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Detection and Evaluation of Amplitude Modulation From a Wind Energy Development, Ireland

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Summary

Amplitude modulation (AM) is a characteristic of wind turbine noise that has only been recognised as an issue in recent years. It is a characteristic related to aerodynamic noise and descriptions of it include "swishing", "whooshing" or less frequently a "thumping" sound. Due to increased awareness among exposed communities AM presents a potentially serious obstacle to future wind farm developments. This work reports on the application of a recently developed calculation method for AM in a practical setting. Correlations will be drawn with subjective reports of AM by nearby residents keeping a noise diary. The suitability of the method and its ability to quantitatively confirm subjective reports of AM will be assessed. A study is presented here whereby subjectively recorded occurrences of AM by residents living near a wind energy development in Ireland are correlated to calculated levels over a twenty day period. In order to detect and calculate AM a method published by the Amplitude Modulation Working Group of the Institute of Acoustics, referred to as the Reference Method, is applied. A subjective assessment of the sound recordings to confirm the presence of AM is discussed, including estimating the expected frequency range that AM occurs. The results of the Reference Method calculation are presented for periods with and without a subjective report of AM by the residents. Consideration is given to the criteria and thresholds for valid AM ratings within the Reference Method especially where intermittent periods of AM are identified. The Reference Method is shown to be highly suitable as a quantitative measure of AM which correlates well with subjective reports. Caution must be taken when using the method as valid periods of AM may be overlooked due to the rigorous detection thresholds set by the method.

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1. Introduction

Aerodynamic noise is emitted from a wind turbine through a number of sources, broad band noise generated by flow over the blades ("trailing edge noise") being the most significant source [1]. When observed in the far field this noise source may exhibit a certain character which is often described as "blade swish" and is properly defined as amplitude modulation (AM). It is made noticeable to the far field observer by having "a greater than normal degree of fluctuation of sound level" [2] of regular variation at the blade-passing frequency of the turbine rotor (typically in the region of 0.75 Hz for a 3-bladed rotor spinning at 15 rpm). It is perceived as having a characteristic "swishing" or "whooshing" sound.

Noise complaints can be a significant obstacle to new wind farm developments and until recently the environmental noise community lacked a rigorous metric for the detection of AM. The UK based Institute of Acoustics (IOA) formed a working group on the topic to develop a suitable metric which could be applied for the detection and rating of AM in a practical manner. The group concluded its work in August 2016 and released an open source Python code for the implementation of the developed AM metric, referred to as the Reference Method [3]. The IOA working group did not consider as part of their work any acceptable threshold for AM and instead focused entirely on the development of a detection method. Independent work was undertaken by researchers at the University of Salford as part of a RenewableUK funded project to develop a dose-response relationship for AM [4]. As a result of this and other efforts the Department of Energy and Climate Change (DECC) [5] UK, commissioned a report which proposed a penalty scheme based on AM levels (as measured using the IOA metric) with a threshold of 3dB considered as the onset of annoyance.

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At present the authors know of no practical applications of the IOA Reference Method which have been reported in the scientific literature. Furthermore no correlation has been made between the detection of AM using the Reference Method and instances of noise complaints. This work has applied the Reference Method to an existing wind farm development in the Republic of Ireland demonstrating the suitability of the metric for use in a practical setting. The instances of AM detection have been correlated with subjective reports of noise from an exposed community through the use of a noise diary by nearby residents.

1.1. Amplitude Modulation

An observer standing close to a wind turbine will always perceive some blade swish as a result of the directional characteristics of the sound energy radiated from each blade as it rotates, with the higher sound pressure levels being generated in the direction of the downward-rotating blade [6]. Amplitude modulation generated by this mechanism is often termed "normal" AM (NAM) and in most cases is only clearly detectable near to the turbine and is not expected to be detectable to any significant extent at distances greater than around 400-500 metres. The level or rating of AM is described by the degree of variation in the A-weighted sound pressure level (the "modulation depth" or the "peak-to-trough" values). The ETSU-R-97 guidance [1] indicates that modern wind turbines might be expected to exhibit AM with peak-to-trough levels up to 3 dB close to the turbine, although at larger distances, in the presence of hard reflecting surfaces, peak-to-trough variations of up to 6 dB had been observed [1]. However, some larger turbines have been found to generate higher levels of AM, detectable at larger distances and sometimes causing the noise to exhibit a more intrusive "whooshing" or "thumping" quality. Research sponsored by RenewableUK [5] concluded that this characteristic is the result of a different source mechanism and that it may be related at least in part to strong wind shear conditions i.e. a vertical variation in wind speed. The term "Other AM" (OAM) has been coined for AM arising from this mechanism. It would be expected that this effect would be more pronounced for larger turbines, since the change in wind speed between the lowest and highest position of the tip of a rotating blade will be greater. A study by Oerlemans *et al.* indicates that OAM may be expected in downwind and upwind conditions [6].

1.2. The IOA Reference Method

The magnitude of AM can often be difficult to quantify because it can be masked by background noise and different methodologies can gain results that are not comparable [7]. In response to uncertainty and public concern over "blade swish" the UK Institute of Acoustics undertook considerable work developing a robust procedure for calculating AM, termed the Reference Method [3]. The methodology uses a frequency domain procedure to reliably determine the modulation depth of the AM whilst filtering out variations in sound which are outside the frequency range of the wind turbine noise sources. It is a metric that allows the physical conditions generating AM (operational and meteorological) to be investigated and it also allows for a consistent basis for regulating AM.

The method uses 100 millisecond L_{Aeq} measurements in one- third octave bands that are evaluated over three frequency ranges: 50 – 200 Hz; 100–400 Hz; 200–800 Hz. Each 10-minute sample is separated into sixty 10-second minor intervals of 100-millisecond data. Fast Fourier Transform (FFT) analysis is carried out for each minor interval to determine its power spectrum level, identify any fundamental frequency of modulation, the associated first and second harmonics and determine their prominence. Inverse FFT is carried out retaining the sound energy of the fundamental frequency and harmonics to reconstruct a frequency filtered detrended 10-second time series. The modulation depth is calculated for each of the valid 10-second time series using L_{A5} to L_{A95} (where L_{A5} is the noise level exceeded 5% of the time and L_{A95} is the noise level exceeded 95% of the time). If there are at least thirty valid 10-second minor intervals out of sixty in each 10-minute sample in any of the frequency bands (50 – 200 Hz, 100–400 Hz, 200–800 Hz) then the presence of AM is confirmed and a rating level is calculated (90th percentile of the 10-second interval values). The 10-second minor interval valid AM ratings are scatter plotted based on frequency ranges and a best fit linear regression used to establish the overall AM rating level and predominant frequency band for AM. The definitions of L_{Aeq} and L_{AN} are in accordance with ISO1996-1:2016 and measurements were taken in accordance with ISO1996-2:2017.

It was concluded by the IOA Working Group that for frequencies less than 50 Hz and greater than 800 Hz there is little evidence of wind turbine generated AM. Consequently, the IOA Reference Method can be used to screen extraneous noise outside of the frequency bands associated with AM. This is an advantage over time domain methods that can be susceptible to corruption by extraneous noise and which require the use of simultaneous Fast and Slow filters to exclude unwanted frequency components. Time domain methods were developed and described in detail by the works of Tachibana *et al.* [8, 9, 10]. The work of Okada *et al.* recently applies these time domain methods to a wind turbine with reference to the meteorological conditions [11].

A topic of interest in this work is whether occurrences of AM qualitatively reported by an exposed community can be quantitatively confirmed using the Reference Method. It is worth considering what is known about the dose-response relationship of AM to put into context the measured values presented. The threshold for perception is expected at an AM rating level of 2dB based on a literature review carried out in 2016 by Parsons Brinkerhoff for the Department of Energy and Climate Change (DECC) [5], UK. The review indicated that AM (as measured using the IOA metric) with a modulation depth up to 3 dB (peak-to-trough) could be considered normal and that AM levels above 6 dB would be likely to cause adverse comment or complaints; this is a relatively simplistic view which does not consider the influence on subjective response of changes in individual fluctuations of sound pressure levels or averaged values over a series of data. There is no level of AM at present which is agreed to be unacceptable since annoyance is not just a function of modulation depth [4]. Research indicates that annoyance is chiefly controlled by the L_{Aeq} although a regularly fluctuating sound with a modulation depth of 3 dB or greater is generally agreed to be more annoying than a steady sound of the same L_{Aeq} [4].

No attempt is made in this work to assess the annoyance caused by the calculated levels of AM. However, the IOA method is one that facilitates investigations of human response to AM, albeit requiring additional variables as well as modulation depth to be considered such as L_{Aeq}, L_{A90} and frequency spectra [4, 12].

2. Experimental Methods

Sound level monitoring was carried over twenty days at a residential site near a wind farm in Ireland, approximately 480 m and 600 m from the nearest two wind turbines, at a direction 190° due south of the midway point between them (Figure 1).

The site is located in a rural area along a boreen (rural road) and 1.2 kilometres from a regional road. The residents living at the site were requested to record occurrences of wind turbine noise noticeable to them over the period of monitoring, log the date and time and describe the noise characteristics.

It is standard procedure based on the ETSU-R-97 guidance to correlate sound pressure levels to the hub height wind speed corrected to 10 metres height [6]. However, while the SCADA data for the wind energy development was available to the authors it is confidential and not available for publication here. Shannon Airport is the nearest meteorological station to record weather over the monitoring period. The use of meteorological data remote from a site being assessed is not recommended by the authors. However, in this instance the wind speed at which AM occurred is not critical in the evaluation of whether or not AM can be detected using the Reference Method.

The meteorological station is 10 metres above ground level, 6 metres above mean sea level. Measurements are taken and reported by the station once every hour on the hour. The wind directions over the twenty days were predominantly southwesterly and southeasterly (Figure 2), with the site expected to have been crosswind and upwind of the wind farm under those conditions.

For the assessment of AM, alternate 10-minute Z-weighted audio signals, in the form of .WAV files with a bit depth of 24 bit, were collected. They were recorded using a Class 1 Brüel and Kjær Type 2250 Light integrated logging sound level meter, meeting the requirements of BS EN 67672-1 [13]. The microphone employed was a Type 4964 one-half inch low frequency microphone with a dynamic range of 14.6 to 146 dB and frequency range of 0.8 Hz to 20 kHz. The check-calibration of the microphone

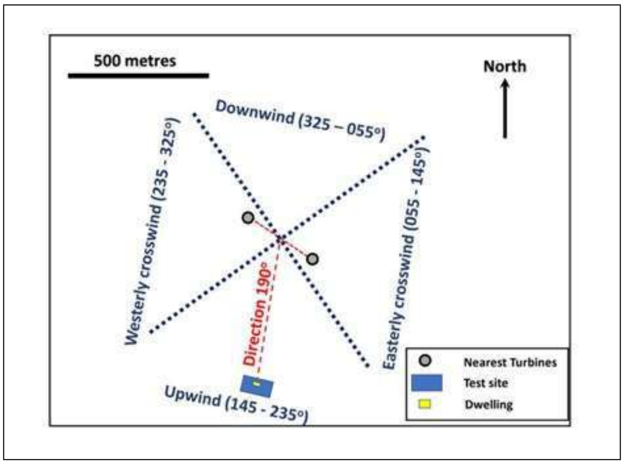

Figure 1. Wind directions relative to the nearest two wind turbines. Note, there are more than two wind turbines comprising the wind energy development.

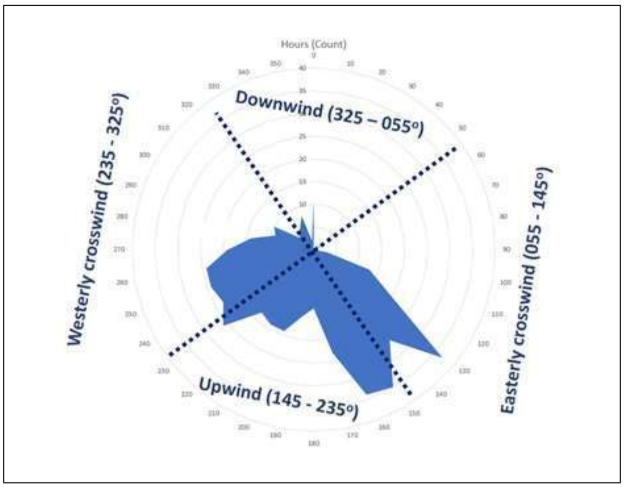

Figure 2. Wind rose for Shannon Airport for the period of twenty days that sound level monitoring was carried out.

was carried out using a Type 1 calibrator during the installation and removal of the equipment at the site. The calibration drift on each occasion was less than 0.5 dB from the manufacturer's initial calibration.

Open source Python code of the Reference Method was published by the IOA to calculate the AM rating [3]. A custom data processing tool was used to interface and implement the unmodified IOA code. The tool uses calibrated microphone data, converts the calibrated data to 1/3 octave band 100-millisecond L_{Aeq} and passes this data to the unmodified IOA code. The Python implementation of the octave band and A-weighting filters was crosschecked with a Brüel and Kjær Pulse system and National Instruments Labview and the differences between all three systems were found to be less than 0.5 dBA in any given octave band.

3. Results

3.1. Subjective Data Analysis

A compilation of the results of the logged occurrences, sound pressure levels, meteorological data from Shannon

Airport, the subjective description of the audio by the authors and the calculated AM rating levels for each frequency band are presented in Table I.

Descriptions by residents of sounds including "swishing" or "swooshing", believed to be a characteristic of AM, were logged by the residents on thirteen occasions over the twenty days at times during day-time and night-time. Samples of audio were selected for the application of the Reference Method based on the closest time that audio was collected to the logged occurrence and confirmation of AM through a subjective assessment of the audio recordings. This is a similar approach to investigating AM related complaints by focusing on times of a complaint, as recommended by Perkins *et al.* [14].

Samples over periods of rainfall were excluded and were not selected for calculation, as is best practise for the assessment of wind turbine noise [1], even though the Reference Method does not state that any data including rainfall should be removed [3]. Samples that AM has been logged and confirmed by listening to the audio were selected to apply the Reference Method i.e. event numbers 1, 2, 3, 6, 7, 9 and 11. Event numbers 8 and 12 were removed from the assessment because the audio was contaminated by machine noise and wind turbines were not considered to be operational for the respective samples.

Based on an assumption that the meteorological conditions at the site were similar to those that occurred regionally (measured at Shannon Airport) during the monitoring period then the wind directions were predominantly southerly and westerly with wind speeds between low and high wind speeds (Table I). The validity of this assumption was assessed by considering the wind speeds, wind directions and air temperatures for each event three hours before and after the sound measurement was recorded i.e. over a six hour window. This insured that the meteorological conditions were stable in the locality. In order to illustrate the AM levels recorded over a longer period of time the Reference Method has also been applied for a set of data relating to an approximately twelve hour period of time between 19.30 hours on monitoring day 1 and 07:20 hours of monitoring day 2 (Table II). The meteorological conditions over the period of monitoring were stable with the range of wind speeds being $3 - 6m/s$, the wind directions being $240 - 270°$ and air temperatures being $12 - 14°C$ over the twelve hour period. The Reference Method has been applied to all of the audio samples between these times which are considered to be less likely to be contaminated by extraneous noise because they were collected during the evening and night time hours.

Measured $L_{\mathrm{Aeq,10min}}$ and $L_{\mathrm{A90,10min}}$ values are presented in Table I and Table II. Sound pressure levels for wind turbine noise are usually specified to be measured as $L_{\mathrm{A90,10min}}$ values. The individual measured $L_{\mathrm{A90,10min}}$ values for night-time in Table I and Table II are below the recommended night-time threshold for noise in the Wind Energy Development Guidelines [15] of 43 dB(A) respectively, which are currently being amended. They are also below the recommended day-time threshold of 45 dB(A),

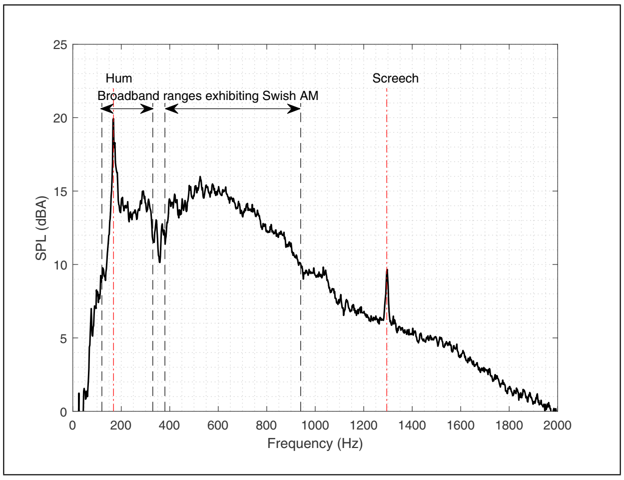

Figure 3. Discrete Fourier Transform for the sample at 21:50 on monitoring day 1 including the subjective interpretation.

although it was not established during planning whether the site might be located in a quiet area i.e. have a recommended fixed lower limit between 35 and 40 dB(A) [15]. The purpose of highlighting these guideline values is to put into context the measurements with respect to general planning practise in Ireland.

3.2. Results of the FFT-analysis

The audio recordings were reviewed for all the data presented in Table I and Table II to confirm the sources of sound and subjective association with frequency content from the results of FFT-analysis. Many of the samples have a combination of all of the components of wind turbine noise subjectively described as a low frequency hum, swishing and repetitive high frequency screeching. A review of the audio samples for the logged occurrences of AM indicate that a swishing sound was audible for nine of the thirteen logged occurrences by the residents. Seven of the logged occurrences have had the AM rating calculated using the Reference Method.

Following the subjective assessment of the audio narrow band spectra were calculated to assess the components and frequency ranges of the noise, a selection of which are reported here. All narrow band spectra reported were calculated from audio files with a sample rate of 16 kHz for a duration of 10 minutes and processed with a block length of 8192 points to give a frequency resolution of 1.9 Hz using 2341 averages with a 50% overlap and a Hanning window applied. The results of the FFT-analysis for a sample in which the low frequency hum and swishing are audible are presented in Figure 3.

In the Discrete Fourier Transform (DFT), represented in Figure 3, a continuous swishing sound was the dominant audible sound in the audio sample as well as a continuous low frequency hum. The low frequency hum is represented by the saw-tooth profile in Figure 3 with a peak at approximately 160 Hz. The swishing sound is believed to potentially occur over two frequency ranges, approximately 120–300 Hz and 400–900 Hz.

Table I. Results of the author's subjective data analysis and rating calculation for occurrences of amplitude modulation logged by the residents. First line: Event Number, Day, Reported Time, Description of noise by residents, 10-minute Sample: Start Time (hr:min), L_{Aeq10min} (dB), $L_{\mathrm{A90_{10min}}}$ (dB), Estimated Wind Direction Range, Estimated Air Temp. (°Celsius) Estimated Wind Speed (m/s), AM Rating 50–200 Hz (dB), AM Rating 100–400 Hz (dB), AM Rating 200–800 Hz (dB). Following line(s): Subjective description of audio and comments by author. In events 4, 5, 10, 13 no samples were selected due to rainfall. Event 8 there was no detection of AM due to machinery noise, and aswell as event 12 because turbines were non-operational.

<table>
<tr><td>1:</td><td>Day 1,</td><td>21:00</td><td>Swishing noisy sound</td><td>21:10</td><td>41.2</td><td>38.4</td><td>240-270°</td><td>12-14</td><td>3-6</td><td>0.0</td><td>4.1</td><td>6.5</td></tr>
<tr><td></td><td colspan="12">Continuous swishing. Low frequency continuous hum. Intermittent repetitive high frequency screech. Some intermittent rustling of vegetation. Swishing dominant.</td></tr>
<tr><td>2:</td><td>Day 2,</td><td>11:00</td><td>Swishing heard inside</td><td>10:50</td><td>41.3</td><td>37.9</td><td>280-300°</td><td>15</td><td>3-8</td><td>0.0</td><td>0.0</td><td>6.1</td></tr>
<tr><td></td><td colspan="12">Continuous swishing, intermittently intense. Low frequency continuous hum. Continuous repetitive high frequency screech. Vehicle passage. Intermittent birdcall. Vegetation rustling.</td></tr>
<tr><td>3:</td><td>Day 3,</td><td>08:00</td><td>Swishing heard inside</td><td>08:10</td><td>47.2</td><td>33.3</td><td>160-230°</td><td>12</td><td>2-4</td><td>0.0</td><td>0.0</td><td>0.0</td></tr>
<tr><td></td><td colspan="12">Continuous swishing. Continuous birdcall. Aircraft noise (08:11:30 - 08:13:30 and 08:18:00 - 08:19:30).</td></tr>
<tr><td>4:</td><td>Day 6,</td><td>19:30</td><td>Swooshing heard inside</td><td>–</td><td>–</td><td>–</td><td>120-170°</td><td>14</td><td>3-6</td><td>–</td><td>–</td><td>-</td></tr>
<tr><td></td><td colspan="12">Intermittent rainfall audible through samples around this time. Swishing is audible at a low level.</td></tr>
<tr><td>5:</td><td>Day 7,</td><td>01:30</td><td>Swooshing heard inside</td><td>–</td><td>–</td><td>–</td><td>140-160°</td><td>13</td><td>5-8</td><td>–</td><td>–</td><td>-</td></tr>
<tr><td></td><td colspan="12">Intermittent rainfall audible through samples around this time. Swishing and hum is audible at a low level.</td></tr>
<tr><td>6:</td><td>Day 7,</td><td>20:00</td><td>Swishing heard inside</td><td>20:20</td><td>38.1</td><td>36.1</td><td>200-360°</td><td>9</td><td>0-6</td><td>0.0</td><td>2.4</td><td>2.8</td></tr>
<tr><td></td><td colspan="12">20:20 sample selected because birdcall in 20:00 sample. Continuous swishing, more intense intermittently. Low frequency continuous hum. Continuous repetitive screech at a high frequency.</td></tr>
<tr><td>7:</td><td>Day 8,</td><td>20:00</td><td>Swooshing heard inside</td><td>20:00</td><td>42.3</td><td>34.8</td><td>200-220°</td><td>12</td><td>7-11</td><td>0.0</td><td>0.0</td><td>2.5</td></tr>
<tr><td></td><td colspan="12">Continuous swishing (subjectively low frequency in nature). Intermittent birdcall. Intermittent repetitive screech at a low level. Two vehicle passages. No low frequency continuous hum. Low level dog barking for short period.</td></tr>
<tr><td>8:</td><td>Day 10,</td><td>14:00</td><td>Swooshing</td><td>–</td><td>–</td><td>–</td><td>160-240°</td><td>17</td><td>2-6</td><td>–</td><td>–</td><td>–</td></tr>
<tr><td></td><td colspan="12">Machine noise (subjectively nearby) and intermittent rainfall through samples around this time. Low frequency hum and intermittent high frequency screech audible.</td></tr>
<tr><td>9:</td><td>Day 11,</td><td>10:00</td><td>Very loud swishing</td><td>10:00</td><td>46.1</td><td>41.7</td><td>210-250°</td><td>13</td><td>5-11</td><td>0.0</td><td>0.0</td><td>0.0</td></tr>
<tr><td></td><td colspan="12">High noise level from rustling vegetation around this time. Low frequency hum slightly audible. Intermittent swishing audible. Intermittent screeching.</td></tr>
<tr><td>10:</td><td>Day 14,</td><td>19:00</td><td>Swooshing (airboat sound)</td><td>–</td><td>–</td><td>–</td><td>210-240°</td><td>16</td><td>7-11</td><td>–</td><td>–</td><td>–</td></tr>
<tr><td></td><td colspan="12">Continuous high level of rustling vegetation and rainfall audible through samples around this time. Low frequency hum.</td></tr>
<tr><td>11:</td><td>Day 15,</td><td>09:50</td><td>Loud swishing heard inside</td><td>09:50</td><td>49</td><td>42.4</td><td>240-270°</td><td>14</td><td>6-9</td><td>0.0</td><td>0.0</td><td>5.2</td></tr>
<tr><td></td><td colspan="12">Swishing audible (subjectively intense and intermittent). Birdcall dominant at times. Rustling of vegetation. Low frequency hum.</td></tr>
<tr><td>12:</td><td>Day 16,</td><td>20:00</td><td>Swishing heard inside</td><td>–</td><td>–</td><td>–</td><td>140-360°</td><td>11</td><td>0-3</td><td>–</td><td>–</td><td>–</td></tr>
<tr><td></td><td colspan="12">Turbines were not audible around this time (20:10: L_{A90} = 24 dB). Slight road noise audible. Access to confidential SCADA data confirms that turbines were not operational.</td></tr>
<tr><td>13:</td><td>Day 18,</td><td>20:00</td><td>Loud swishing heard inside</td><td>–</td><td>–</td><td>–</td><td>120-150°</td><td>13</td><td>7-8</td><td>–</td><td>–</td><td>–</td></tr>
<tr><td></td><td colspan="12">Continuous rainfall, vegetation and vehicles audible through samples around this time.</td></tr>
</table>

A review of the audio data identified a "screech" sound occurring at frequencies between approximately 1.0 kHz and 1.3 kHz, evident in the results of the FFT-analysis visible in Figure 3 and Figure 4. The screech has fluctuating sound pressure levels between a frequency range of approximately 1 kHz and 1.3 kHz and is repetitive. This specific sound was logged separately by residents in their noise diaries. The source has not been identified.

The subjective analysis suggested that the high frequency screech would be filtered out of the AM rating calculation using the band filter, but that high levels of low frequency noise may corrupt any AM rating calculation in the 50–200 Hz and 100–400 Hz frequency bands. This is a factor to bear in mind when reviewing the AM rating levels, that is, extraneous noise sources might have an adverse effect on the calculation.

Table II. Results of the author's subjective data analysis and rating calculation for occurrences of amplitude modulation for a 12-hour period over monitoring days 1 and 2. The columns depict: 10-minute Sample: Start Time (hr:min), $L_{\text{Aeq},10\text{min}}$ (dB), $L_{\text{A90},10\text{min}}$ (dB), Description of audio by Author, AM Rating 50–200 Hz (dB), AM Rating 100–400 Hz (dB), AM Rating 200–800 Hz (dB), AM Reference Method Overall AM Rating (dB).

19:30	40.7	37.9	Continuous swishing and low frequency continuous hum. Intermittent repetitive high frequency screech at a low level. Some birdcall and intermittent rustling of vegetation. Swishing dominant.	0.0	4.8	6.0	6.0
19:50	41.1	38.2	Continuous swishing. Low frequency continuous hum. Intermittent repetitive high frequency screech at a low level. Some birdcall and intermittent rustling of vegetation. Swishing dominant.	0.0	4.3	5.7	5.7
20:10	42.7	39.8	Continuous swishing. Low frequency continuous hum. Some birdcall and intermittent rustling of vegetation. Swishing dominant.	0.0	5.1	6.0	6.0
20:30	41.9	39.1	Continuous swishing. Low frequency continuous hum. Intermittent repetitive high frequency screech at a low level. No birdcall or rustling vegetation. Swishing dominant.	0.0	4.4	6.1	6.1
20:50	42.8	40.5	Continuous swishing. Low frequency continuous hum. Intermittent repetitive high frequency screech at a low level. Some intermittent rustling of vegetation. Swishing dominant.	0.0	4.1	4.5	4.5
21:10	41.2	38.4	Continuous swishing. Low frequency continuous hum. Intermittent repetitive high frequency screech at a low level. Some intermittent rustling of vegetation. Swishing dominant.	0.0	4.1	6.5	6.5
21:30	37.1	34.6	Continuous swishing. No low frequency hum. Swishing dominant.	0.0	4.0	5.6	5.6
21:50	39.7	37.5	Continuous swishing. Continuous low frequency hum. Swishing dominant.	0.0	4.0	5.3	5.3
22:10	39.3	37	Continuous swishing. Continuous low frequency hum. Swishing dominant.	0.0	4.6	6.0	6.0
22:30	41.1	38.3	Continuous swishing. Continuous low frequency hum. Swishing dominant. Vehicle noise (22:34:25 - 22:34:35 and 22:39:10 - 22:39:20)	0.0	4.1	5.8	5.8
22:50	40	37.4	Continuous swishing. Continuous low frequency hum. Swishing dominant.	0.0	5.0	7.0	7.0
23:10	40.4	37.9	Continuous swishing. Continuous low frequency hum. Swishing dominant.	0.0	4.8	6.1	6.1
23:30	42.1	39.3	Continuous swishing. Low frequency continuous hum. Intermittent repetitive high frequency screech at a low level. Some intermittent rustling of vegetation. Swishing dominant.Vehicle noise (23:31:56 - 23:32:06)	0.0	4.7	6.1	6.1
23:50	42.7	40.2	Continuous swishing. Low frequency continuous hum. Intermittent repetitive high frequency screech at a low level. Some intermittent rustling of vegetation. Swishing dominant.	0.0	4.9	5.6	5.6
00:10	41.2	38.3	Continuous swishing. Low frequency continuous hum. Intermittent repetitive high frequency screech at a low level. Some intermittent rustling of vegetation. Swishing dominant.	0.0	4.5	6.9	6.9
00:30	40.2	37.5	Continuous swishing. Low frequency continuous hum. Some intermittent rustling of vegetation. Swishing dominant.	0.0	5.0	6.8	6.8
00:50	41	38.7	Continuous swishing. Low frequency continuous hum. Some intermittent rustling of vegetation. Swishing dominant.	0.0	4.7	6.1	6.1
01:10	40.6	38.2	Continuous swishing. Low frequency continuous hum. Some intermittent rustling of vegetation. Swishing dominant.	0.0	5.1	6.3	6.3
01:30	41.3	38.7	Continuous swishing. Low frequency continuous hum. Some intermittent rustling of vegetation. Swishing dominant.	0.0	5.3	6.5	6.5
01:50	40.5	38	Continuous swishing. Low frequency continuous hum. Some intermittent rustling of vegetation. Swishing dominant.	0.0	5.2	6.6	6.6
02:10	40.2	37	Continuous swishing. Low frequency continuous hum. Some intermittent rustling of vegetation. Swishing dominant.	0.0	4.9	5.9	5.9
02:30	40.9	37.4	Continuous swishing. Low frequency continuous hum. Intermittent repetitive high screech. Swishing dominant.	6	5.0	7.3	7.3

Table II. Continuation.

02:50	40.7	38.1	Continuous swishing. Low frequency continuous hum. Intermittent repetitive high screech. Swishing dominant.	0.0	0.0	6.5	6.5
03:10	41.2	38	Continuous swishing. Low frequency continuous hum. Intermittent repetitive high screech. Some rustling vegetation. Swishing dominant.	0.0	4.5	7.7	7.7
03:30	41.2	38.9	Continuous swishing. Low frequency continuous hum. Intermittent repetitive high screech. Some intermittent rustling vegetation. Swishing dominant.	0.0	4.7	6.4	6.4
03:50	40.1	38.1	Continuous swishing. Low frequency continuous hum. Intermittent repetitive high screech. Some intermittent rustling vegetation. Swishing dominant.	0.0	4.4	6.4	6.4
04:10	41.9	39.1	Continuous swishing. Low frequency continuous hum. Intermittent repetitive high screech. No rustling vegetation. Swishing dominant.	0.0	4.7	6.2	6.2
04:30	40.7	38.1	Continuous swishing. Low frequency continuous hum. Intermittent repetitive high screech. No rustling vegetation. Swishing dominant.	0.0	4.4	5.9	5.9
04:50	42.9	40.2	Continuous swishing. Low frequency continuous hum. Intermittent repetitive high screech. No rustling vegetation. Swishing dominant.	0.0	4.5	6.0	6.0
05:10	40.4	38.1	Continuous swishing. Low frequency continuous hum. Some intermittent rustling vegetation. Swishing dominant.	0.0	4.7	6.1	6.1
05:30	41.7	39.2	Continuous swishing (subjectively low frequency at times). Low frequency continuous hum. Intermittent repetitive high screech at a low level. No rustling vegetation. Swishing dominant.	0.0	4.9	6.5	6.5
05:50	41.8	39.3	Continuous swishing. Low frequency continuous hum. Intermittent repetitive high screech at a low level. No rustling vegetation. Swishing dominant.	0.0	4.5	6.8	6.8
06:10	41.2	38.5	Continuous swishing. Low frequency continuous hum. Intermittent repetitive high screech. No rustling vegetation. Swishing dominant.	0.0	5.0	6.7	6.7
06:30	41.9	38.4	Continuous swishing. Low frequency continuous hum. No screech screech. No rustling vegetation. Swishing dominant. Vehicle passage 06:36:05 to 06:36:17. Intermittent birdcall from 06:36.	0.0	4.6	6.0	6.0
06:50	43.4	38.7	Continuous swishing. Low frequency continuous hum. Birdcall. No rustling vegetation. Swishing and birdcall dominant.	0.0	5.0	6.4	6.4
07:10	44.4	38.3	Continuous swishing. Low frequency continuous hum. Birdcall. No rustling vegetation. Swishing and birdcall dominant.	0.0	4.7	6.2	6.2
			Average	0.2	4.5	6.2	6.2

Two additional data files from the dataset were selected as representative of measurements in which AM was both identified and not identified by the process of the Reference Method. These are presented in order to provide insight into the general noise environment of the site. The AM sample was selected from the evening of the first day of monitoring and the no-AM sample was selected from the morning of day 11. Figure 5 reports the narrow band spectra data for these two data files.

The autocorrelation function was used to determine if the BPF of the turbine could be detected in the recordings. The data was low-pass filtered using a digital Butterworth filter to remove data above 10 Hz. The autocorrelation function for the same two data files is shown in Figure 6. The sample with AM identified shows a clear periodicity in the autocorrelation with a frequency of 0.85 Hz which is as would be expected for the turbine BPF.

The data files were then passed through the custom Python code to calculate the 100 ms L_{Aeq} in the 200–800 Hz frequency band prior to calculation in the IOA Reference Method script; the results are reported in Figure 7. As can clearly be seen from Figure 5 and Figure 7 the

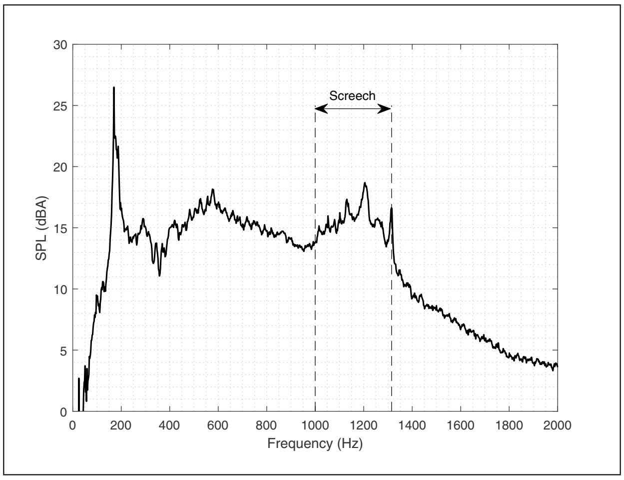

Figure 4. Discrete Fourier Transform for sample at 20:50 on monitoring day 1 including the subjective interpretation of the screeching noise.

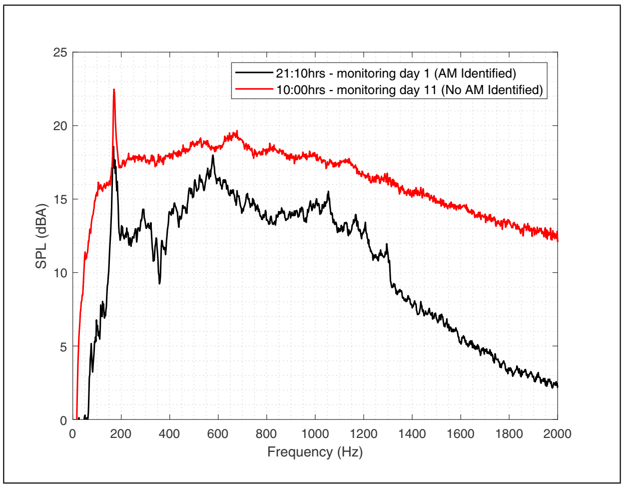

Figure 5. Narrow Band Spectra of measurements with AM (21:10 hrs relates to Event 1 Table I) and without AM identified by the Reference Method.

background sound pressure level of the sample with AM detected is significantly lower. The $L_{\mathrm{A}10}$ and $L_{\mathrm{A}90}$ values of each ten minute period are given in the Table III.

It should be noted that the sample without AM identified has high values of both the $L_{\mathrm{A}10}$ and $L_{\mathrm{A}90}$ indicating higher background noise and also the presence of other noise sources. The increase in the L_{Aeq} values in the no AM sample, particularly seen around 7 minutes, is related to road traffic noise. This indicates that AM may be hidden by higher background noise and other noise sources. A counter intuitive result of this fact may be that noise complaints related to wind farms may increase in quieter environments.

3.3. Results of calculation

Five of the seven logged occurrences of AM which the Reference Method was applied to had valid AM ratings (events 1, 2, 6, 7 and 11, Table I). There were AM rating levels between 2.5 and 6.5 dB in the 200–800 Hz frequency band. Two of the logged occurrences did not meet the Reference Method threshold criteria for valid AM ratings (events 3 and 9). All thirty-six of the samples for the extended 12 hour period for event 1 had valid AM ratings with rating levels in the 200–800 Hz frequency band between 3.7 and 7.7 dB (Table II and Figure 8).

The analysis also identified AM in the 100–400 Hz frequency bands up to 5.3 dB (Table II). However, the dominant frequency range in which AM occurred was between 200 and 800 Hz and it is indicated in Tables I and II that

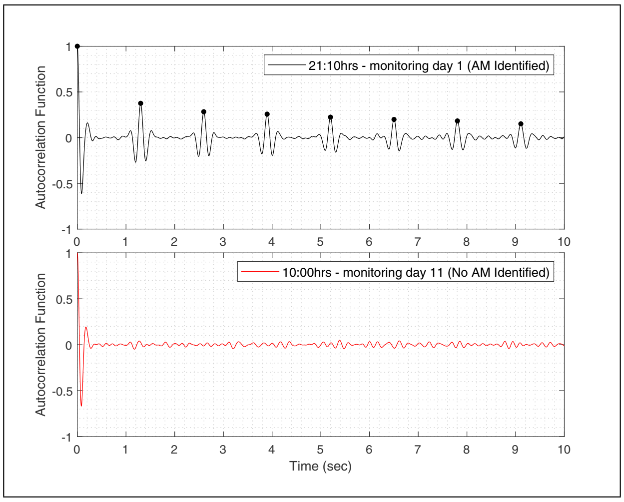

Figure 6. Autocorrelation function of measurements with and without AM identified by the Reference Method.

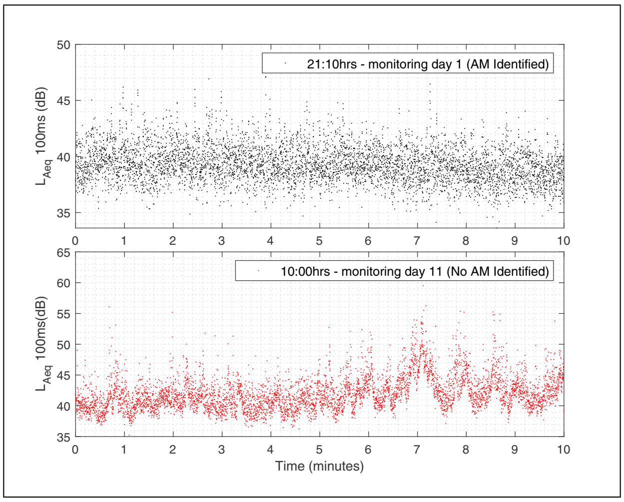

Figure 7. 100-millisecond A-weighted sound pressure levels between 200–800 Hz in the 10-minute samples with and without AM identified.

Table III. $L_{\mathrm{A}10}$ and $L_{\mathrm{A}90}$ values of samples with and without AM identified by the Reference Method.

	21:10 Day 1	10:00 Day 11
$L_{\mathrm{A}10}$	43.1	48.7
$L_{\mathrm{A}90}$	38.4	41.7

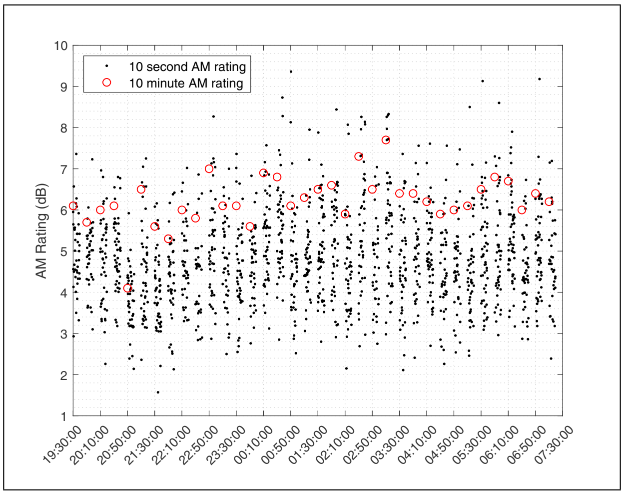

Figure 8. 10-second minor interval and 10-minute AM rating calculations for the 200–800 Hz frequency band for the period 19.30 hrs on monitoring day 1 to 07:20 hrs of monitoring day 2.

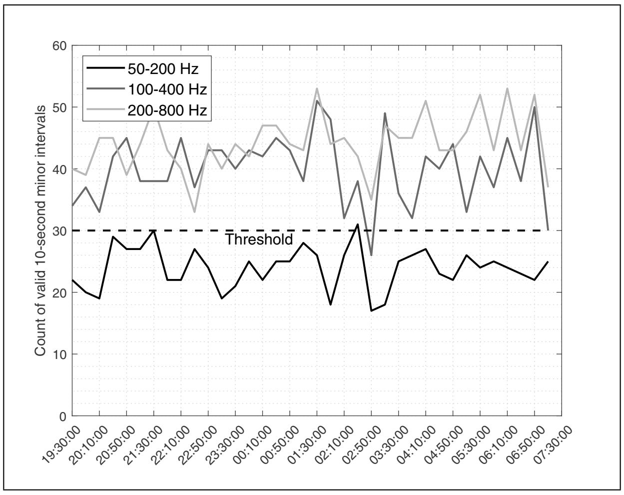

Figure 9. Number of valid 10-second minor intervals for amplitude modulation for the twelve hour period monitored between 19:30 and 07:20 hrs on monitoring days 1 and 2.

the highest levels of AM occurred during westerly crosswinds.

4. Discussion

Five of the seven valid AM ratings in Table I have rating levels between those expected to be just perceptible and being potentially likely to result in adverse comment from residents. However, there were two instances of subjectively reported AM which had no AM rating according to the Reference Method. A review of these samples indicates that there was intermittent "swishing" in the audio of one of the samples (event 9) and 3.5 minutes of aircraft noise out of 10 minutes in the other sample (event 3). While the Reference Method has been found to be robust to detect AM for the confirmed logged occurrences of AM it is likely to under-rate AM where there is extraneous noise in the frequency band in which AM occurs, particularly if the AM is intermittent. If there is intermittent AM during a 10 minute measurement period then the method is restrained by the threshold of thirty valid 10-second minor intervals out of sixty. This threshold seeks to ensure that the detection can be considered robust (i.e. it does not generate false positive results) but may prove to be limiting when making measurements in challenging environments with extraneous noise.

The regional meteorological data for Shannon Airport indicates that the highest AM ratings have been gained under crosswind conditions, potentially at a range of wind speeds (Tables I and II). This is similar to findings by Paulraj and Välisuo [16] from the assessment of long-term monitoring from a wind farm in Finland. They found for a twelve month monitoring period that the frequency of occurrence of AM increases with wind speed but that the highest rating levels are influenced by wind direction. A high instance of modulation depths between 4.5 dB and 8.5 dB was detected in the Finish study under crosswind conditions. To note, these values cannot be compared directly with those derived using the IOA metric, although they would generally be of similar order. Crosswind conditions have also been the cause of the highest levels of AM at the site presented here, based on meteorological data from Shannon Airport.

For the twelve hour period that AM was calculated the dominant frequency band for AM was 200-800 Hz. However, it was also identified that there was the potential for low frequency AM from the review of the FFT-analysis (Figures 4 and 5). A review of the number of valid 10-second minor intervals indicates that even though there were valid 10-second minor intervals in the 50-200 Hz frequency band there were generally not the thirty or more valid minor intervals required to calculate a valid 10-minute AM rating level (Figure 9). Therefore it is debatable whether the Reference Method has successfully identified AM in this frequency range. Evaluation using the Reference Method may result in periods of intermittent AM not being identified, although in practice individual peak-to-trough variations in noise level may be apparent to the listener.

As can be seen from Figure 9 the number of 10-second minor intervals was frequently just below the required thirty valid samples, with only one 10-minute sample having the required thirty, suggesting that there was intermittent low frequency AM throughout the twelve hour period. The 90th percentile value of the 10-second minor intervals for each 10-minute interval in the 50–200 Hz frequency band were generally less than in the 200–800 Hz but greater than the 100–400 Hz frequency band (irrespective of whether there was a valid 10-minute AM rating level i.e. thirty or greater valid 10-second minor intervals). These results are shown in Figure 10 which shows that the level of the 50–200 Hz AM exceeded that of the 200–800 Hz AM for a portion of the twelve hour period, however due to the threshold criteria set by the Reference Method these values are rejected when calculating the overall AM rating.

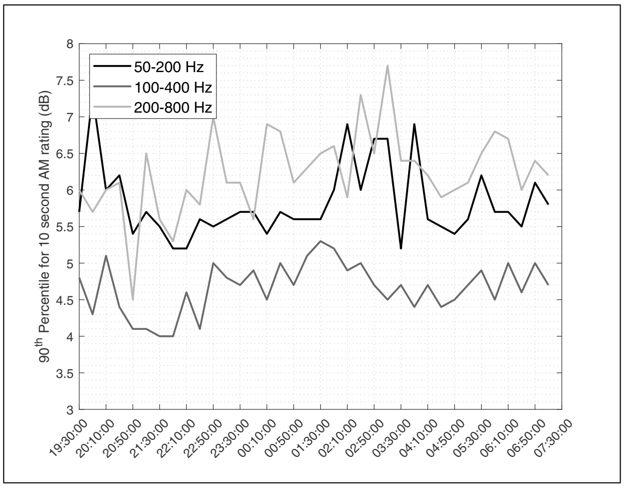

Figure 10. 90th percentile values of the valid 10-second minor intervals for amplitude modulation for the twelve hour period monitored between 19:30 and 07:20 hrs on monitoring days 1 and 2.

Consequently, even though the Reference Method results indicated that there was no AM in the 50–200 Hz frequency band it is worth examining no-AM ratings to gain an understanding of the potentially intermittent nature of AM. In this case it could be argued that valid measurements of AM were recorded despite the lack of a 10-minute AM rating in the 50–200 Hz range. Therefore it is possible for the Reference Method to underestimate the AM rating in certain cases. In cases such as this it may be possible to modify the requirements of the method and for example, investigate if there are fifteen valid minor intervals in a five minute period. This approach keeps the same detection criteria as the Reference Method but over a shorter time frame.

5. Conclusions

The Reference Method, developed by the IOA, has been shown to be a reliable method to detect and confirm the presence of AM that was subjectively reported by residents living near a wind energy development. Therefore it can be recommended as a suitable tool for policy makers and legislative bodies interested in defining acceptable criteria for AM from wind farm developments.

There is the potential in the method for intermittent AM and AM that is contaminated by extraneous noise to generate no-AM ratings. Subjective analysis of audio recordings and FFT-analysis is vital to give an indication of the frequency bands in which to expect AM to occur. The assessment of AM only in frequency bands that have valid ratings using the Reference Method can result in ignoring intermittent AM in other frequency bands. This intermittent AM may be noticeable and potentially cause a noise complaint. It is recommended that in addition to the calculation of AM at various frequency bands using the Reference Method that a subjective assessment of the recordings should be carried out to investigate the prevalence of AM in other frequency ranges. Based on this assessment it may be necessary to consider carefully the suitability of the Reference Method's threshold of thirty valid 10-second minor intervals out of sixty. The authors believe it is necessary to monitor the number of AM ratings detected and if this falls just below the threshold of thirty valid readings that additional steps should be taken including subjective assessments and FFT-analysis. Future research should consider if annoyance can be caused by less than thirty 10-second instances of AM in each of the different frequency bands and, if necessary, the Reference Method updated to reflect this.

The dominant frequency range in which AM occurred at this site was 200 – 800 Hz with AM rating levels calculated between 2.5 dB and 6.5 dB for the occurrences logged by residents. This correlates well with the expectations from literature that the perception threshold for AM is 2 dB and that the threshold for annoyance occurs from 3 dB. The twelve hour period following the first subjective report of AM produced AM ratings between 3.7 dB and 7.7 dB during a time when crosswind conditions most likely occurred. This demonstrates the importance of the wind direction when assessing complaints related to AM and also the potential for disturbance by AM to extend over long periods.

Acknowledgement

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