Journal of Sound and Vibration 455 (2019) 136–149

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Prevalence of wind farm amplitude modulation at long-range residential locations

Kristy L. Hansen [a,*], Phuc Nguyen [a], Branko Zajamšek [b], Peter Catcheside [b], Colin H. Hansen [c]

[a] College of Science and Engineering, Flinders University, Tonsley, 5042, Australia
[b] College of Medicine, Flinders University, Bedford Park, 5042, Australia
[c] School of Mechanical Engineering, The University of Adelaide, Adelaide, 5005, Australia

ARTICLE INFO

Article history:
Received 27 September 2018
Revised 1 May 2019
Accepted 3 May 2019
Available online 13 May 2019
Handling Editor: R.E. Musafir

Keywords:
Amplitude modulation
Wind farm noise
Low-frequency noise
Tonal noise

ABSTRACT

The presence of amplitude modulation (AM) in wind farm noise has been shown to result in increased annoyance. Therefore, it is important to determine how often this characteristic is present at residential locations near a wind farm. This study investigates the prevalence and characteristics of wind farm AM at 9 different residences located near a South Australian wind farm that has been the subject of complaints from local residents. It is shown that an audible indoor low-frequency tone was amplitude modulated at the blade-pass frequency for 20% of the time up to a distance of 2.4 km. The audible AM occurred for a similar percentage of time between wind farm percentage power capacities of 40 and 85%, indicating that it is important that AM analysis is not restricted to high power output conditions only. Although the number of AM events is shown to reduce with distance, audible indoor AM still occurred for 16% of the time at a distance of 3.5 km. At distances of 7.6 and 8.8 km, audible AM was only detected on one occasion. At night-time, audible AM occurred indoors at residences located as far as 3.5 km from the wind farm for up to 22% of the time.

1. Introduction

The rapid global expansion of wind energy has been associated with widespread complaints regarding annoyance, sleep disturbance and adverse health effects from people who have been exposed to wind turbine noise [1]. Therefore, to ensure that residents living near wind farms are not subjected to excessive noise-related disturbance, it is important to identify potentially disturbing wind farm noise components. Moreover, suitable methods for quantifying these components are required. Acceptable threshold levels also need to be defined to determine the prevalence of potential noise disturbance.

Several researchers have shown that amplitude modulation (AM) of wind farm noise contributes to annoyance [2–5]. Despite this finding, many regulations and guidelines concerning wind farm noise do not include penalties for this characteristic, possibly due to the ongoing debate as to what constitutes a reasonable penalty [6]. As discussed by Perkins et al. [7], the exposure-response to wind turbine AM noise is influenced by several factors including AM depth, noise level, duration/consistency of AM, time of occurrence and noise sensitivity of the individual.

Several methods have been developed to determine the AM depth of wind farm noise based on analysis in the time-domain, frequency-domain and a combination of both [8]. Recently the AM Working Group (AMWG), on behalf of the UK

* Corresponding author.
E-mail address: kristy.hansen@flinders.edu.au (K.L. Hansen).

https://doi.org/10.1016/j.jsv.2019.05.008
0022-460X/

Institute of Acoustics, conducted an extensive review of existing methods for AM detection and quantification [8]. Following this review and a period of consultation, the group developed a method referred to as the IOA 'reference method' [9], which incorporates concepts developed by other research groups including Fukushima et al. [10] and Renewable UK [2] into a hybrid (time- and frequency-domain based) method. The main advantages of this method are that it can be automated, allowing analysis over long time periods, and it is robust to background noise contamination, reducing the instances of false positives.

This study investigates the suitability of the IOA 'reference method' for detecting low-frequency AM of a tone that is generated by wind turbines. The motivation for this analysis is to investigate the prevalence of a low-frequency 'thumping' or 'rumbling' noise that has been mentioned in complaints from residents. In fact, during a study by the South Australian Environmental Protection Agency in 2013, at least 14 (out of 15) residents living at various distances up to 8 km complained of 'thumping' and/or 'rumbling'. Their responses were documented in noise diaries that were collected over several weeks and these were provided to our research group. Since the IOA 'reference method' has been validated using broadband noise [2,11], which is representative of wind farm noise at distances less than 1 km from a wind farm, some modifications are proposed to extend its applicability to tonal AM measured at larger distances. These include changes to the analysis bandwidth, reduction in the prominence factor representing 'valid AM', assessment of the tonal audibility and reduction in the AM depth for cases when the tonal audibility is less than 0 dB at AM 'troughs'. The modified algorithm is then applied to outdoor and indoor data measured at 9 residences over a total of approximately 64 days of continuous recording to investigate the prevalence of AM and the associated AM depth. Relationships between AM and distance from the wind farm, AM and wind farm operating conditions and AM and time of day are also explored.

2. Measurement set-up

Outdoor measurements were carried out for a total of approximately 64 days at 9 different residences located between 1 and 9 km from the nearest wind turbine of a South Australian wind farm, which at the time of measurements was made up of 37 operational turbines, each with a rated power of 3 MW. The wind farm is positioned along the top of a ridge and the wind turbine hub height relative to the residences varies between 85 and 240 m. The wind turbine and residence locations are shown in Fig. 1. Time series data were acquired both outdoors and indoors using National Instruments 9234 (at 10240 Hz sampling rate) and Bruel and Kajer LAN-XI Type 3050 (at 8192 Hz sampling rate) data acquisition systems, respectively. The outdoor microphone was a G.R.A.S type 40AZ with a 26CG preamplifier, which has a noise floor of 16 dB(A) and a flat frequency response down to 0.5 Hz. The outdoor microphone was mounted at a height of 1.5 m and protected using a spherical secondary windscreen with a diameter of 450 mm. Details of the construction of this windscreen are provided in Hansen et al. [12]. The outdoor microphone was typically positioned at least 20 m away from the residence and at least 10 m from surrounding vegetation to minimise façade reflections and wind-induced vegetation noise, respectively. A typical outdoor measurement set-up is shown in Fig. 2. The indoor microphone was a B&K type 4955, which has a noise floor of 6.5 dB(A) and a flat frequency response down to 6 Hz. The indoor microphone used in the analysis was mounted on a mini tripod and positioned approximately 100 mm from a room corner, at the intersection between two walls and the floor. Two other indoor microphones were mounted at heights of 1.5 m

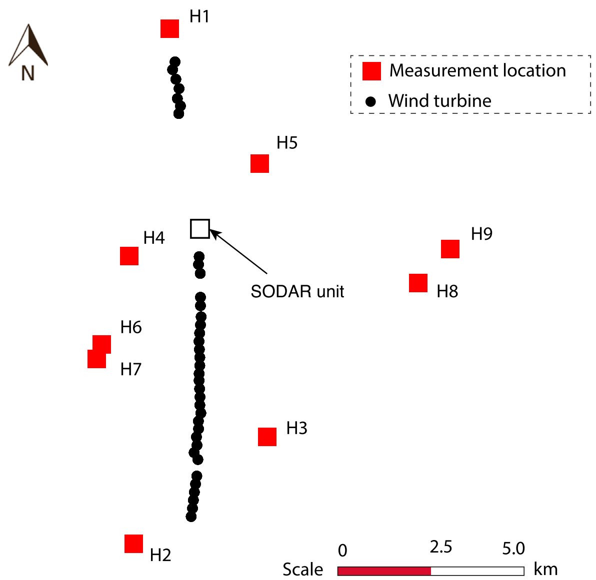

Fig. 1. Scaled diagram showing position of residences relative to the wind farm.

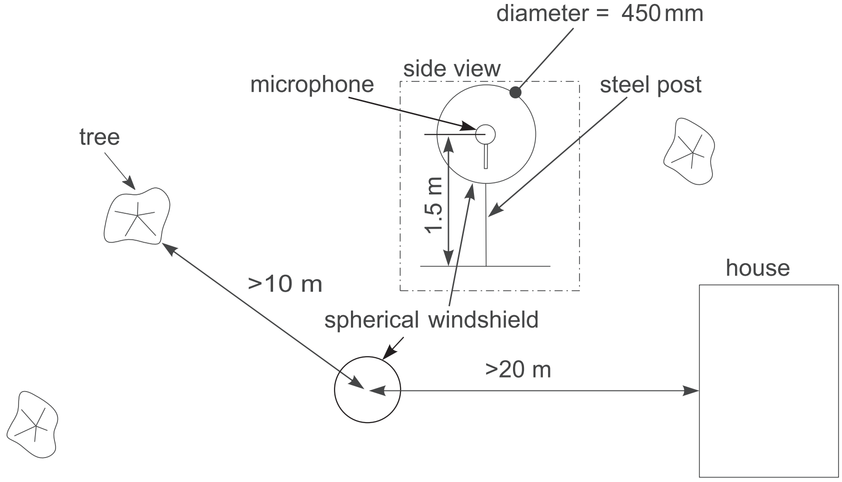

Fig. 2. Schematic showing a typical outdoor measurement set-up.

Table 1
Number of 10-min samples measured outdoors and indoors at each residence.

Residence	H1	H2	H3	H4	H5	H6	H7	H8	H9
Distance (km)	1.3	2.3	2.4	2.5	3.3	3.4	3.5	7.6	8.8
Outdoors	833	700	471	1548	1087	640	1659	999	848
Indoors	834	803	860	1561	1091	640	1344	989	850

and positioned randomly within the room. At all residences, the indoor measurements were taken in a room that faced as closely as possible towards the wind farm and the windows were closed. A total of 8716 and 8972 10-min samples of outdoor and indoor data, respectively, were analysed in this study. The number of 10-min samples taken outdoors and indoors at each residence is shown in Table 1.

Hub-height wind speed data for the nearest wind turbine to each residence were available from the wind farm operator for all residences except H5, for which the hub height data were measured using a Fulcrum 3D SODAR. The SODAR was located on the same ridge-top as the wind turbines, as shown in Fig. 1. The resolution of this device is ± 0.01 m/s, according to the manufacturer. Power output data for the wind farm were obtained from the Australian Energy Market Operator website [13] in 5-min averages. These data pertain to the entire wind farm and data for each individual wind turbine were not available.

3. Analysis techniques

3.1. AM detection and quantification method

Several methods have been developed for detecting and quantifying AM and they can be divided into 3 categories: time-domain [10], frequency-domain [4] and 'hybrid' methods [9], the latter of which involves analysis in both the time and frequency domains. A comprehensive review of these methods can be found in Refs. [8,14]. In this study, the IOA 'reference method' [9], a hybrid method, has been used for detecting and quantifying AM. However, to ensure reliable detection of the low-frequency tonal AM that is characteristic of the wind farm noise analysed in this study, several modifications were required, which are as follows:

1. The bandwidth of analysis was limited to a single 1/3-octave band containing AM with the highest associated AM depth.
2. The prominence factor described in the IOA 'reference method' was reduced to 3. This means that the spectral peak at the BPF did not need to be as high above the noise floor of the power spectrum to be considered as wind farm AM.
3. The audibility of the tone was assessed based on the sound pressure level (SPL) in the 50 Hz 1/3-octave band and masking noise in the first critical band (20–120 Hz).
   (a) The normal hearing threshold curve specified in ISO 389-7 [15] was used to determine if the SPL in the 50 Hz 1/3-octave band was sufficiently high to be potentially audible.
   (b) For cases identified in (a), the tonal audibility was assessed using the method outlined in the IEC 61400-11 standard [16]. Note that this standard does not explicitly state that the tone should be above the hearing threshold. However, this is an important consideration for low level tones, and thus audibility was also evaluated using ISO 389-7 [15].

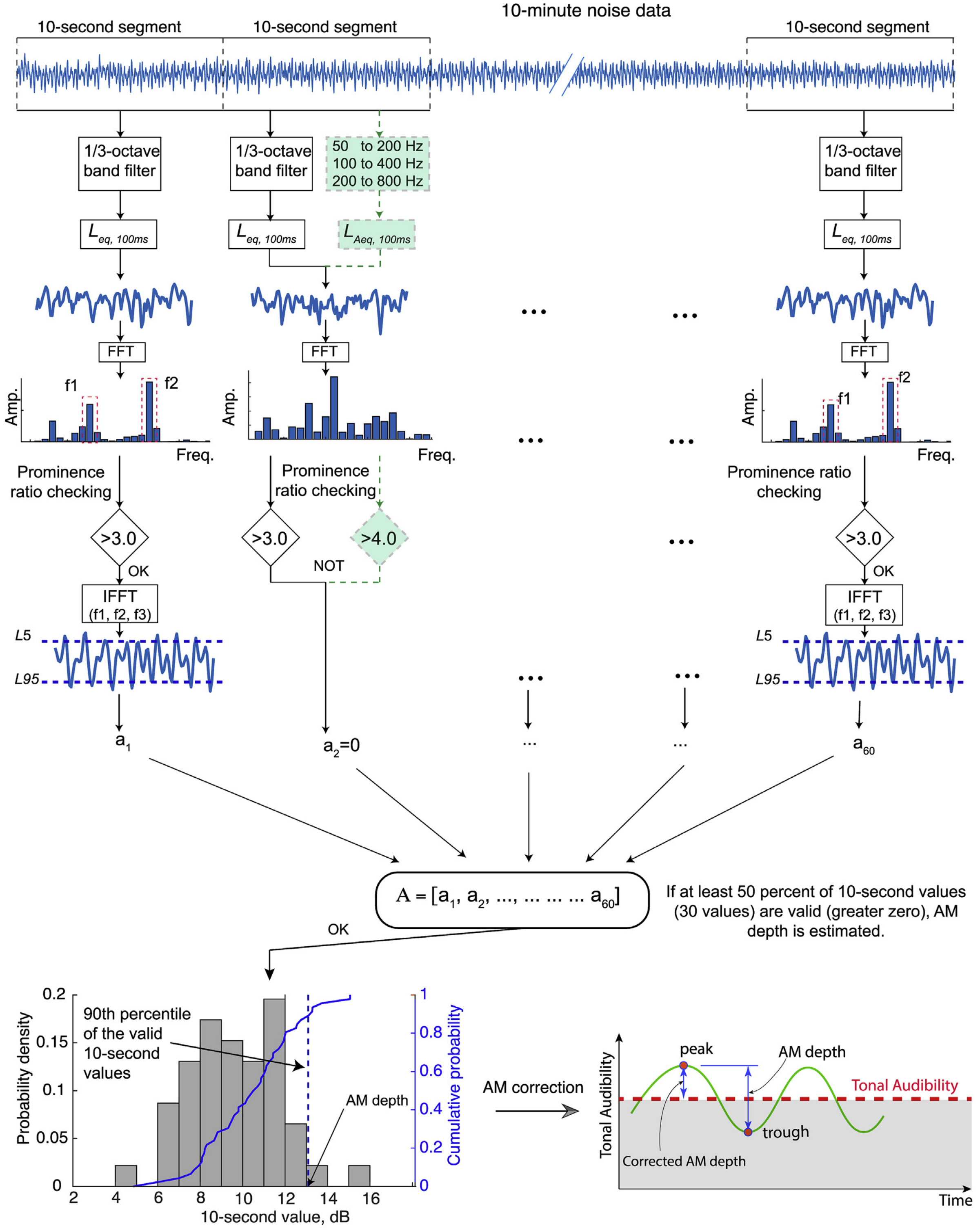

Fig. 3. A summary of the steps for determining and quantifying AM based on the IOA 'reference method' that has been modified to suit analysis of AM of a low-frequency tone. The Inverse Fast Fourier Transform (IFFT) is calculated using the fundamental and first two harmonics. The values in the box shaded green with dashed grey outline are the original values used in the IOA 'reference method'. The modifications are applied for all 10-s segments. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

4. If the AM troughs, as pictured in the bottom-right of Fig. 3, were not expected to be audible based on the calculated tonal audibility, the AM depth was reduced. For instance, if the tonal audibility was 0 dB and the AM depth was 6 dB, the reduced AM depth would be 3 dB. This is referred to as the ‘AM correction’ hereafter.

For the specific wind farm and receiver distances analysed in this study, narrowband analysis revealed that the most significant AM occurs at approximately 46 Hz [17]. Therefore, due to the tonal nature of the AM, the analysis bandwidth was reduced to the 50 Hz 1/3-octave band. Although Bass et al. [9] suggest an analysis bandwidth of 50 Hz–200 Hz, it is highlighted that this bandwidth precludes the audible tone and that even if the lower bound were extended to 40 Hz, the AM depth would be much lower. This is expected for the tonal AM analysed in this study but the approach may not be valid for broadband AM such as ‘swish’. In fact, it is recommended that before deciding on the analysis bandwidth, it is important to identify the frequency range in which AM occurs. To ensure that the AM depth is not underestimated, it is important to choose a bandwidth that results in the highest AM depth. In this analysis, a narrow bandwidth of 2 Hz, centred on the tone, was also investigated but it was found that the AM depth was close to that obtained using 1/3-octave bands. Moreover, use of 1/3-octave bands is required by the New Zealand standard for wind farm noise measurement [18] and has been used by other researchers [19,20] for AM analysis.

The prominence ratio was reduced from 4 to 3 based on a systematic analysis, which is described in Section 3.2. Fig. 3 shows a summary of the steps for determining and quantifying AM based on the IOA ‘reference method’ with the modifications discussed above.

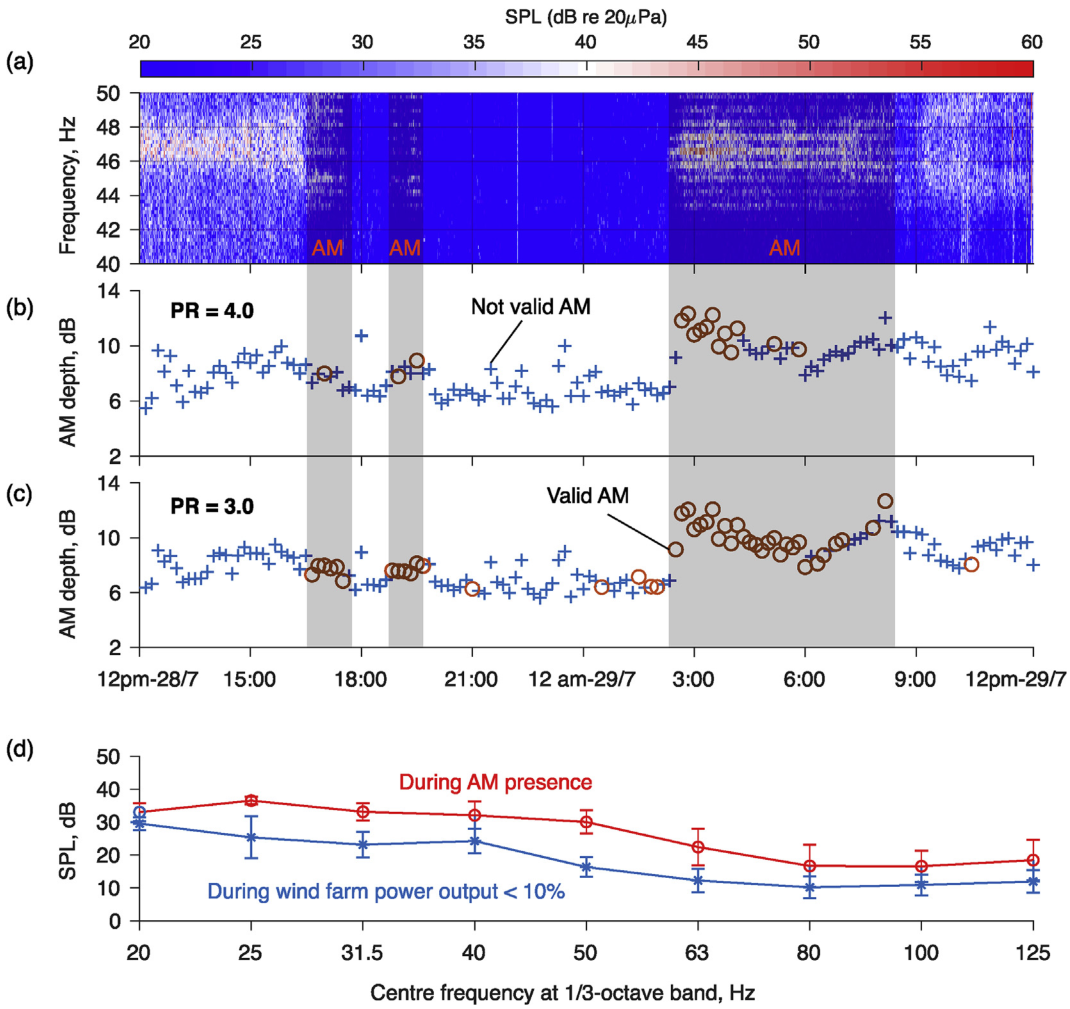

Fig. 4. The effect of prominence ratio on the result of AM detection for measurements at H5. (a) Spectrogram showing the presence of AM, as determined by a human scorer, shaded in grey. The AM is characterised by horizontal bands of relatively high SPL spaced at the BPF. (b), (c) Results of AM detection corresponding to prominence ratios of 4.0 and 3.0, respectively. The red and blue markers show AM depth for 10-min data points that are considered valid and not valid, respectively using the IOA ‘reference method’ [9]. (d) Mean and standard deviation of 1/3-octave spectra corresponding to data containing wind farm AM (red) as shaded in (a–c), and the period with negligible wind farm noise (blue), as indicated by the low-level signal without AM in the centre of (a–c). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.2. Validation of AM detection algorithm

To show a visual representation of the accuracy of the IOA 'reference method' with prominence ratios of 3 and 4, comparison is made to a spectrogram plot in Fig. 4. These data were measured at H5 over 24 h, during which there were some periods with AM present and other periods with AM absent. The plot was constructed using a Hamming window, frequency resolution of 0.1 Hz, time resolution of 5 s and 50% overlap. As shown in Fig. 4(a), use of a spectrogram plot is an effective method of identifying AM of a tone, which is visible as horizontal lines in the spectrum spaced vertically at the blade pass frequency (BPF) of 0.8 Hz. The disadvantage of this approach is that it requires significant computational resources and a human for visual data interpretation. Hence, it was used in this study as a validation tool only. The results of applying the IOA 'reference method' with modifications are shown in Fig. 4(b) and (c). Here the AM depth is plotted against time, and 10-min periods with and without AM are shown using red circles and blue plus signs, respectively. Fig. 4(d) shows that the SPL of low-frequency noise is much higher during periods containing wind farm AM compared to periods when the ambient noise is dominant.

Comparison between Fig. 4(a) and (b) indicates that the prominence ratio of 4 that is recommended by Bass et al. [9] fails to detect many occurrences of AM. On the other hand, selection of a more conservative prominence ratio of 3 results in a better correlation between the AM visible in Fig. 4(a) and the 10-min periods identified as containing AM in Fig. 4(c). The rate of detection of true and false positives for various prominence ratios is discussed in more detail below.

To further refine the selection of the prominence ratio for the entire data set, a Receiver Operating Curve (ROC) analysis was carried out using the methodology outlined by Fawcett [21]. The aim of the ROC analysis was to systematically examine true versus false positive and negative detection rates at each possible prominence ratio to find the optimal prominence ratio cut-off that simultaneously maximised both true positive (sensitivity) and true negative (specificity) detection. This is done by comparing the algorithm output to a 'gold standard' which in this case is the human-scored presence of AM. To construct the 'gold standard' data set, 96 10-min periods (equivalent to 16 h of continuous measurement) were randomly selected from each of the 9 data sets. These data were plotted in spectrograms with the same criteria used to plot Fig. 4(a). One investigator (PN) manually reviewed and classified each of the resulting 864 spectrogram segments into those containing ($N = 200$) versus not containing ($N = 664$) visually discernible AM for at least 50% of the time, as consistent with the IOA 'reference method'. The IOA 'reference method' was then employed to detect AM, using prominence ratios between 2.5 and 4.5, with steps of 0.25, and the resulting ROC curve is shown in Fig. 5(a). The standard IOA 'reference method' and prominence ratio cut-off of 4 showed high specificity (0.99) but poor sensitivity (0.09) for detecting 'gold standard' classified AM events compared to a prominence ratio of 3; which achieved a more reasonable balance of lower specificity (0.82) and higher sensitivity (0.62). A prominence ratio of 3 is closest to the top-left corner (0,1) of the ROC which represents an ideal classifier and so provides the best compromise between true and false positive rates [22]. The total area under the ROC curve (AUC) is 0.783 (95% confidence interval 0.751 to 0.815), which indicates that the IOA 'reference method' is a reasonably good discriminator of AM, but could potentially be improved. Fig. 5(b) shows an alternative method for measuring algorithm performance using the number of true and false positives for each value of the prominence ratio investigated. For each prominence ratio, the vector containing a binary

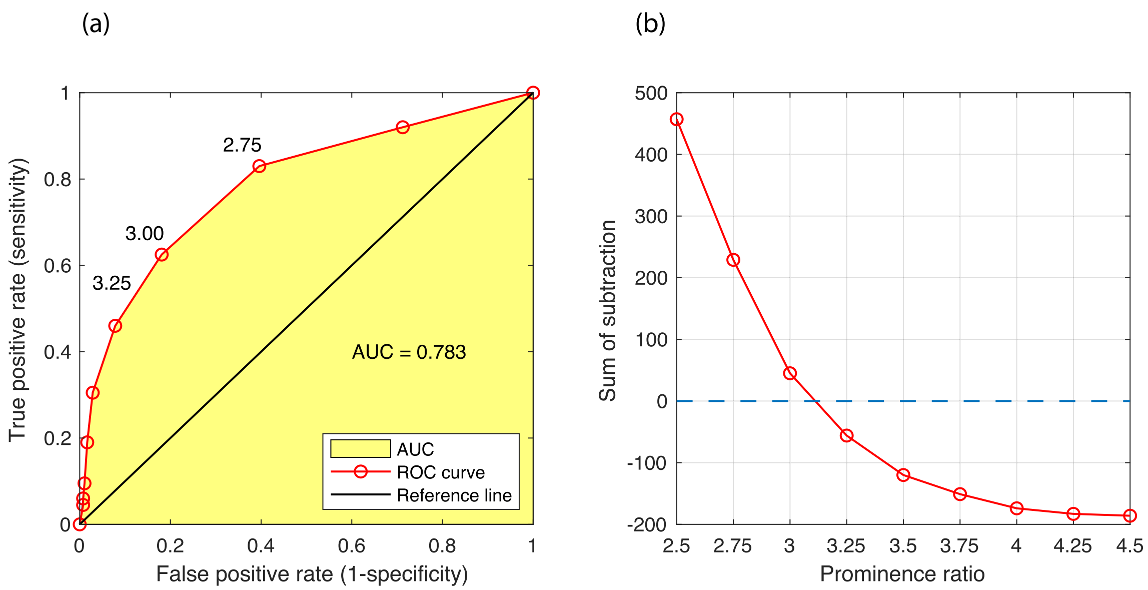

Fig. 5. Selection of the most suitable prominence ratio. (a) ROC curve analysis and (b) Sum of subtraction method.

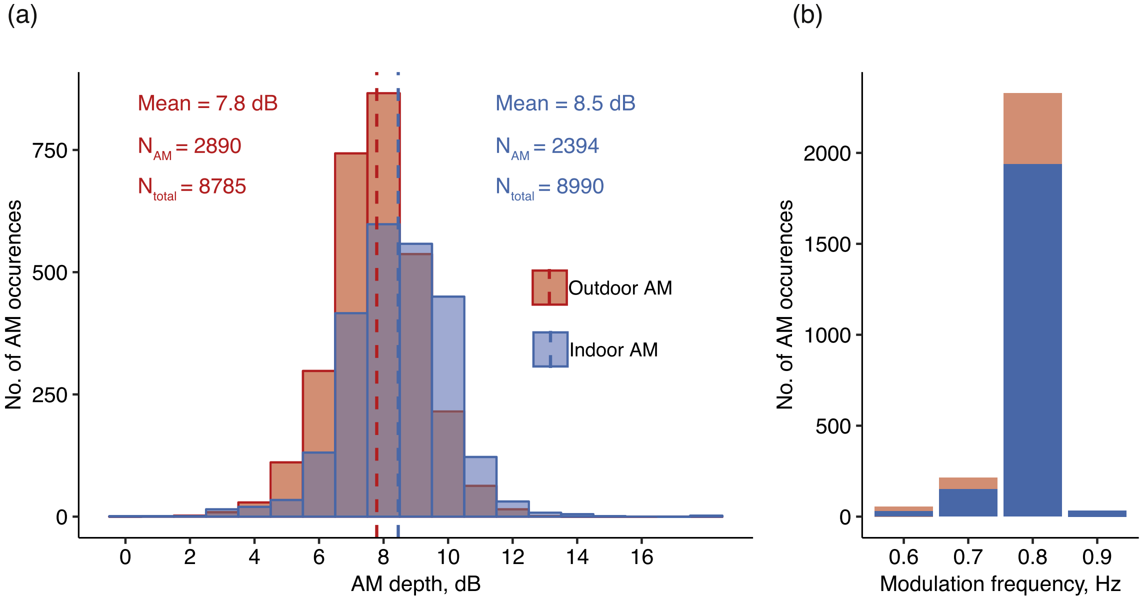

Fig. 6. AM analysis of outdoor (red) and indoor (blue) noise measured at 9 different residences located near a wind farm. The overlap between outdoor/indoor AM data is shown in purple. The 'AM correction' has not been applied. (a) Histogram of AM depth. (b) Histogram of modulation frequency. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

outcome for the presence/absence of AM from the 'gold standard' data set is subtracted from the corresponding vector obtained using the IOA 'reference method'. All elements in the resulting vector are summed and the entire process is labelled 'sum of subtraction' in Fig. 5(b). The results show that at low prominence ratios, there is a high rate of false positives whereas at high prominence ratios, there is a high rate of false negatives (i.e. non-detection of AM). The curve asymptotes near a value of −200 as this corresponds to the number of AM events in the 'gold standard' data set and thus indicates that few AM events were detected using high prominence ratios. The point closest to the blue dashed line, which reflects maximum true positives and true negatives, corresponds to a prominence ratio of 3, which is in agreement with the ROC analysis. Hence, a prominence ratio of 3 was selected for this study. Use of a higher cut-off, such as 3.5, could be used to reduce the false positive rate to more confidently 'rule-in' the presence of AM (i.e. higher specificity), but also increases the chances of missing AM (i.e. lower sensitivity). Similarly, use of a lower cut-off, such as 2.5, could be used to more confidently ensure that AM is not missed (i.e. higher sensitivity), but at the expense of falsely detecting AM in some cases (i.e. lower specificity). Ultimately AM classification methods need to both reliably detect the most annoying features of AM when AM is present, and reliably rule out AM when it is absent.

4. Results

4.1. Prevalence of AM

The results of applying the modified AM algorithm without the 'AM correction' for audibility to outdoor and indoor data measured at 9 different residences located near a wind farm are shown in Fig. 6. In Fig. 6(a), the number of AM events is plotted against the AM depth. It is evident that the mean AM depth for indoor noise was higher than that for outdoor noise. The reason for this is that the background noise in the 50 Hz 1/3-octave band was higher indoors, resulting in less AM events being detected, and thus a shift in the mean value. Given that the AM occurs in the 50 Hz 1/3-octave band, where the equal loudness contours are closer together than for mid-frequency noise, the fluctuation in loudness as a result of AM would be greater and hence potentially more annoying. On the other hand, to obtain a more realistic prediction of annoyance, the 'AM correction' should be applied, as outlined in Section 4.2. Fig. 6(b) shows that the modulation frequency was consistently 0.8 Hz, which corresponds to the expected blade-pass frequency when the wind turbines are operating at their nominal speed of 16.1 rpm [23].

4.2. Prevalence of audible AM

To determine which data points required an 'AM correction' to more accurately reflect the perception of AM depth, the tonal audibility was assessed as described in Section 3.1. Results of this assessment are shown in Fig. 7(a) and it can be seen that the tone was potentially audible both outdoors and indoors. In fact, the tone would have been audible in more cases than reflected in Fig. 7(a) since the tonal audibility assessment is based on mean values and therefore the peak audibility of an AM tone is higher.

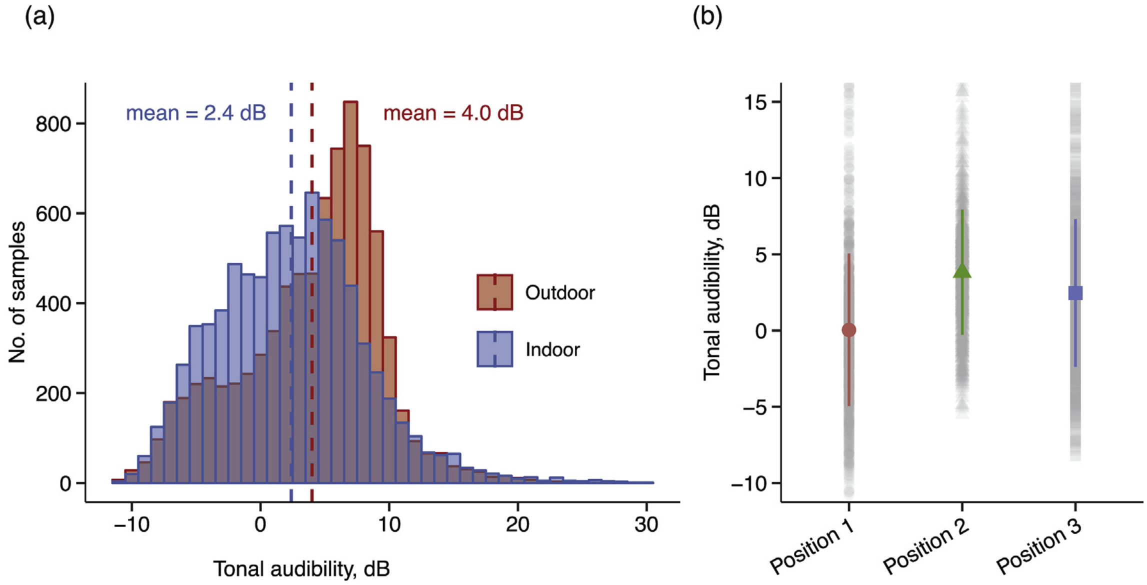

Fig. 7. (a) Histogram of tonal audibility measured outdoors (red) and indoors (blue) using the corner microphone. (b) Tonal audibility measured at 2 random locations within a room (Positions 1&2) and in the corner location (Position 3). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

The mean tonal audibility outdoors and indoors was 4 dB(A) and 2.8 dB(A), respectively. As the histogram for the outdoor data is negatively-skewed, the mode was much higher at 7 dB(A). The lower tonal audibility indoors may be the result of higher indoor masking noise.

An unexpected result was obtained when comparing the tonal audibility at various positions around the room for H5. It was found that the mean tonal audibility was highest at randomly chosen ‘Position 2’ in Fig. 7(b), where the microphone was mounted near the centre of the room at a height of 1.5 m. At the corner ‘Position 3’ in Fig. 7, the mean tonal audibility was slightly lower and therefore the results shown in Fig. 7(a) may not reflect worst case conditions. The reason that the tonal audibility is not necessarily highest in the corner is that the corner is an anti-node for all room response modes and therefore the masking noise in the critical band containing the tone would have been higher as well. At another randomly chosen location near the centre of the room at a height of 1.5 m, the mean tonal audibility was shown to be lower than the other two positions and therefore for consistency, the corner position was used in the tonal audibility assessment. However, these results indicate that it

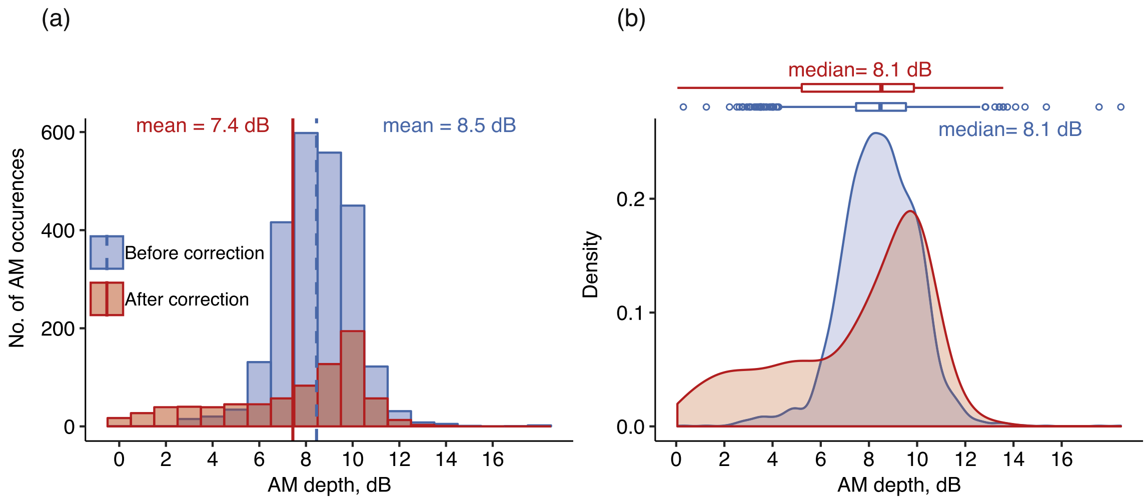

Fig. 8. Indoor noise measurements taken at 9 different locations near a wind farm before and after the ‘AM correction’ (blue and red, respectively). (a) Histograms of AM depth. (b) Probability Density Function of AM depth. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

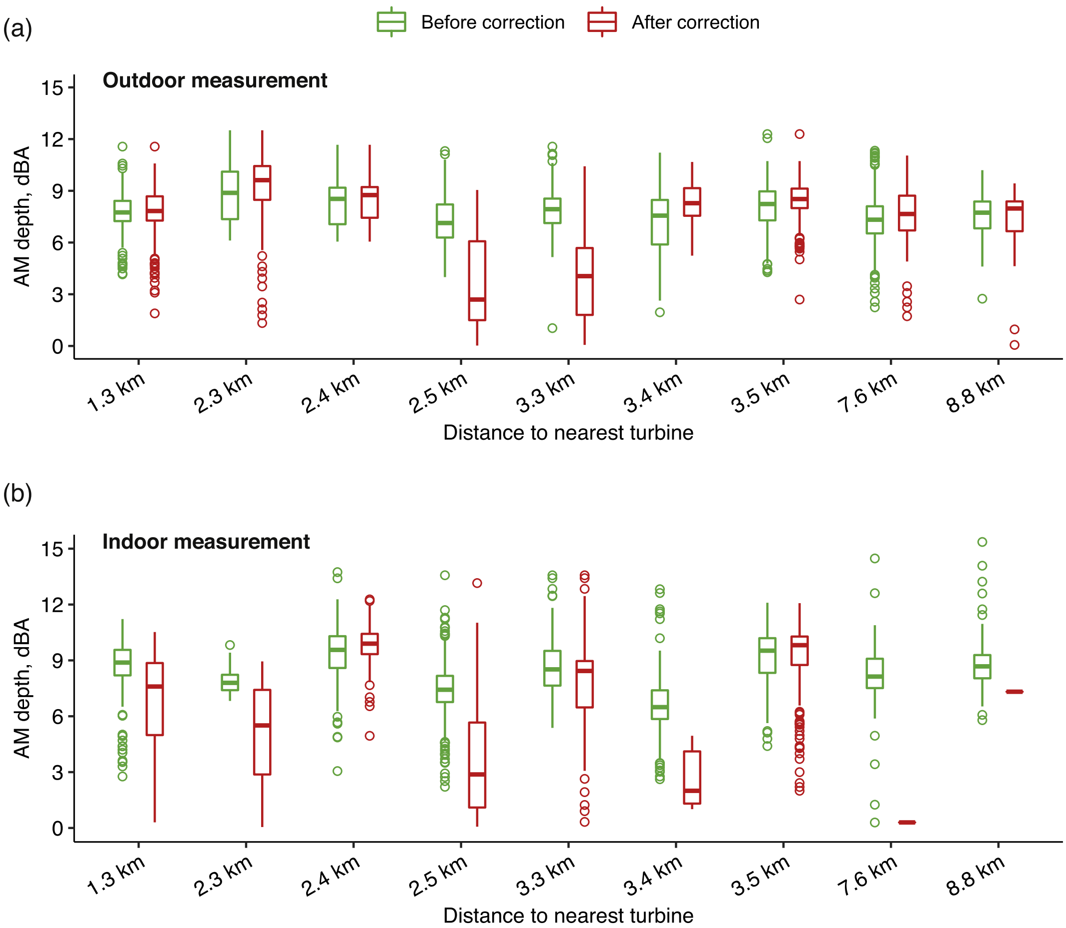

Fig. 9. Relationship between AM depth and distance from the wind farm before (green) and after 'AM correction' (red). (a) Outdoor measurement, (b) Indoor measurement. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

could be advantageous to involve the resident when selecting measurement positions when a tone is involved, since the corner position may not represent the worst case in this situation.

The results obtained after applying the 'AM correction' to the indoor data are shown in Fig. 8(a) and (b). It is evident that the 'AM correction' is necessary for a large number of data points, resulting in a reduction in the mean AM depth from 8.5 dB to 7.4 dB. This indicates that the tonal audibility at 46 Hz was often less than 0 dB, as shown in Fig. 7(a). The overall number of AM events is also much lower, indicating that a large proportion of detected AM events were entirely below the hearing threshold. Fig. 8(b) shows that the median AM depth is the same before and after correction but that the mode is higher after correction. Also, the distribution shape changes significantly and becomes negatively-skewed, which is expected as the 'AM correction' involves a subtraction only. Similar trends were observed for the outdoor data and thus the results are not presented here.

4.3. Relationship between distance from the wind farm and AM

Fig. 9(a) and (b) show uncorrected and corrected AM depth as a function of distance from the nearest wind turbine for data measured outdoors and indoors, respectively. There is no clear relationship between the AM depth and distance for both outdoor and indoor data before the 'AM correction' is applied. This is anticipated as the difference between the peak and trough SPL remains constant. Also, our previous analyses [17] have shown that the wind turbine signal is as high as 15 dB above ambient noise levels in the 50 Hz 1/3-octave band at a distance of 8.8 km from the nearest wind turbine, suggesting that masking in this frequency range may only occur during periods of low wind farm power output. In these cases, it is possible that the AM would not be detected as valid due to relatively high ambient levels. Differences in the AM depth measured at the various residences can be explained by differences in the positioning of the residences with respect to the wind farm. This affects the distance between the residence and the wind turbines other than the closest one. Also, the number of wind turbines that are orientated in a given direction with respect to the residence varies with both wind direction and residence position.

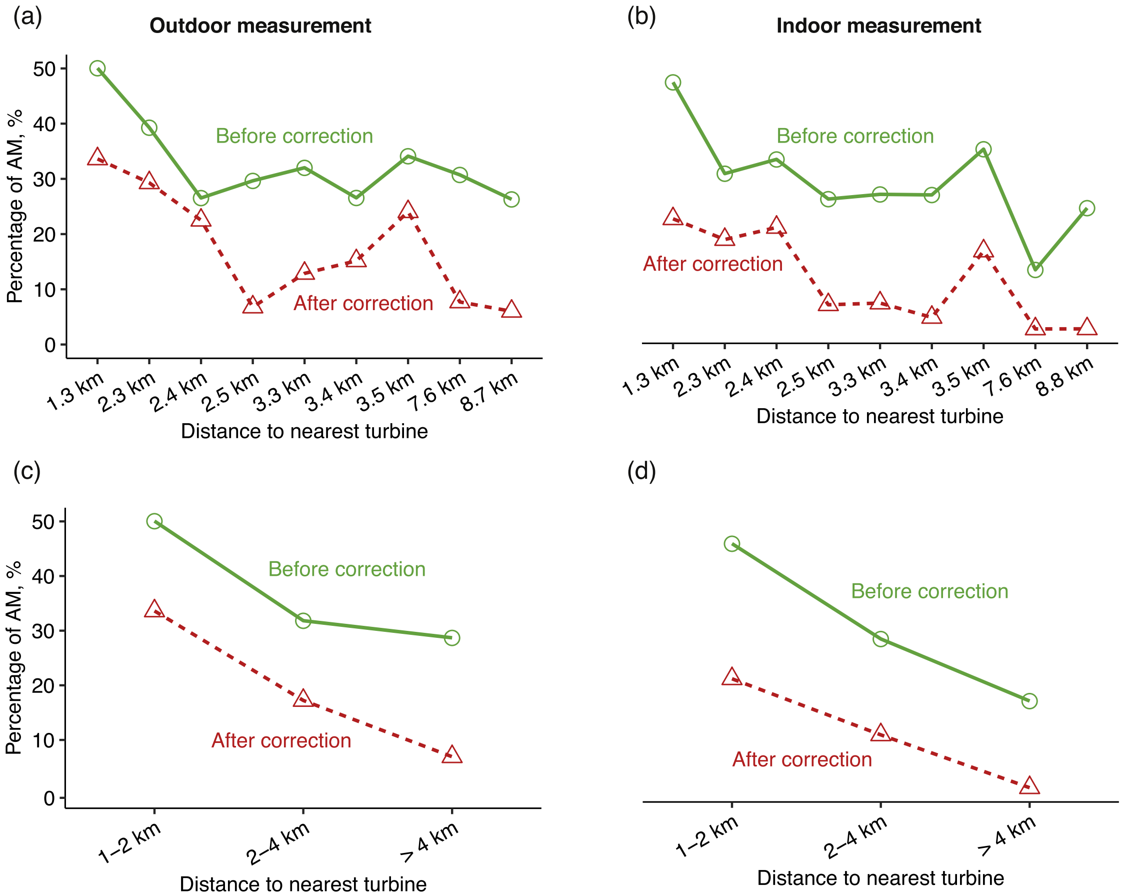

Fig. 10. Outdoor and indoor noise measurements taken at 9 different locations near a wind farm. (a, b) Relationship between the percentage of time that AM was present and the distance from the wind farm. (c, d) Relationship between percentage of time that AM was present and distance from the wind farm, where the results have been combined into three distance bins of 2 km width.

The AM depth is expected to reduce with distance when the 'AM correction' is applied, since tonal noise at 46 Hz is less likely to be audible at larger distances from the wind farm. However, this relationship is not evident in Fig. 9(a) and (b). The reason for this is that audibility of wind farm noise is dependent on the wind turbine power output and this was not the same during the measurements taken at each residence. In fact, the reduced tonal audibility and lower AM depth after 'AM correction' at 2.5 and 3.3 km in Fig. 9(a) may indicate that worst-case conditions, in terms of AM depth and audibility, were not captured at these residences. It is interesting to note that although the number of AM events is lower at 8.8 km relative to 1.3 km, the AM depth is similar outdoors both before and after the 'AM correction', as shown in 9(a). For the indoor data, there was only one instance of audible AM at 8.8 km but the associated AM depth was also similar to that measured at 1.3 km. The variation in the AM depth with distance for the indoor data after 'AM correction' shown in 9(b) can be attributed to differences in housing construction and orientation of the room relative to the wind farm. These factors affect the indoor SPL and hence audibility.

The large number of outliers, shown by the green and red open circles, in Fig. 9(a) and (b) is attributed to meteorological effects such as changes in wind direction, atmospheric stability and atmospheric turbulence. However, the number of outliers is small (10%) compared to the total number of data points, from all locations, that were used for the averages. Fewer outliers are associated with the red data points as the 'AM correction' reduces the overall number of AM events, however, the actual percentage of outliers remains the same.

Fig. 10(a) and (b) provide insight into the percentage of time that AM occurred at each residence both outdoors and indoors. These numbers should be interpreted with caution due to differences unrelated to distance such as: size of the data set, position of the residence with respect to the wind farm, worst case atmospheric conditions for wind farm AM not captured, housing construction, room orientation relative to the wind farm and room size. The latter three characteristics are only relevant when considering the results after 'AM correction'. Valid AM was detected less often indoors, which may be related to background noise, as some of the residences (but not the measurement room) were occupied during the measurement period.

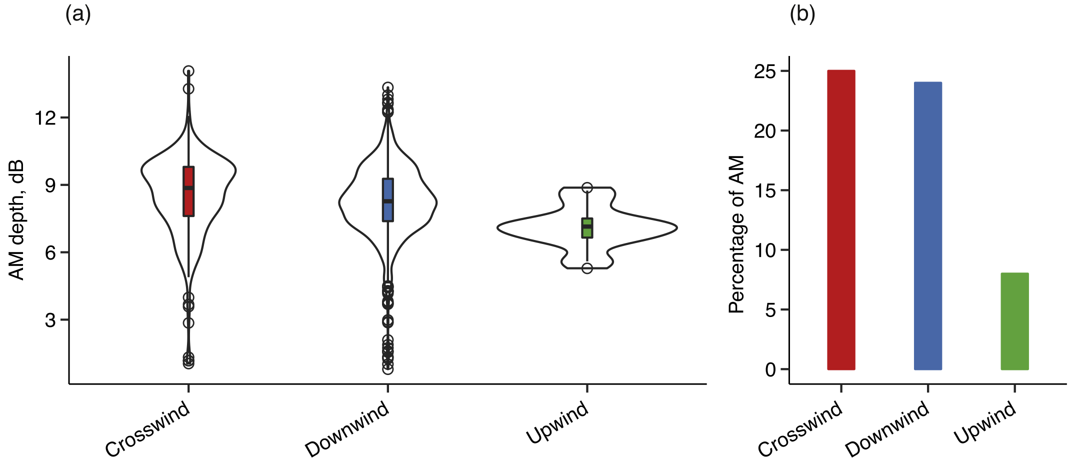

Fig. 11. Indoor noise measurements taken at 9 different locations near a wind farm. (a) Bean plot of AM depth against hub-height wind direction. (b) Percentage of time that AM was present during various hub-height wind directions.

Fig. 10(a) and (b) indicate that tonal AM was present outdoors between 25 and 50% of the time and indoors between 14 and 46% of the time. Applying the ‘AM correction’ results in fewer AM events, however, the tonal AM is shown to be audible outdoors and indoors up to distances of 3.5 km for as much as 24 and 16% of the time, respectively. At distances of 7.6 and 8.8 km, it is expected that the tonal AM would generally not be audible for a person with hearing in the normal range. The tonal AM could be audible at these distances for a small proportion of the population that have sensitive hearing (i.e. 2.5% of the population have a hearing threshold that is 10–12 dB less than the ISO 389-7 [15] threshold curve [14]). The results at 2.5 and 3.5 km are not considered representative for the reasons discussed in the paragraphs above. Therefore, to further investigate the relationship between percentage of AM and distance, Fig. 10(c) and (d) were plotted. To reduce the variance between measurement locations in this figure, the data have been categorised into three groups; 1–2, 2–4 and > 4 km. A clear trend of reducing AM with distance is apparent from these figures both before and after the ‘AM correction’. In fact, it is shown that the occurrence of AM may be reduced by a factor of two after a distance of 2 km. A lower AM detection rate at distances greater than 2 km may be associated with a reduced signal-to-noise ratio, particularly during periods of low wind farm power output.

4.4. Wind farm operating conditions and AM

Fig. 11(a) provides insight into the relationship between AM depth and hub-height wind direction for the indoor data without ‘AM correction’. It can be seen that the mean AM depth is similar for crosswind and downwind conditions but slightly lower for upwind conditions. Also, the distribution shapes vary such that there are more AM events with a higher AM depth under crosswind conditions. Fig. 11(b) indicates that the percentage of time that AM was present during each wind direction is similar for downwind and crosswind directions but much lower for the upwind direction. For the entire data set, crosswind, downwind and upwind conditions occurred 17%, 80% and 3% of the time, respectively. For the results shown in Fig. 11, the wind direction is defined based on the line joining the nearest wind turbine to the receiver with a margin of ±45°. This is an approximation as wind turbines adjacent to the nearest wind turbine are orientated differently for a given wind direction. On the other hand, since the wind farm layout is approximately linear in the North-South direction and most of the residences are located to the East and West of the wind turbines, the direction categories are usually applicable to the adjacent wind turbines as well.

The relationship between wind farm power output, hub-height wind speed and the presence of AM indoors is presented in Fig. 12(a) and (b). In these figures, the grey and green bars correspond to periods of no AM and valid AM, respectively. The line plot indicates the percentage of time that AM was present for the entire measurement period. As shown in Fig. 12(a), a large number of measurements were taken when the wind farm was operating at a percentage power capacity of <5% as there were several periods during which the wind speed was less than the cut-in wind speed of 3.5 m/s [23].

Fig. 12(a) and (b) indicate that the highest number of AM events is associated with a wind farm percentage power capacity and hub-height wind speed of approximately 40% and 10 m/s, respectively. After applying the ‘AM correction’, the peak in the percentage of time that AM was present is less distinct and it is more useful to consider a range of operating conditions. Referring to the dashed line in Fig. 12(a) and (b), it can be seen that audible tonal AM was present indoors for at least 20% of the time when the hub-height wind speed at the nearest wind turbine was between 11 and 14 m/s and the percentage power capacity was between 40 and 85%.This indicates that AM is more likely to be detected when the wind turbines are operating below their maximum rated power. It is unclear if this is a source characteristic or an environmental effect, as the background

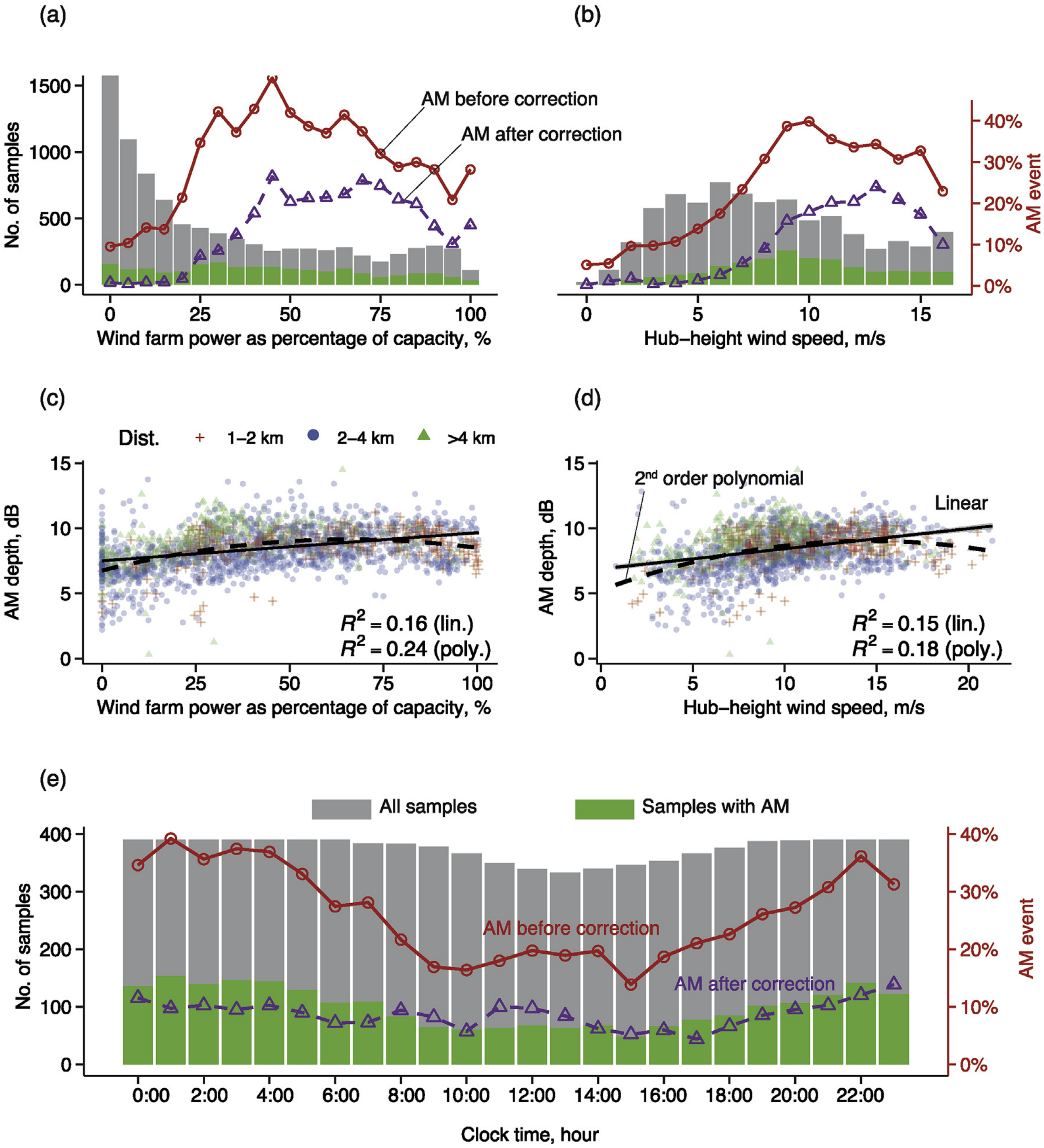

Fig. 12. Indoor noise measurements taken at 9 different locations near a wind farm. (a) Number of AM events and percentage of time that AM was present before and after 'AM correction' against wind farm percentage power capacity, (b) Number of AM events and percentage of time that AM was present before and after 'AM correction' against hub-height wind speed, (c) AM depth against wind farm percentage power capacity, where the data has been separated into 2 km-wide distance bins and the regression fits applied to all data, (d) AM depth against hub-height wind speed, where the data has been separated into 2 km-wide distance bins and the regression fits applied to all data, (e) Number and percentage of time that AM was present as a function of time of day.

noise may also be higher due to wind noise at the receiver when the wind farm is operating at higher power capacities. This could result in non-detection of AM, even though it may be present.

In Fig. 12(c) and (d), the AM depth without the correction for audibility is plotted against the percentage power capacity and wind speed at hub height, respectively. There is a poor correlation between the AM depth and percentage power capacity as well as hub-height wind speed, as indicated by the low R^2 values obtained for both linear and second order polynomial regression fits. However, according to the second order polynomial regression fit, which has a higher R^2 value, there is a general trend that the AM depth increases slightly up to a percentage power capacity and wind speed at hub height of 70% and 15 m/s, respectively, after which it decreases slightly. Limited improvement in the correlation between AM depth and percentage power capacity as well as hub-height wind speed is obtained when the data are separated into 2 km-wide distance bins. This is indicated by the large scatter in the data points for each distance bin shown in Fig. 12(c) and (d). Hence, the large variation in AM depth for the various power capacities and wind speeds at hub height is most likely attributable predominantly to meteorological effects. Detection of valid AM at a power output of 0% can be explained by the 18% false positive rate using a prominence ratio of 3, as shown in Fig. 5(a).

Fig. 12(e) shows that tonal AM occurs much more frequently during the night-time, particularly between 10pm and 5am. In fact, compared to daytime hours from 9am to 5pm, there are twice as many AM events during the night-time. This is in agreement with the findings of Van den Berg [24] and supports the idea that AM is more likely to occur during stable conditions, which occur more often at night-time. A larger proportion of AM events that occurred during the daytime were audible compared to the night-time. A possible explanation is that inaudible AM events are less likely to be detected during the daytime when the background noise level is higher. Approximately 10% of the total measurement time at night-time contained audible AM. However, at residences located up to 3.5 km from the wind farm, audible AM occurred for as much as 22% of the measurement time at night-time.

5. Conclusions

Low-frequency tonal AM with a modulation frequency consistent with the expected blade-pass frequency, has been measured between 1 and 9 km from a wind farm. The mean AM depth was 8.5 dB for noise measured indoors, slightly higher than the mean of 7.8 dB which was measured outdoors. On the other hand, when the tonal audibility was taken into account, the mean AM depth reduced to 7.4 dB for noise measured indoors and there was a similar reduction for the outdoor data.

Despite the relatively low noise levels, it was found that the tonal AM could be audible both outdoors and indoors up to distances of 3.5 km from the nearest turbine in the wind farm. The tonal audibility was higher outdoors than indoors, possibly due to higher indoor masking noise relative to the tonal noise. The indoor tonal audibility was dependent on the microphone location and the highest tonal audibility was not measured in the corner. This is because both the tonal level and masking noise are higher in the corner position since it is an anti-node for all room response modes. The relatively higher masking noise at the corner location can therefore give rise to a relatively lower tonal audibility.

There was no clear relationship between the AM depth and distance from the wind farm before the 'AM correction' for audibility was applied. This is expected, as AM depth is not affected by distance, and masking of the wind farm noise by ambient noise in the 50 Hz 1/3-octave band can be negligible, even at distances as far as 8.8 km from the nearest wind turbine. Due to differences in the power output that occurred during the measurement period at each residence, it was not possible to draw conclusions about the relationship between AM depth and distance from the wind farm after 'AM correction'. However, for the outdoor data, it was observed that the AM depth after correction was similar at the various distances. The percentage of time that AM was present was shown to reduce significantly with distance from the wind farm both before and after the 'AM correction'. This observation is consistent with noise attenuation during propagation, which results in a decrease in the wind farm noise level and hence, a reduction in tonal audibility and valid AM. Tonal AM was shown to be audible outdoors and indoors up to distances of 3.5 km for as much as 24 and 16% of the time, respectively. At distances of 7.6 and 8.8 km, the results indicate that the tonal AM would generally not be audible for a person with hearing in the normal range.

The percentage of occurrence and AM depth were both found to be higher during downwind and crosswind conditions. However, under crosswind conditions, the AM depth was higher for a larger number of AM events. The AM occurred most often when the wind farm percentage power capacity was approximately 40% both before and after the 'AM correction' was applied to account for the tonal audibility. Audible tonal AM was shown to be present indoors for at least 20% of the time for the entire data set when the hub-height wind speed at the nearest wind turbine was between 11 and 14 m/s and the percentage power capacity was between 40 and 85%.

Tonal AM occurred most often at night-time, during the hours between 10pm and 5am. Approximately 10% of the total measurement time at night-time contained audible AM. At residences located up to 3.5 km from the wind farm, audible AM occurred for as much as 22% of the time at night. This has important implications for possible sleep disruption from wind farm AM, particularly as ambient noise levels in rural South Australia can be as low as 15 and 5 dBA, outdoors and indoors, respectively. Further research is needed to determine the prevalence of AM on an annual basis. Further work is also needed to quantify the annoyance and sleep disturbance potential of this type of tonal AM.

Acknowledgements

The authors gratefully acknowledge financial support from the Australian Research Council, Projects DP120102185 and DE180100022 and fellowship FT120100510 and the National Health and Medical Research Council, Project 1113571. We also acknowledge Mahmoud Alamir's assistance in developing the AM detectison code.

References

[1] Gorica Micic, Branko Zajamsek, Leon Lack, Kristy Hansen, Con Doolan, Colin Hansen, Andrew Vakulin, Nicole Lovato, Dorothy Bruck, Ching Li Chai-Coetzer, et al., A review of the potential impacts of wind farm noise on sleep, Acoust Aust. 46 (1) (2018) 87–97.

[2] U.K. Renewable, Wind Turbine Amplitude Modulation: Research to Improve Understanding as to its Cause and Effect, Technical report, Renewable UK, 2013.

[3] B. Schffer, S.J. Schlittmeier, R. Pieren, K. Heutschi, M. Brink, R. Graf, J. Hellbrck, Short-term annoyance reactions to stationary and time-varying wind turbine and road traffic noise: a laboratory study, J. Acoust. Soc. Am. 139 (5) (2016) 2949–2963.
[4] S. Lee, K. Kim, W. Choi, S. Lee, Annoyance caused by amplitude modulation of wind turbine noise, Noise Control Eng. J. 59 (1) (2011) 38–46.
[5] C. Ioannidou, S. n Santurette, C. Jeong, Effect of modulation depth, frequency, and intermittence on wind turbine noise annoyance, J. Acoust. Soc. Am. 139 (3) (2016) 1241–1251.
[6] D. Bowdler, M. Cand, M. Hayes, G. Irvine, Wind turbine noise amplitude modulation penalty considerations, Proc. Inst. Acoust. 40 (Pt. 1) (2018) 253–261.
[7] R. Perkins, B. Berry, C. Grimwood, S. Stansfeld, A review of research into the human response to amplitude modulated wind turbine noise and development of a planning control method, in: INTER-NOISE and NOISE-CON Congress and Conference Proceedings, vol. 253, Institute of Noise Control Engineering, Hamburg, Germany, 2016, pp. 5222–5233.
[8] J. Bass, M. Cand, D. Coles, R. Davis, G. Irvine, G. Leventhall, T. Levet, S. Miller, D. Sexton, J. Shelton, Discussion Document: Methods for Rating Amplitude Modulation in Wind Turbine Noise, Technical report, IOA noise working group (wind turbine noise): amplitude modulation working group. 2015. Available at: https://www.ioa.org.uk/sites/default/files/AMWG20Discussion20Document.pdf.
[9] J. Bass, M. Cand, D. Coles, R. Davis, G. Irvine, G. Leventhall, T. Levet, S. Miller, D. Sexton, J. Shelton, Final Report: A Method for Rating Amplitude Modulation in Wind Turbine Noise. Technical report, IOA Noise Working Group (Wind Turbine Noise): Amplitude Modulation Working Group, 2016. Available at: https://www.ioa.org.uk/sites/default/files/AMWG20Final20Report-09-08-2016_1.pdf.
[10] A. Fukushima, K. Yamamoto, H. Uchida, S. Sueoka, T. Kobayashi, H. Tachibana, Study on the amplitude modulation of wind turbine noise: Part 1physical investigation, Internoise (2013) 2013.
[11] S. Yokoyama, S. Sakamoto, H. Tachibana, Perception of low frequency components contained in wind turbine noise, in: 5th International Meeting on Wind Turbine Noise, Denver, Colorado, 2013.
[12] K. Hansen, B. Zajamek, C. Hansen, Identification of low frequency wind turbine noise using secondary windscreens of various geometries, Noise Control Eng. J. 62 (2) (2014) 69–82.
[13] Australian Energy Market Operator, Wind Farm Power Output Data, 2015, http://www.nemweb.com.au/REPORTS/ARCHIVE/DispatchIS_Reports/.
[14] C.H. Hansen, C.J. Doolan, K.L. Hansen, Wind Farm Noise: Measurement, Assessment and Control, 1 edition, John Wiley & Sons Ltd, 2017.
[15] ISO389-7, Acoustics: Reference Zero for the Calibration of Audiometric Equipment Part 7: Reference Threshold of Hearing under Free-Field and Diffuse–Field Listening Conditions, 2005.
[16] IEC61400-11, Wind Turbines Part 11: Acoustic Noise Measurement Techniques, vol. 3, 2012. 0.
[17] K. Hansen, B. Zajamek, C. Hansen, Comparison of the noise levels measured in the vicinity of a wind farm for shutdown and operational conditions, in: Internoise2014, Melbourne, Australia, 2014.
[18] NZS 6808, in: Acoustics - wind farm noise, 2010.
[19] J.N. McCabe, Detection and quantification of amplitude modulation in wind turbine noise, in: Fourth International Meeting on Wind Turbine Noise, Rome, Italy, 2011.
[20] J. Cooper, T. Evans, Automated detection and analysis of amplitude modulation at a residence and wind turbine, in: Acoustics 2013, Victor Harbor, Australia, 2013.
[21] T. Fawcett, An introduction to roc analysis, Pattern Recogn. Lett. 27 (8) (2006) 861–874.
[22] N.J. Perkins, E.F. Schisterman, The inconsistency of optimal cut-points using two roc based criteria, Am. J. Epidemiol. 163 (2006) 670–675.
[23] Vestas, General Specification V90 3.0 MW VCRS, 2006. Available at: https://report.nat.gov.tw/ReportFront/PageSystem/reportFileDownload/C09503816/002.
[24] G.P. Van den Berg, The beat is getting stronger: the effect of atmospheric stability on low frequency modulated sound of wind turbines, J. Low Freq. Noise Vib. Act. Control 24 (1) (2005) 1–24.