz and therefore risk not being captured by methods based on an averaging time of several seconds or minutes.

One potential example previously discussed by Hansen *et. al.* [18] showed fluctuations in the measured noise level (or “rumbling noise” in certain operating conditions at receptor which was 3.3 kilometres from a 37-turbine wind farm in Australia). These were analysed by the authors using the IOA AM analysis method [4], showing a strong modulation at a rate of 0.8 Hz. A plot of 1/3 measured octave band spectra in [18] shows a clear peak at 50 Hz, above the ISO 389-7 hearing threshold, which is more suggestive of a fluctuating tone than the broadband amplitude modulated sounds considered in previous AM research [3]. This does raise the question of the appropriate way to assess such modulated tones. This will be illustrated in this paper through an example.

3.1 Example description

Measurements were undertaken using the advanced HALO noise monitoring system developed by Hoare Lea described in [10], in the vicinity of a small-scale wind farm, with rotor diameters of less than 100 m, at a distance of just over 5 rotor diameters from the nearest turbine: this may therefore not necessarily be representative of receptor locations in other wind farms.

The HALO measurement system implemented the IOA AM analysis method [4]: this requires the AM analysis to be undertaken in three different frequency band regions: 50-200 Hz, 100-400 Hz and 200-800 Hz, to account for the different frequencies which can dominate modulation, depending on site/turbine specific characteristics. For example, smaller turbines will tend to have broadband noise emissions (and therefore modulation) dominated by higher-frequencies in the 200-800 Hz band.

Figure 1 shows the resulting analysis for a representative part of the data, focusing on night-time periods where corruption from other sources was likely to be minimal. Figure 1 illustrates a trend in which the AM ratings in the 50-200 Hz band are sometimes much higher (by 4 to 8 dB) than for the other bands: this is unusual in our experience of analysing the modulation of broadband wind turbine noise. Further review of the samples with strong modulation in the 50-200 Hz band showed that most of these periods included a modulated tone in the 63 Hz 1/3 octave band which was detected by the AM rating method, in a similar manner as for [18].

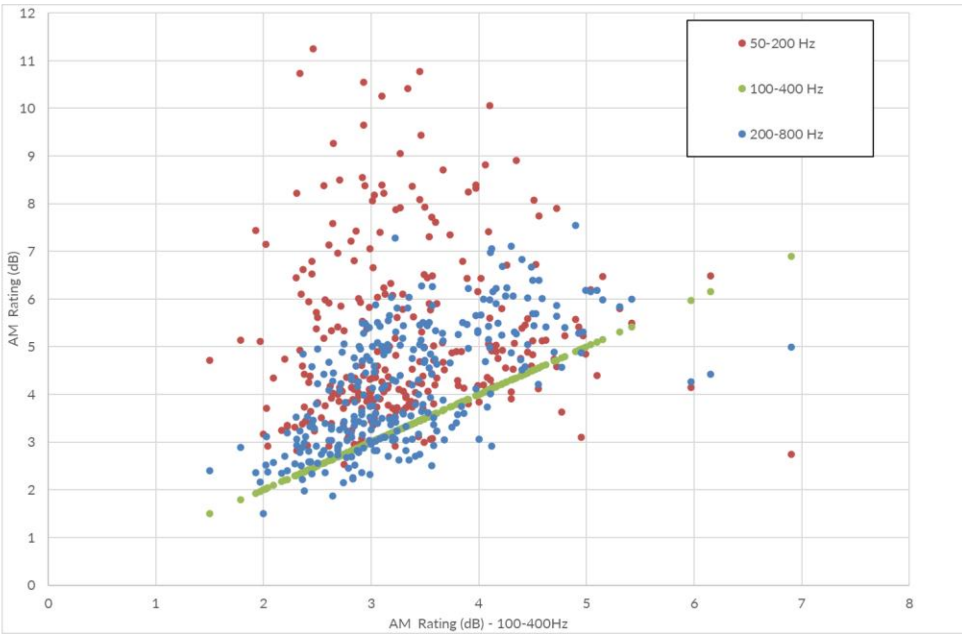

Figure 1: Comparative analysis of IOA AM ratings in different frequency bands – non-zero values, night-time periods. Results for all three frequency bands are shown relative (plotted against) results in the 100-400 Hz frequency band.

3.2 Sample Analysis

A review of audio recordings and narrow-band spectrograms showed that the atypical periods identified included a tonal feature, with a frequency peak close to 60 Hz, which is intermittent in nature. Its magnitude varied at a rate consistent with the rotation of the turbine blades, 0.4 Hz: in this case the samples were measured at low wind speed conditions and the turbines were likely rotating slowly. Figure 2 illustrates this by showing an example of the measured variations in the 63 Hz 1/3 octave band over one of the periods identified. This also shows that the levels measured are 3 to 10 dB or more above the threshold of audibility at times and therefore are potential audible (this is an important check to undertake when considering tonality at lower frequencies).

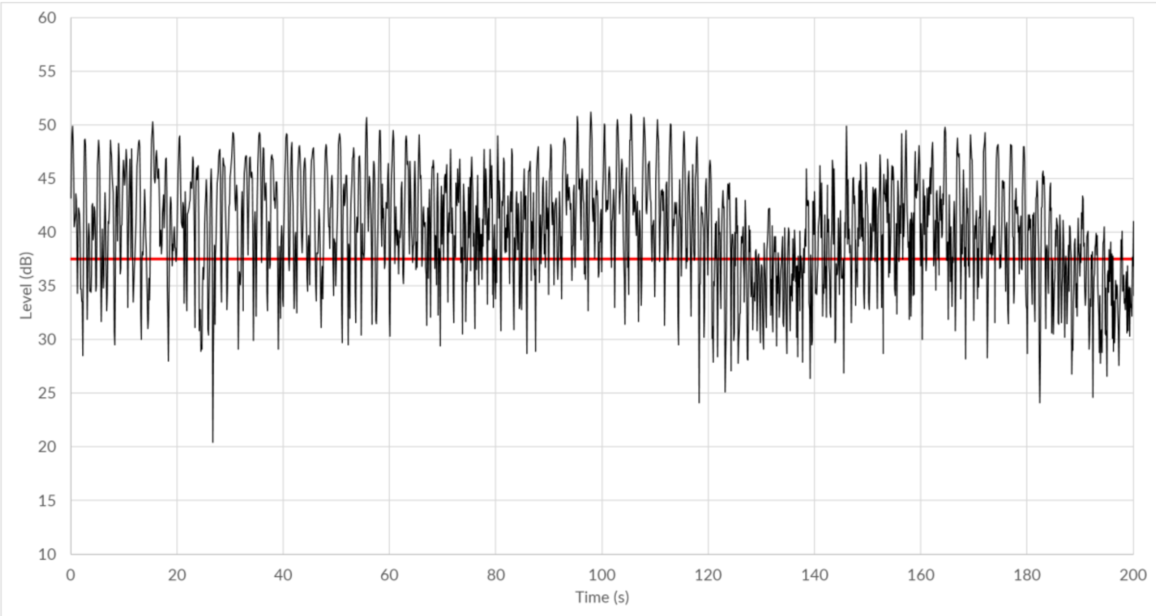

Figure 2: Measured noise level ($L_{eq,100ms}$) in the 63 Hz 1/3 octave band over a 200 s period, recorded during one of the atypical periods identified in Figure 1 (sample A). The threshold of audibility at 63 Hz (from ISO 226) is also indicated in red.

The recordings being analysed also sometimes included other noise features identified above 500 Hz correspond to bird noise, but these periods were excluded. A comparative tonal analysis can then be undertaken on samples of approximately 30 s length including the intermittent feature identified but without other features: 2 samples (A and B) are considered in this study.

Table 1: Analysis results for example samples (Audibility/modulation rating, dB).

Method	ETSU-R-97	JNMv2	PAS 20065			IOA AM Method	
Type/ Method	Hybrid (400 ms analysis) see 1.1	Stationary (30 s average)	Stationary (30 s average)	Non-stationary (3 s samples)	Non-stationary (400 ms samples)*	50-200 Hz	63 Hz 1/3 octave band*
Sample A	17.3	11.0	7.2	8.0	13.5	7.1	11.2
Sample B	18.1	13.8	10.4	10.3	16.5	9.3	16.6

**NB: this is a deviation from the method as written.*

Table 1 presents the results of the tonal analysis undertaken using different methods discussed above. First of all, the ETSU-R-97 analysis for a 2 minute period, using the average spectrum but considering fluctuations in the level of spectral lines identified as the tone, with a time resolution of 400 ms. With the JNM v2 method, a clean 30 second period was analysed, but analysis of short-term spectra variations at 400 ms resolution led to mis-identification of spectral lines as tonal. The PAS 20065 method was applied to the average 30 s spectrum, as well the same period divided into 3 s sub-periods, which had similar results (given the fluctuation speed). Using a shorter 400 ms interval is not allowed by PAS 20065 and provided some spurious results; however a result was still generally obtained at the correct tonal frequency (57 or 60 Hz): if only these were retained and averaged, this resulted in overall audibility values 5-6 dB higher and more representative of the modulation peaks.

An analysis of modulation in the signal was also undertaken using AM rating methodologies: first of all, the IOA AM method was applied as written over the full 50-200 Hz band, but additionally based on an analysis using only the fluctuating 63 Hz 1/3 octave band, as suggested by Hansen [18], which was also more representative of the fluctuations.

The samples were finally analysed with an implementation of the HMT method, which accurately captured the temporal variation of the tonality, which varied in time between 0 and 0.3 T_U, therefore remaining below the threshold of a prominent tone according to this method.

4. Conclusions

Narrow-band analysis always involves a balance between time and frequency resolution. Most tonal analysis methods investigated are based on averaging over periods that do cannot capture short-term fluctuations at a turbine rotational speed and therefore the associated fluctuating tones when they occur. The ETSU-R-97 method is the most robust in this regard but is rarely used outside the UK.

The use of the IOA AM method to analyse a fluctuating tone, particularly when restricted to a single 1/3 octave band as shown above, should be approached with caution: although it presents an analysis of fluctuation in the noise level, it is not necessarily representative of the modulating broadband noise which were generally studied when developing this analysis method. The results obtained therefore cannot be related to the subjective listening studies [3,5] which were undertaken on the basis of broadband modulated stimuli. However, the IOA method is attuned to variations at the turbine rotational rate by design and can therefore detect such fluctuations when they occur.

As the ETSU-R-97 method accounts for the fluctuation, adding the resulting penalty to a rating provided from the AM results would be excessive. It could be argued that in the example shown and probably in many cases such as these, the tonal element is the main subjective feature of the noise, with its intermittency or variability a secondary feature which can make it more audible. BS 4142 allows for additional characteristics to be considered using additional penalties to represent other character in the sound, with further penalties. Such a possibility was not implemented in the ETSU-R-97 method, and could be the subject of further research and listening tests.

5. ACKNOWLEDGEMENTS

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