Special Noise Character in Noise from Wind Farms

Valeri V. LENCHINE[1]; Jonathan SONG[2]

SA Environment Protection Authority, Australia

ABSTRACT

Noise produced by wind farms may exhibit a multitude of different noise characters, ranging from amplitude modulation, tonality and low frequency noise. The presence of the noise characters is able to increase the annoyance factor caused by a noise source significantly. A penalty to the noise levels is applied in accordance with some regulations when a noise character is detected. This paper discusses a noise character that can be described as "rumbling" that was detected during a long term monitoring program which was conducted in an area adjacent to a wind farm. The objective assessment of the data and subjective assessment of relevant audio records were performed to analyze the effect. The frequency spectra of the rumbling events indicate connection of the effect with low frequency noise and one of the low frequency components. The character was detected at low noise levels and might not be audible to a typical listener, however it is possible the character may cause an increased annoyance to people who have a higher sensitivity to the lower frequencies. Environmental conditions were also considered when discussing the occurrence of this noise character. The possible mechanism of the rumbling effect is suggested in the paper. The wind farm manufacturers may have to consider potential for low frequency impact of wind turbines and presence of prominent components at the design stage.

Keywords: Noise Character, Wind Farm, Rumbling I-INCE Classification of Subjects Number(s): 14.5.4, 52.5, 63.2

1. INTRODUCTION

Noise is one of the aspects that is taken into account for new and existing wind farm developments when assessing potential environmental impact. Multiple regulatory documents and research papers recommend noise assessment procedures for receivers situated in areas adjacent to wind farms (1, 2, 3). Noise emission from a well serviced wind turbine may have one or more noise characters such as amplitude modulation ("swish"), tonality or low frequency content. Some regulatory documents recognize the presence of these noise characters during wind farm operation and address this by assigning stricter noise limits compared to other types of noise sources (2). Other regulatory procedures suggest penalties to be applied to the measured noise descriptors (1, 3). Noise limits applicable to wind farms are normally very low and it is very difficult to suggest reliable methods of the noise characters assessment. The use of subjective assessment can be very important in deciding if a noise character is excessive or not.

Sometimes residents living around wind farms report unusual noise effects that may be attributable to the operation of wind turbine generators (WTGs). They are not easily classified into one of the typical noise characters as mentioned above. This paper presents the investigation of one such effect detected during a long term noise monitoring program performed at one of the modern wind farms. Objective assessment of acquired noise descriptors along with analysis of available audio records are utilized to characterize noise effect which is described as "rumbling". The paper also considers environmental conditions and the results of the noise measurements that may be linked to the effect. The rumbling character was identified by listening to the amplified records and detected at low overall sound pressure levels (SPLs).

1 valeri.lenchine@epa.sa.gov.au

2 jonathan.song@epa.sa.gov.au

2. RUMBLING CHARACTERISTIC IN WIND FARM NOISE

2.1 Detection of a special character

For the duration of this long term noise monitoring program, residents living in the vicinity of the wind farm were actively providing noise diaries based on their experiences. Typically, diary entries supplied by the respondents could not be attributed to the wind farm operation. Only a small fraction of the entries enabled identification of the wind farm noise. During these periods, some of the entries mentioned a special noise character that can be described as "rumbling" and may have originated from the wind farm. Presence of this character has been confirmed through analysis of amplified audio records at three monitoring locations separated by significant distances. Association of this effect with operation of the wind farm was confirmed by the data and audio records during one of the start/stop events. The effect was present before and after the wind farm shutdown and was not detected during the non-operational period. This effect could be detected at low overall noise levels of around 30dB(A) or below.

2.2 Subjective assessment of the character

Auditory mechanisms of perception of different noise characters typically consider a variety of stimulus such as tones and their masking, amplitude and phase modulation, rhythm etc. (4). Some researchers attribute the noise character in wind turbine noise described as "thumping" to excessive amplitude modulation of the noise at the blade pass frequency (5). Comparison of the available audio records with the "classical" effects of amplitude and frequency modulation, which causes sensations of fluctuation strength, roughness and sharpness, sometimes evokes similarities with the wind farm audio records, but the "rumblings" that can be heard from audio records have distinct differences. This may be connected to a lower frequency imbalance of the noise spectrum. This is considered in more detail later.

Audio records with this "rumbling" character could be detected at 3 different locations. Relatively clear audio records of this "rumbling" character were identified at only one location. The effect at this location was more distinct inside the house when not affected by extraneous noises. This rumbling was more perceivable outside when the background noise levels are low, which typically occurs during night or early morning hours. Rumbling outside of the houses was sometimes accompanied by a slight modulation character that is associated with wind farm noise.

2.3 Environmental conditions and monitoring places

As was previously noted, it was possible to detect the rumbling effect by analyzing amplified audio records during periods reported by the respondents. Analysis of environmental conditions corresponding to the presence of this "rumbling" character at the monitoring location indicates that the effect occurs during downwind propagation from the nearest WTGs at relatively high wind speeds (8m/s and above as reported from the hub height sensors).

The three monitoring locations where the rumbling was detected are situated at distances approximately 2.5km from the nearest turbine. The wind farm has a line layout where a row of turbines is placed along the top of a ridge. The buffer between the monitoring locations and the wind farm is mainly occupied by agricultural lands with sparse trees and other vegetation.

The effect was not detected at other monitoring places, one of which was located at approximately half of the separation distance and another one at a distance about 3.5km from the wind farm.

The hypothesis about excessive generation of noise characters when turbines operate in an aerodynamic wake of other turbines is not confirmed in this case. Orientation of the WTGs during the downwind conditions for all of the three locations does not correspond to the situation when turbulence from one of the turbines is transported to another turbine.

3. ACOUSTIC DESCRIPTORS AND SPECTRAL PATTERNS

3.1 Characteristics of the wind turbine generator

The wind farm area, where the rumbling was detected, is equipped with Vestas V90-3MW turbines which have operating rotor frequencies in the range of 8.6 to 18.4rpm. They have been operated in Mode "0" during the monitoring period. This mode is the most efficient in terms of electricity generation but it is also accompanied with the highest noise emission (6). Acoustical tests of the turbine did not reveal the presence of tones (7, 8). However, a report containing information about the spectral content at lower frequencies (8) indicates the presence of prominent 1/3 octave component at mid to high wind speeds.

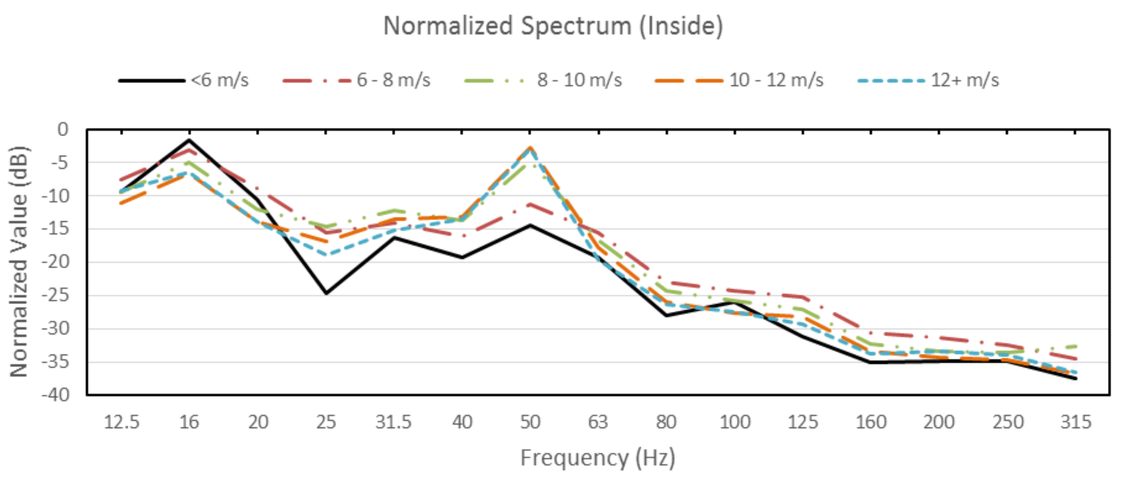
3.2 Possible reasons of the rumbling effect

The preliminary information suggests that the rumbling character is linked to the prominency of the 50Hz component. This component was not prominent at another site situated closer to the wind farm (approx. 1.3km) and noise there did not exhibit this rumbling character.

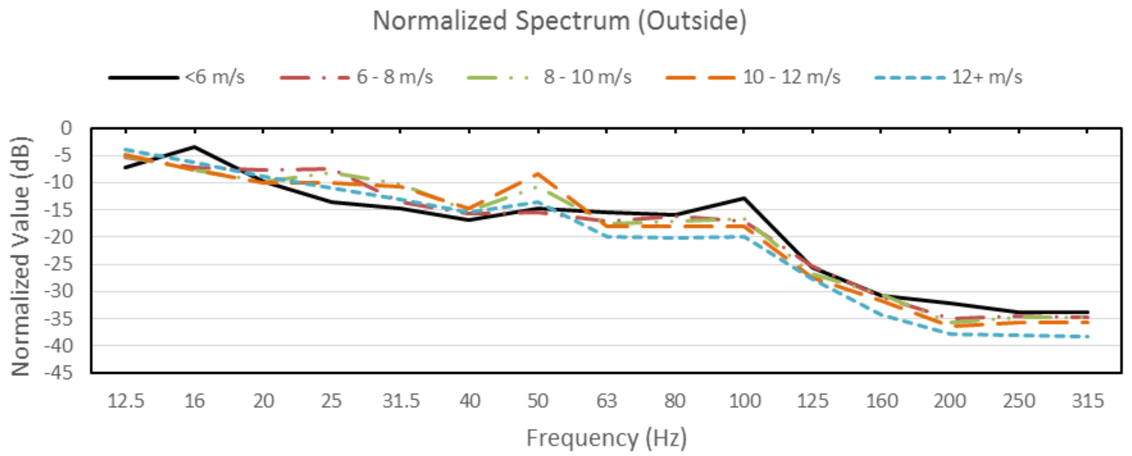
Analysis of the data did not allow for detection of a clear modulation pattern when the effect was most distinct (even for band-pass, low- or high- pass filtered data). Typically the effect reported is associated with low frequency noise, therefore the analysis is concentrated on the frequency content of the spectrum.

Vasudevan and Gordon (9) explored complaints expressed by a group of listeners which is similar to that presented in this study. They described a "throbbing" effect that was caused by noise with significant low frequency content between 20 and 100Hz and a particular roll-off rate at low frequencies (about 7-8dB/octave). Results of the relevant 1/3 spectrum data did not show similarity of the spectra shapes.

Normalized spectrum for the location where this effect was most distinct is shown in Figure 1. The data represents energy averages for particular wind speed ranges (10min averages measured at the nacelle of nearest WTG) at downwind conditions. It could be seen that the 50Hz component becomes more distinct at wind speeds above 8m/s which coincides with appearance of the rumbling character.



(a)



(b)

Figure 1- Normalized averaged 1/3 octave spectrum measured (a) inside and (b) outside the house

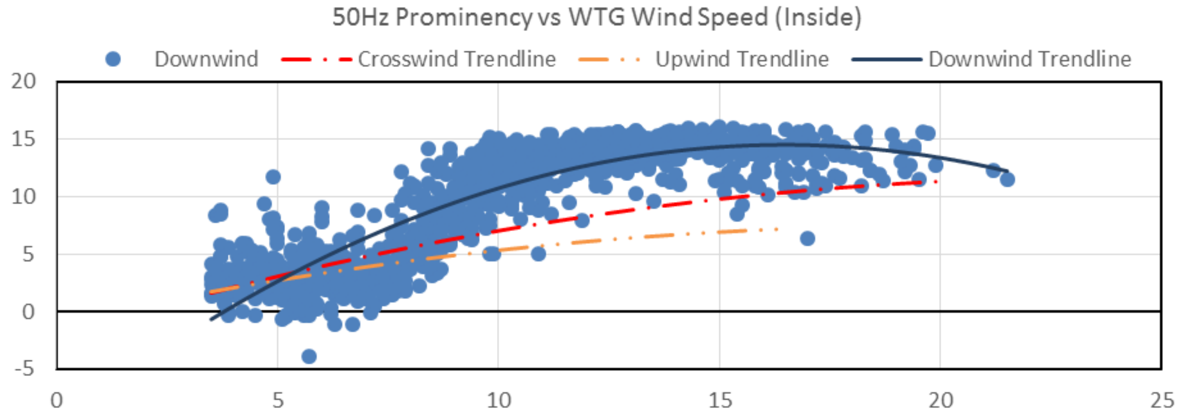
Prominency of the component can be investigated in a manner similar to assessment of tonality suggested in some standards (1,10):

$$P = L_i - 0.5(L_{i-1} + L_{i+1}), \quad (1)$$

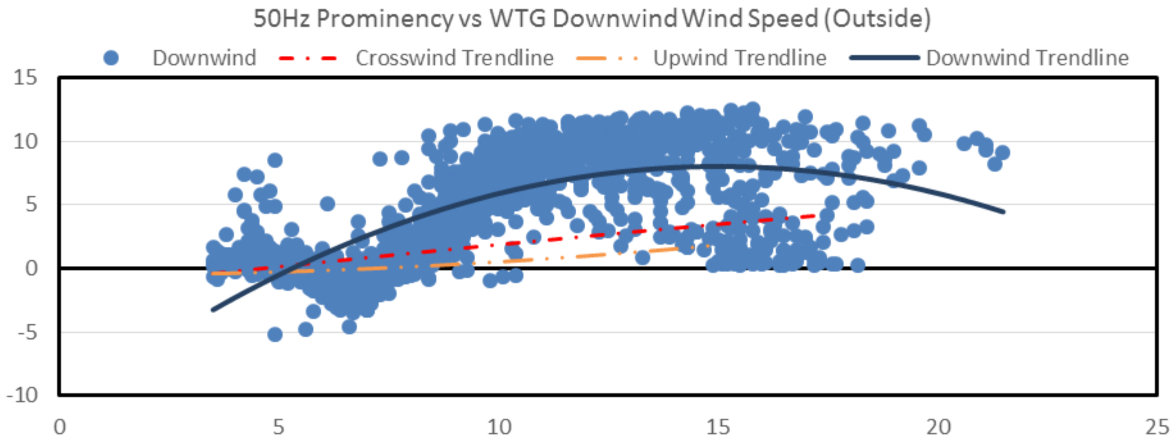
where L_i is the magnitude of the 1/3 octave component, L_{i-1} and L_{i+1} are the magnitudes of adjacent 1/3 octave components.

Analysis of the 50Hz component prominency for the location with most distinct effect versus the WTG wind speed shows a complex dependence (Figure 2) with indoor prominency marginally greater than outdoor values at high wind speeds and typically exceed 10dB. The statistical polynomial trendlines shown in Figure 2 for downwind conditions are significantly higher than for crosswind and even more so for upwind conditions when compared.

Prominency of this low frequency 50Hz component correlates well with subjective assessment of the audio records when the rumbling is present. Therefore this is considered as one of major hypothesis for the origin of the rumbling effect.



(a)



(b)

Figure 2- Prominency of 50Hz 1/3 octave component and corresponding polynomial fits (a) inside and (b) outside the house

3.3 Methods of rumbling assessment

Earlier works regarding presence of rumbling that were related to assessment of low frequency noise were mainly performed for assessment of noise from HVAC systems. It was based on the concept of low frequency imbalance. Implementation of this concept for objective assessment of rumbling is based on comparison of levels in the low frequency span (31.5-250Hz octaves) with the higher frequency span (500-8000Hz octave central frequencies). The method used for rumbling assessment is suggested in work (11). However, it was not directly applicable to the considered situation since the higher frequency content when the rumbling was detected in the amplified audio records is too low (typically below 25dB). The ratio between the high frequency content and low frequency content, when compared within the rumble evaluation chart, lays outside of the designated “no rumble”, “rumble possible” or “rumble expected” zones. Modification of method suggested in (11) simplifies the approach and suggests that the noise may be “rumbly” if level difference between the low frequency and higher frequency content exceeds 30dB(12). This difference sometimes exceeds 35dB for periods with most distinct rumbling.

Some studies referenced in work (13) suggest that rumbling is perceived when difference between unweighted and A-weighted SPL is above 20dB and when the A-weighted SPL is low, listeners have an increased sensitivity to 30-50Hz frequencies, which is similar to the case under consideration. During the most prominent rumbling events recorded throughout the monitoring period, the unweighted and A-weighted difference of levels exceeded 30dB and the spectrum comprised of a prominent component at around 50Hz.

Broner in research (13) suggested the use of “Quality Assessment Index” (QAI) for evaluation of potential problems in perception of noise. QAI represents the maximum difference in deviations from applicable RC-curves (14) calculated for three frequency spans. The measured levels were too low to correspond to any of the RC Mark II curves (the lowest curve is RC25). Analysis of data corresponding to the rumbling periods performed for RC25 curve or extrapolated RC15 curve indicates that QAI is below 20, which means “neutral subjective response” in accordance with recommended RC or QAI criteria (13). It should be noted that analysis of the spectral data versus RC chart does not evoke possibility of perceivable vibration since the measured levels were below the recommended limits (14).

Only assessment in accordance with (12) indicates potential for the rumbling effect. However it is difficult to accept that low frequency spectral imbalance as the only cause of the rumbling during the wind farm operation. Audio records with the rumbling character have been band pass filtered within frequencies corresponding to 1/3 octave band with 50Hz central frequency. The audio still evoked the sensation of rumbling. However, there were differences with the original noise. It emphasizes the importance of temporal fluctuations in generation of the rumbling character. It was not possible to get a reliable estimate of the modulation depth utilizing methods explored in work (15) (even for the band pass filtered signals). Wavelet analysis of relevant SPL time histories (16) typically brings average estimates of the modulation depths below 2dB. Amplitude modulation with the modulation depth below 3dB should not cause sensation of fluctuation strength in accordance with work (4). However more recent investigations dedicated to perception of amplitude modulated sound from wind turbines (15) show that even a small modulation of noise (modulation depth around 1dB) can be discernible by a listener. Therefore the hypothesis about influence of SPL variations on the rumbling effect in absence of significant masking noise is plausible.

3.4 Possible perception mechanisms causing rumbling

The widely used IEC standard (17) for assessment of acoustical characteristics of wind turbines contains an elaborate procedure for evaluation of possible tones. The tone’s audibility is based on comparison of the tone level with the masking level in the critical frequency band centered at the frequency of the possible tone. The standard uses this formula for critical bandwidth from earlier psychoacoustic investigations (4):

$$\Delta f_{cr} = 25 + 75 \cdot (1 + 1.4\left[\frac{f_c}{1000}\right]^2)^{0.69}, \quad (2)$$

where f_c is the frequency of a spectral maximum.

Narrow band analysis of spectra for rumbling events shows a relatively wide spectral maximum with an actual peak at a frequency marginally below 50Hz. It should be reminded that perception of the rumbling is different from that of audible tones. The critical bandwidth in accordance with formula (2) for a 50Hz component comprises frequencies from above 0 to approximately 100Hz. For this particular investigation, the spectral levels in the low frequency span has insignificant magnitude in terms of human perception (Figure 3). The spectral components below 50Hz are frequently less than the low frequency audibility threshold in accordance with ISO 226 (18). Respectively, if there is a significant offset from the hearing threshold, the low frequency noise would not participate in masking of the prominent component which may lead to audibility of the component at times. It should be noted that the Standard specifies audibility thresholds for pure tones and perception of more complex sounds may be different.

Levels of an environmental noise typically vary depending on different factors. Even if variations of the low frequency noise levels are insignificant it may lead to noticeable changes in the 50Hz component perception if it crosses the audibility threshold, increasing and decreasing the masking noise in a “relay” manner. It may exacerbate perception of the noise for a sensitive person exposed to the effect for prolonged periods even if overall levels would not be considered as representing a nuisance.

This hypothesis is partly confirmed by analysis of filtered audio records. The records, which have been band pass filtered within 50Hz 1/3 octave, still exhibit rumbling but perception of the character is significantly distorted in comparison with the original record. Low pass filtering with cut-off frequency 44Hz (lower limit of 50Hz 1/3 octave band) or high pass filtering with cut-of frequency 57Hz (higher limit of 50Hz 1/3 octave band) eliminates the rumbling effect. It is interesting to note that low pass filtering of the audio records brings different effects on reproduction of essential features of rumbling. If increase of the cut-off frequency of the low-pass filtered record from 57 to approximately 75Hz brings a marginal improvement of the effect replication in comparison with the original noise, further increase of the cut-off frequency does not evoke changes in the perception of rumbling. It may not necessarily mean that the critical frequency range detected by formula [2] is incorrect. One can see from Figure 1 a significant decrease of spectral magnitudes above 63Hz, therefore absence of the noticeable differences with inclusion of the higher frequencies in the analyzed records emphasizes a lack of sufficient energy at higher frequencies of the critical span to influence the masking.

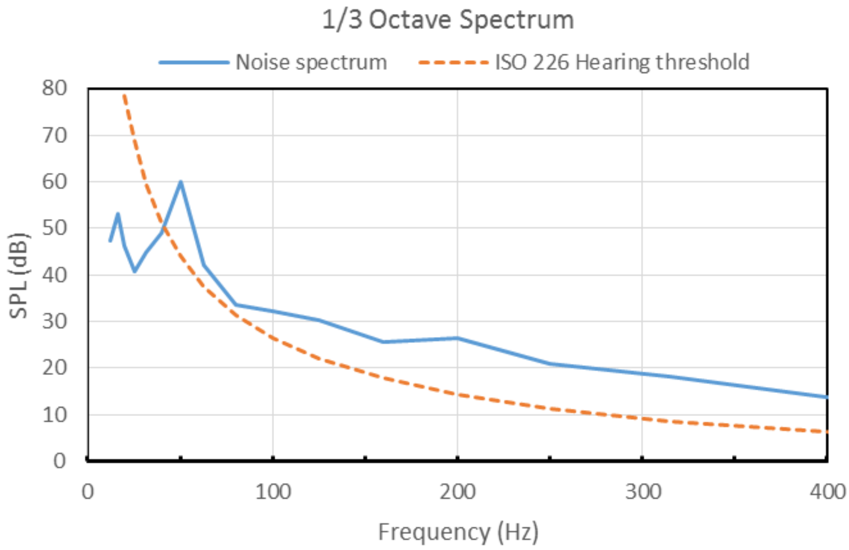


Figure 3- Measured 1/3 octave spectrum corresponding to the rumbling character and audibility threshold in accordance with ISO 226

4. SUMMARY

A particular noise character, which can be described as “rumbling”, has been detected at a few monitoring sites situated around a wind farm area under a range of downwind conditions. The rumbling was only discernible to a typical listener when replayed at amplified audio records, actual noise levels were low, approximately 30dB(A) or less. Analysis of shutdown and adjacent periods at one of the monitoring sites indicated a direct link between operation of the wind farm and this particular noise character. This effect is most commonly recorded at the monitoring sites under downwind conditions. It is most prominent when the local background noise was low, notably at low local wind speeds but high hub height wind speeds.

Conventional methods of rumbling assessment are based on the concept of low frequency spectral imbalance. Methods of assessment based on this concept cannot always be applicable to rumbling evaluation because of very low SPLs associated with rumbling from wind farms. Analysis of the filtered audio records indicated that the rumbling is also linked to the noise level variations.

Spectral analysis showed that the effect could have been linked to a prominency of 50Hz component when parameter *P* exceeded 10dB. The component was not that prominent at other monitoring locations and noise there did not exhibit the rumbling character. The rumbling was not combined with tonal perception of the noise and is most likely caused by a combination of the temporal fluctuations and the imbalanced low frequency spectrum. As a part of simplified approach to detecting potential rumbling from wind farms, the predicted noise levels can be further analysed in accordance with the method suggested in work (12). It was found that using this method, the times when the rumbling in audio records could be heard produced positive results. The QAI calculated during these times were shown to be less than 20dB which is considered Neutral (no rumbling should be detected).

In spite of the fact that the overall noise levels met regulatory requirements, it is possible that people who have a higher sensitivity to the lower frequencies in particular may detect these characteristics, which may cause increased annoyance for those who have been aware of it for a prolonged period. Also, due to the very low A-weighted noise levels that were recorded during these events, it may be possible that listeners are more sensitive to frequencies between 30-50Hz. The wind farm manufacturers may have to consider potential for low frequency impact of wind turbines and presence of prominent components at the design stage. It can help to avoid presence of the characters in the wind farm noise and improve perception of the noise by sensitive listeners.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to Dr Norm Broner from Jacobs SKM for advice on methods of low frequency noise assessment and fruitful discussion on the relevant topics which allowed the authors to improve the paper presented.

REFERENCES

1. Standards New Zealand. *Acoustics- Wind Farm Noise*, NZS 6808, Wellington, New Zealand, 2010.
2. SA Environment Protection Authority. *Wind farms environmental noise guidelines*, SA Government, Adelaide, Australia,2009.
3. NSW Department of Planning and Infrastructure, *Draft NSW planning guidelines: wind farms*, NSW Government, Sydney, Australia, 2011.
4. Fastl H, Zwicker E. Pycho- acoustics facts and models. Berlin, Germany: Springer-Verlag; 2007.
5. Bowdler D, Amplitude modulatiojn of wind turbine noise. A review of evidence. Institute of Acoustics Bulletin 2008; Vol 33, no 4.
6. Vestas Wind Systems. General Specification V90–3.0 MW VCS 50 Hz, Document no.: 0000-5450 V06, Denmark; 2010.
7. Marshall Day Acoustics. Waterloo wind farm: post- construction noise compliance assessment, Report. No. 002 2010277, Australia; 2011.
8. DELTA. Measurement of noise emission from Vestas V90 3MW wind turbine Mode “0”, Test report, Project No.A581149, Denmark; 2009.
9. Vasudevan R, Gordon C. Experimental study of annoyance due to low frequency environmental noise. Applied Acoustics 1977: 10 (1): p.57-69.
10. Acoustical Society of America. *Quantities and Procedures for Description and Measurement of Environmental Sound- Part 4: Noise Assessment and Prediction of long-term community response*, ANSI S12.9-2005/Part 4, American National Standard Institute, New York, USA, 2005.
11. Ebbing CE, Fragnito D, Inglis S. Control of low frequency duct generated noise in building air distribution systems. ASHRAE Transactions 1978: 84(2): p.191-203.
12. Blazier WE. Revised noise criteria for application in the acoustical design and rating of HVAC systems. Noise Control Engineering 1981: 16(2), p.64-73.
13. Broner N. Rating and assessment of noise. Proc. AIRAH conference, 2004, Melbourne, Australia, p.21-25
14. ASHRAE. Handbook- HVAC Applications. Chapter 48: Noise & Vibration Control. USA: ASHRAE Publication; 2011.
15. RenewableUK. Wind turbine amplitude modulation:research to improve its understandingas to its

cause and effects,Research report, UK; 2013.

16. Lenchine VV. Variations in sound pressure levels under random change of atmospheric conditions. Proc. AAS Acoustics 2012 conference, 2012, Fremantle, Australia.
17. International Electrotechnical Commission. *Wind turbines- Part 11: Acoustic noise measurement techniques*, IEC 61400-11, Geneva,Switzerland,2012.
18. International Organization for Standardization.*Acoustics – Normal equal-loudness-level contours*, ISO 226, Geneva, Switzerland, 2003.