INFRASOUND AND BLADE PASS FREQUENCY LEVELS IN AREAS ADJACENT TO WIND FARMS

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

SA Environment Protection Authority, Australia

ABSTRACT

Concerns have been expressed by sections of surrounding community about infrasound produced by wind farm renewable energy facilities from specific nearby wind farm locations in Australia. This has received regular media attention. There are various methods which can be used to determine the contribution of infrasound by wind farm facilities. However sometimes they do not produce conclusive results. This paper discusses the use of statistical hypothesis tests to determine infrasound contributions of wind farms. Verification of equivalency of means and equivalency of variance hypotheses were used on several shutdown and similar operational periods to check for infrasound impact. The data sets were collected during infrasound measurements performed at 3 different locations with a distance range of approximately 1.3km to 3.5km. Results show that the wind farms tested can contribute to infrasound at large distances but levels were significantly lower than the conservative perception threshold of 85dB(G). The blade pass frequencies were also analysed for the same set of data to detect any potential to exacerbate human perception of infrasound. It was found that the blade pass frequency was not very prominent at all monitoring locations and was detected at levels significantly below the perception threshold. There was also a minimal difference in blade pass frequency magnitudes and its prominency for indoors and outdoors measurements. In general infrasound impact from modern turbines at the distant receivers cannot be considered excessive and its magnitudes are significantly below the perception threshold.

Keywords: Infrasound, Blade Pass Frequency, Wind Farm I-INCE Classification of Subjects Number(s): 14.5.4, 21.8.1

1. INTRODUCTION

Electricity produced by wind farms is considered as an attractive type of energy which imposes minimal adverse impact on the environment. Wind energy generating capacity around the world has been growing steadily during the last decade. However, some aspects of environmental impacts from these renewable energy facilities are still not clear. The potential of excessive infrasound is sometimes used to oppose the development of wind farms in an area. In some cases, wind turbines may generate prominent blade pass frequency components. Some researchers suggest that this may exacerbate perception of wind farm noise.

These issues are explored in this paper with data collected at few locations in areas adjacent to wind farms. Operational data and data from the wind farm shutdowns were utilised for comparison and check of statistical hypothesis regarding whether operation of the wind farms contributes to noise at a distant receiver. Magnitudes and prominency of the blade pass frequency component is also explored in this paper and compared with available criteria.

2. INFRASOUND IMPACT: OVERALL LEVELS

Assessment of noise impact at infrasound frequencies is not a thoroughly explored topic. ISO 7196 (1) is a widely used document for analysing and reporting results of noise measurements in infrasonic frequency span. It recommends that assessment of infrasound impact to be made on basis of G-weighting.

There are also works of other researchers that explore sensitivity of human hearing to noise at very low frequencies. It is suggested that 85dB(G) is a conservative estimate for audibility of infrasound, which is 5dB(G) lower than the limit suggested by the ISO standard where infrasound may be considered “significant for human perception”. Comparison of relevant standards for audibility at low

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

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

frequencies shows that G-weighting is sufficiently conservative and 1/3 octave audibility thresholds based on 85 or 90dB(G) levels are typically consistent with results of relevant research or standards (2) and 85dB(G) criterion can be considered as strict enough since it is lower than other mean hearing threshold reported in many relevant studies.

Noise emission from wind turbines is considered to be correlated with wind speeds. Recent modifications of regulatory documents and standards recommend reporting of sound power characteristic of turbines and noise assessment at a distant receiver to be made versus the hub height wind speed. Typically, an inbuilt sensor system reports parameters related to operation of wind turbines in 10-min intervals and measured noise is correlated with the available averages.

Wind farm noise is not subjected to abrupt impulsive variations like from agricultural bird scaring devices and military weapons. Equivalent sound pressure levels (SPLs) are used for assessment of noise from sources where impulsiveness is not a part of a noise source characteristic. It is reasonable to accept equivalent SPLs as the major acoustical descriptor for wind farms.

2.1 Challenges of wind farm noise measurements

Normally wind farm developments are designed to introduce a significant buffer between turbines and nearest noise sensitive receivers. Under such circumstances contribution from a wind farm can be comparable or even less than the contribution from natural background or other ambient sources. Some of regulatory documents and research works recommend start/stop method to estimate contribution from a wind farm (3, 4, 5).

However, sometimes differences in the measured levels during wind farm shutdowns and similar operating periods is not conclusive. In this case, statistical tests on the equivalency of mean and standard deviations for arrays of data collected during shutdowns and relevant operating periods can be utilised. These tests can help in determining whether operation of a wind farm can change the noise impact or if the difference is too small to give a reliable estimation.

2.2 Statistical estimates of overall levels predicated on operational and shutdown differences

This section details the analysis of G-weighted levels measured during monitoring programs at locations close to wind farm sites. The wind farm operators had agreed to organise full scale shutdowns at the site (all turbines switched off); there were also times when shutdowns happened due to technical reasons. Pre-shutdown and after shutdown transition periods have not been taken into account for the present analysis.

Instead of using simple comparison of average parameters (or parameters range) for shutdowns and relevant operating periods, the influence of the wind farm operation on the infrasound levels at a distant receiver is explored on basis of statistical hypothesis for equivalency of means and standard deviations (variances). Statistical descriptors have been compared for arrays of data collected during the wind farm shut down periods and corresponding arrays where data has been collected during the wind farm operation under similar wind conditions.

Hypothesis about equivalency of variances can be checked using F- test. Hypothesis of equivalency of the mean values was checked using Student's t- test (6, 7). Both of these tests were performed with a level of significance (α) of 0.05.

Monitoring equipment at Location 1 was positioned about 1.5km from the site equipped with Suzlon S88-2.1MW turbines. Locations 2 and 3 were situated approximately 1.3km and 3.5km respectively from the wind farm with operated Vestas V90-3MW turbines. Measurements of infrasound levels were performed with B&K Type 4193 microphones equipped with low frequency adaptors. Signals from the microphones were coupled with multi-channel Soundbook analyzers. Measurements have been performed both outside and inside of the houses on the side facing the wind farms. The microphones were positioned 1.3-1.5m above ground or floor level (single story buildings). Outdoor microphones were fitted with multi-layer wind shields to reduce wind induced component of the measured noise. Details of the wind shields can be found in work (2).

Location 1 shutdown period involved greater variations of wind speeds from 4 to over 11m/s, the wind direction was relatively stable and can be considered as crosswind. Full scale shutdowns at Locations 2 and 3 were organised for a greater variety of environmental conditions. Wind speeds were in the range where the sound power characteristic of the turbine were close to maximum. The general environmental conditions are summarized in Table 1. The data is represented as measured at the hub height of nearest turbines (10min averages).

During the shutdowns at Locations 2 and 3, estimated time of the each shutdown was around 50 minutes. It provides a very small number of points for a viable statistical comparison if 10 minute data is used. ISO 7196 recommends minimum 10sec averaging period for reporting G-weighted levels (1). Data with 10sec intervals was available during the shutdown and similar operating periods. They were utilised for the analysis in this section.

Table 1 Summary of general environmental conditions for shutdown periods

Location	Shutdown	Hub height wind speed, m/s	General wind direction
1	1-1	4.3-5.8	Crosswind
	1-2	10.1-11.3	Crosswind
2	2-1	9-9.5	Downwind/crosswind
	2-2	8.6-9.1	Upwind
	2-3	7.5-9.1	Upwind/crosswind
	2-4	11.2-11.6	Upwind/crosswind
	2-5	8-8.8	Downwind/crosswind
	2-6	6-7.3	Downwind
3	3-1	9.7-11.7	Downwind/crosswind
	3-2	11.2-12.8	Downwind/crosswind
	3-3	9.7-10.7	Upwind/crosswind
	3-4	10.4-11.5	Upwind/crosswind
	3-5	7.1-9.2	Upwind/crosswind
	3-6	7.3-8.5	Crosswind

Operating periods with similar weather conditions to the shutdowns were selected for the comparative analysis from the available data set. Wind speed and direction from the wind turbine generator are major parameters characterising the source and noise propagation from the source. Therefore matching these parameters for choosing comparative operating periods is crucial for the corresponding operating periods. Shutdown and operating data arrays comprised about 200-300 values. Means and standard deviations of infrasound levels measured outside and inside of houses at monitoring locations are summarised in Table 2. Results of the statistical tests are shown in Table 3.

It can be seen from Table 2 that significant difference in the mean infrasound levels is observed not only at downwind or crosswind conditions, it is also noticeable for upwind/crosswind conditions as well (shutdowns 2-3, 3-4, 3-5). Results of the tests were dominantly negative (Table 3) and were consistent for indoor and outdoor measurements. This means that hypothesis about equivalency of the means and standard deviations is not valid. However, the meaning of these results may be different depending on the difference between the means compared. For some of the locations and environmental conditions operational levels significantly exceed the shutdown magnitudes and it means that operation of the wind farm provides significant contribution to the measured levels (for example shutdowns 2-5, 2-6 or 3-4, 3-5, 3-6). Negativity of the statistical tests, where the shutdown mean G-weighted SPL marginally exceeds the comparative operational values means that other sources influenced infrasound at the shutdown (refer to values for shutdowns 1-2, 2-4, 3-3).

Comparison of the means for shutdowns 2-2 and 3-2 would raise expectations that results of the statistical test would be positive, which would mean that there were no difference between operating and similar shutdown periods in terms of the infrasound impact. However this is not the case, as the test results were negative in spite of the small difference. The statistical test result may indicate that the wind farm influences the measured infrasound, but contribution from the wind turbines is below the background noise (at Location 3).

Table 2 Mean value and standard deviations of infrasound magnitudes measured during shutdowns and similar operating periods (second number)

Location	Shutdown	Indoor		Outdoor	
		Mean, dB(G)	STD, dB(G)	Mean, dB(G)	STD, dB(G)
1	1-1	35.6/49.3	2.6/4.0	40.0/49.3	2.8/3.2
	1-2	54.0/51.6	1.2/2.3	59.3/57.9	1.1/1.7
2	2-1	48.7/55.9	2.8/2.0	53.5/59.2	4.1/0.8
	2-2	49.6/50.7	7.0/2.5	48.3/53.1	1.8/1.2
	2-3	47.5/52.9	2.3/3.1	48.7/55.8	2.0/1.7
	2-4	50.1/47.6	2.6/1.7	50.7/51.3	2.2/1.0
	2-5	44.5/53.1	2.9/1.6	48.6/58.6	2.4/1.5
	2-6	43.8/55.2	3.6/5.1	47.2/55.5	1.9/2.2
3	3-1	43.5/50.9	3.5/1.1	46.4/58.7	3.0/0.7
	3-2	50.6/51.7	1.6/2.0	58.0/58.3	1.1/0.8
	3-3	55.5/55.0	3.7/3.1	57.6/56.3	3.9/2.3
	3-4	40.1/52.8	2.5/2.7	46.7/53.7	2.5/2.7
	3-5	42.8/48.3	2.4/1.7	50.0/57.3	2.8/1.6
	3-6	43.6/51.8	3.0/1.9	54.9/59.1	3.9/1.3

It should be noted, that independent of the results produced by the statistical analysis, mean magnitudes of the G-weighted levels were low and below the conservative hearing threshold for the infrasound of 85dB(G).

Operation of the wind farms may have decreased scattering of the data. It can be said that the wind turbines influenced the standard deviation since results of the statistical tests are dominantly negative (Table 3). However, it does not always reduce scattering of the data even when contribution from the wind farms controls the infrasound levels, i.e. operation of the wind turbines does not necessarily reduce the span of variations of the infrasound SPLs (see comparison for shutdowns 1-1, 2-6 and 3-4 in Table 2).

Table 3 Results of statistical tests for equivalency of mean and STD

Location	Shutdown	Indoor		Outdoor	
		Equiv. of mean	Equiv. of STD	Equiv. of mean	Equiv. of STD
1	1	Negative	Negative	Negative	Negative
	2	Negative	Negative	Negative	Negative
2	1	Negative	Negative	Negative	Negative
	2	Negative	Negative	Negative	Negative
	3	Negative	Negative	Negative	Negative
	4	Negative	Negative	Negative	Negative
	5	Negative	Negative	Negative	Negative
	6	Negative	Negative	Negative	Negative
3	1	Negative	Negative	Negative	Negative
	2	Negative	Negative	Negative	Negative
	3	Positive	Negative	Negative	Negative
	4	Negative	Positive	Negative	Negative
	5	Negative	Negative	Negative	Negative
	6	Negative	Negative	Negative	Negative

2.3 Blade pass frequency component

It can be expected that the blade pass frequency (BPF) component and its integer multipliers may be prominent. For Suzlon S88 turbine, the BPF lies within 0.8Hz 1/3 octave band and Vestas V903MW turbine generates BPF components at 0.5-1Hz central 1/3 octave frequencies when operating in an economically viable generating mode (10rpm and above). Audibility threshold based on 85dB(G) for the components between 0.5-1Hz varies between 149.3 and 128dB (unweighted) (1).

The presence of a prominent BPF may exacerbate perception of wind farm noise. However sensory mechanisms of such influence are not clear since typically BPF magnitude is significantly below the perception threshold. There are methods of assessment of tones based on 1/3 octave data (5, 8). Formally they are not applicable to infrasound. To characterise the prominency of BPF we utilised a parameter which is similar to that used in procedures of the tonal assessment:

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

where L_i is the magnitude of the BPF component, L_{i-1} and L_{i+1} are the magnitudes of adjacent 1/3 octave components. The possibility of the tonal perception of BPF is not discussed in this paper as levels associated with BPF are significantly below the perception threshold (less than 80dB for Location 1 and less than 90dB for Locations 2 and 3). Also, the difference between the spectral components calculated in accordance with formula (1) should be significant for very low frequencies. In accordance with some standards and regulatory procedures, the tone is audible if differences between the spectral components are above 5dB for high frequencies (500Hz and above) and this threshold increases for lower frequencies up to 15dB (25-125Hz 1/3 octave bands) (8). It is expected that this difference should be even higher for infrasound frequencies since sensitivity of human hearing drops significantly at very low frequencies.

Parameter P was calculated on the basis of 10min spectral averages for the same measurement locations as in the previous section for a few hundred of data pairs for each of the locations. The prominency demonstrates a weak dependence on the WTG hub height wind speed. Magnitudes of parameter P rarely exceeded 12dB and were sometimes negative, meaning that no spectral peak at the BPF was detected. Locations 1 and 2 were situated at similar separation distance from the nearest turbine. In general, the calculated prominency magnitudes corresponding to the BPF were higher for Location 1 which was characterised by an almost constant rpm mode of operation. It was found that mean values of the prominency at 0.8Hz inside and outside Location 1 were 5.3 and 4.6dB respectively. Figure 1 shows spectrum with relatively high prominency at Location 1. The mean values were around 1dB or below for other locations.

The set of data collected at 3 locations was utilised to explore few issues from statistical perspective. Spearmen correlation coefficient was used to decide whether parameters related to the BPF component of the spectrum. The Pearson correlation coefficient is sensitive to the normality of distribution of the data and linearity of their dependence, while the Kendall rank correlation coefficient rather emphasises whether the magnitude changes have the same sign in a data set (7, 9). Coefficient of determination for the fitting curve between two variables depends on the type of curve chosen. Spearman's correlation coefficient does not require normality of distribution of the data and can be used for linear and non-linear dependencies between the variables and has less sensitivity to "clustering" of data (9, 10). Therefore it is chosen as the basic statistical indicator of dependence (or independence) of magnitudes in this section. The Spearman's rank correlation coefficient varies from -1 to 1. Higher absolute value means better statistic dependence between 2 arrays of data.

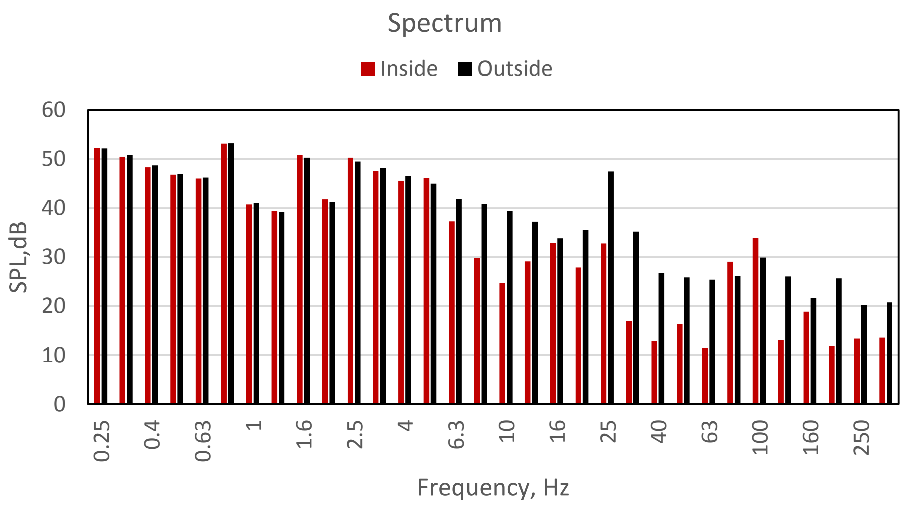

Figure 1 Unweighted 1/3 octave spectrum, 10-min average at Location 1 with BPF (0.8Hz) prominency around 9.7dB

If magnitudes of the BPF component versus wind speeds indicates relatively high correlation with the wind speeds and between components measured inside and outside of the houses (Table 4 and Table 5), then the prominency of the BPF versus wind speeds has small correlation coefficient for all of 3 locations (Table 4). Absence of correlation of BPF for indoor measurements at Location 2 highlights problems with infrasound monitoring in an occupied dwelling. Location 2 is the only occupied house amongst the three locations. The microphone was positioned in an unused room, but there were other factors that influenced the indoor measurements in spite of rectification of the data set from periods containing extraneous noises. Outdoor measurements for Location 2 give the correlation coefficient with the WTG wind speed close to unity.

Table 4 Spearman's correlation of BPF component (unweighted) and its prominency versus WTG and local wind speed

Wind	Location 1				Location 2				Location 3			
	Indoor		Outdoor		Indoor		Outdoor		Indoor		Outdoor	
	L_i	P	L_i	P	L_i	P	L_i	P	L_i	P	L_i	P
WTG	0.54	-0.37	0.48	-0.36	0.02	0.32	0.96	0.20	0.67	0.36	0.68	0.06
Local	-	-	-	-	0.43	0.24	0.75	0.88	0.64	0.28	0.79	0.06

One could expect that prominency also has negative trends versus the wind speeds since the increase of the background should have increased masking effect as well. However such trends were observed for Location 1 only and nature of the dependencies for Locations 2 and 3 is more complex.

Another question related to the infrasound noise exposure is related to the difference in prominency of the BPF component outside and inside the houses:

$$\Delta P = P_{out} - P_{in} \quad (2)$$

where P_{out} is the prominency calculated for outdoor measurements and P_{in} is the paired prominency calculated for indoor measurements. If the ΔP magnitude is positive, it indicates that the BPF is more prominent outside of the house.

The change in the prominency is weakly correlated with the wind speeds (Table 5). The correlation coefficients for ΔP are negative which means opposite trends in the changes of the wind speeds and the prominency difference.

Generally ΔP variations versus the wind speeds are chaotic and the mean magnitudes for any of the three locations does not exceed 1dB absolute magnitude and is close to zero for Location 2. Therefore there is no significant difference between the BPF prominency inside and outside of the houses which could be expected based on the large wavelength corresponding to the BPF frequency.

Room acoustics or the house insertion loss should have a minimal influence on the BPF or adjacent spectral components.

Table 5 Spearman's correlation coefficient for BPF component and difference in prominency

	BPF Outside vs Inside	ΔP vs WTG wind speed	ΔP vs local wind speed
Location 1	0.86	-0.03	-
Location 2	0.70	-0.17	-0.13
Location 3	0.78	-0.33	-0.27

3. Summary

The potential for infrasound impact from wind farms is explored for receivers situated at separation distances of approximately from 1.3km to 3.5km from nearest WTGs. It is shown that wind farms can contribute to the measured infrasound levels even at a great separation distance by checking statistical hypothesis about equivalency of the means for particular environmental conditions. Statistical tests were performed for the infrasound data sets gathered during wind farm shutdowns and similar operating periods. Typically the null hypothesis (on the equivalency of the means) is proven to be not valid even if the means characterising the infrasound levels were very close. Also checking the hypothesis for equivalency of the variance (standard deviation) normally shows that operation of the wind farms influences scattering of the infrasound data, however this influence does not necessarily lead to decrease of the span of variations, even if the wind farm contribution was significant. When the results and contribution from start/stop exercises are not conclusive, the statistical hypothesis check can be used.

Also, the available data set enabled analysis of the BPF component, which lay within the infrasound frequency span. It is shown that the BPF component has minimal influence in perception of infrasound since it is typically detected at levels significantly below the audibility threshold. The prominency of the BPF rarely exceeded 12dB. There was no significant difference between the BPF prominency inside and outside the houses.

Analysis of infrasound data measured at three locations inside and outside the dwellings does not bring evidence that the noise impact from wind farms may be excessive or have features that may exacerbate perception of the infrasound since the analysed levels were significantly below the conservative perception thresholds.

REFERENCES

1. International Organization for Standardization. *Acoustics – Frequency-weighting characteristic for infrasound measurements*, ISO 7196, Geneva, Switzerland, 1995.
2. Evans T, Cooper J, Lenchine V. Infrasound levels near wind farms and in other environments. SA EPA and Resonate Acoustics, Adelaide, Australia 2013.
3. SA Environment Protection Authority, 2009, Guidelines for the use of the Environment Protection (Noise) Policy 2007, SA Government, Adelaide
4. Standards Australia. *Acoustics- Measurement, prediction and assessment of noise from turbine generators*, AS4959-2010, Sydney, Australia, 2010.
5. Standards New Zealand.*Acoustics- Wind farm noise*, NZS 6808:2010, Wellington, New Zealand, 2010.
6. Chung KL. A course in probability theory. 3rd ed. New York, USA:Academic Press;2001.
7. Sokal RR, Rohlf FJ. Biometry. 3rd ed. New York, USA: W.H.Freeman and Company; 2000.
8. Acoustical Society of America, 2005, *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.
9. Agresti A. Analysis of Ordinal Categorical Data. 2nd ed. New York, USA: John Wiley & Sons; 2010.
10. Myers JL, Well AD. Research design and statistical analysis, 3rd ed. New York, USA: Routledge; 2010.