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Wind induced aerodynamic noise on microphones from atmospheric measurements

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ABSTRACT

Wind induced noise is a problem that can affect outdoor acoustic measurements. This issue is particularly relevant in the context of wind farm assessments, where the dependency of ambient noise as a function of the local wind speed is of primary importance when determining the noise criteria for surrounding residences. This paper is a continuation of work presented at the 2008 Australian Acoustical Society conference, which examined the factors that alter the wind-generated microphone noise using wind tunnel measurements. This paper presents the results of atmospheric measurements of wind-generated microphone noise, and provides a relationship between wind speed and microphone-generated L_{Aeq} noise level for a range of wind shields. A method for predicting L_{A90} noise levels due to wind-generated microphone noise is also provided and the results compared to those noise levels predicted using the average wind speeds. Field measurements were necessary to determine the relationship between wind speed and microphone noise as it was previously determined that incident wind turbulence alters the induced aerodynamic noise levels, such that wind tunnel measured noise levels were not able to be applied to environmental noise measurements.

INTRODUCTION

Background

In recent years there has been significant growth in wind farm electricity generation across Australia. The current focus on renewable energy and greenhouse gas emissions reduction is likely to maintain or result in increased growth in this sector.

Early wind farm development frameworks used in Australia were New Zealand Standard 6808 (NZS 6808:1998) and the Wind Farm Environmental Noise Guidelines 2003 (EPA 2003), which were developed by the South Australian EPA. Later versions of both of these documents have now been released. The most recent version of the Wind Farms Environmental Noise Guidelines was released in July 2009 (EPA 2009), and a revised New Zealand Standard released in March 2010 (NZS 6808:2010). The 2009 South Australian Wind Farms Environmental Noise Guidelines are typically used in Australia for the assessment of most wind farm applications, except in Victoria, where New Zealand Standard 6808 (NZS 6808:1998) is still formally cited.

In addition to the above documents, an Australian Standard for the measurement, prediction and assessment of noise from wind turbine generators has now been released (AS 4959:2010). This standard, while not currently formally cited, may in future be used to assess noise from wind farms in Australia.

This paper has been written to assist acoustic consultants to meet the requirements of the above standards, which now refer to wind-generated noise on the microphone. It presents relationships for determining the wind-generated L_{Aeq} noise level on the microphone for several wind shield diameters. Additionally, it provides a method for assessing the influence of wind-generated noise on the measured L_{A90} noise level, which is the descriptor used by the wind farm assessment standards to measure background noise and wind turbine noise levels.

Relevance to wind farm noise measurements

The level of noise that is produced by wind turbines is dependent on the wind speed at the turbines. Generally, as the wind speed increases the sound power level of the turbines also increases. The potential impact of this increase in noise is reduced by the corresponding increase in background noise at the residences due to wind noise in foliage, which assists to acoustically mask the wind farm noise.

The SA Wind Farms Environmental Noise Guidelines, NZS 6808, and AS 4959 all account for varying wind turbine and ambient noise by setting wind farm noise criteria at a level above the existing background noise level. The level of the existing background noise is determined by logging noise levels at the residences adjacent to the proposed wind farm, over the range of wind speeds that the wind farm will be operating. The noise criterion for each integer wind speed is determined from the existing background noise level.

Noise measurements for other types of environmental noise assessments are normally conducted at times of low wind speeds (less than 5 m/s) using wind shields, to reduce the influence of wind generated noise on the measurements. The wind-generated noise takes two forms: wind induced microphone self noise; and increased levels of ambient noise from wind interaction, typically with foliage.

It is not possible to avoid times of high wind speeds during wind farm background noise measurements, as it is necessary to determine the noise criteria, and hence background noise level (L_{A90}), over the range of speeds in which the wind farm normally operates.

The South Australian Wind Farms Environmental Noise Guidelines 2010, AS 4959, and NZS 6808:2010 all suggest that special wind shields to reduce the influence of wind noise on the microphones should be used. The South Australian Wind Farm Noise Guidelines 2010 and AS 4959 both require that evidence is to be provided to show that the wind shield used was suitable where the wind speed at the microphone location could be expected to exceed 5 m/s. Additionally, the South Australian guidelines refer to using manufacturer specifications to determine acceptability of the wind shield, although in practice, manufacturer information regarding wind-induced microphone self noise is not readily available for all microphone and wind shield combinations.

The requirements for protecting the microphone from self-generated wind noise are included in the above standards to ensure that the reported background noise level is the result of wind-induced ambient noise, rather than wind-induced microphone noise.

Previous work

Our paper presented at the 2008 Australian Acoustical Society conference (Leclercq *et al.* 2008) reviewed the mechanism for wind generated noise in microphones and examined the factors which influence the resulting noise level. The key findings of that work were:

- Wind shield diameter is the single most important parameter determining the efficiency of a wind shield.
- Microphone diameter has no significant effect on the measured level of wind shield noise, and therefore neither will microphone model.
- Performance of two wind shields from different manufacturers but same diameter is similar, provided that the wind shield was of a professional quality.
- Irregularities or wires on the surface of the wind shield result in increased noise levels.

The previous measurements were undertaken in a small Anechoic Wind Tunnel at the University of Adelaide, where variables could be quickly altered to allow repeatable comparisons between different tests. The measurements were not suitable for determining the overall level of wind induced noise as it appeared that turbulence incident on the wind shield was influencing the results. The overall level of wind noise when measuring in the atmosphere would therefore be different to that measured in the wind tunnel, as turbulence in the atmosphere was expected to be less than in the wind tunnel.

ATMOSPHERIC MEASUREMENTS

Several commercially available microphone wind screens were tested in the atmosphere to determine a relationship between wind speed at the microphone and noise level.

Test site

The site selected for the test was a low hill near Jamestown in the Mid North of South Australia. This site was selected as the authors had access to the site which was a very quiet locality not typically influenced by noise from transportation, wind noise generated in the grass and trees, or bird noise. The nearest significant road to the test site was at a distance of approximately 1 500 metres but the Annual Average Daily Traffic (AADT) on that road was only 550 vehicles/day. Measurements were timed for the end of summer, so grass cover and therefore wind-generated noise was at a minimum. The site had been heavily grazed so that the typical grass height was less than 25 mm although the occasional seed head stood to about 250 mm.

Measurements were conducted on two afternoons approximately three weeks apart at two separate sites on hill, and temperature during the tests was approximately 35^{o}C. A measure used to describe the wind turbulence is the Turbulence Intensity, which is calculated by dividing the standard deviation of the wind speed by the mean wind speed during the measurement period. The average 10 minute turbulence intensity during the measurements was 0.204 with standard deviation of 0.055.

Experimental set-up

Figure 1 provides an illustration of the test site and equipment setup.

Figure 1. The test site and equipment setup

A Brüel & Kjær 2250 with ½" Type 4189 microphone on a 3 m extension cable was used to measure the wind generated noise. The 2250 was set to log L_{Aeq} and L_A noise levels at 100 ms intervals, with 1/3rd octave L_{Aeq} spectrums averaged over 1 minute intervals. The microphone was mounted with its axis pointing vertically, as would normally be the case for environmental noise measurements. The wind speeds during the test were measured using an NRG #40 anemometer, with average wind speeds recorded over 1 second periods. Both the microphone and anemometer were mounted at a height of 1.2 m above ground level, and were situated approximately 3 m apart to exclude anemometer noise from the measurement. A line drawn between the sensors was perpendicular to the direction of the incident wind. The tested wind screens are listed in Table 1.

Table 1. Wind shields used during the tests

Test no.	*Diameter*	*Description*
1	-	No wind shield
2	30	Ellipsoidal – Manufacturer A
3	65	Circular – Manufacturer B
4	90	Circular – Manufacturer A
5	90	Circular – Manufacturer A, with 3 wires over surface
6	90	Circular – Manufacturer C
7	180	Circular – Manufacturer unknown

All wind screens tested were open cell polyurethane foam shields of the type supplied for use with professional sound level meters. Cheap generic foam wind shields were not tested as the previous wind tunnel testing had indicated that their performance was poor.

RESULTS

The logged 100 ms L_{Aeq} levels were initially converted to 1 second L_{Aeq} levels and analysed against the 1 second average wind speeds, but the correlation between the wind-generated noise and wind speed was poor. It is believed that the poor correlation was a result of the difference in short term wind speeds between the microphone and anemometer (which were separated by a distance of 3 m) and the time taken by the anemometer to respond to a change in wind speed. Various longer averaging times were trialled and an averaging time of 30 seconds finally selected for the analysis, as it provided a reasonable correlation of noise to wind speed without significantly reducing the number of measurement points and range of wind speeds included in the measurements.

Note that previous work had demonstrated a dependency of the wind screen noise level on approximately the 6^{th} power of the flow velocity. The 30 second L_{Aeq} levels were therefore analysed against a 30 second wind speed calculated using the average of the 6^{th} power wind speeds to the 6^{th} root:

$$v_{av} = \left(\frac{v_1{}^6 + v_2{}^6 + \ldots\ldots + v_n{}^6}{n}\right)^{1/6} \quad (1)$$

Where: v_{av} = Average wind speed
v_1 to v_n = 1 second wind speeds

Comparison of different 90 mm wind shields

The results for a plain 90 mm wind shield were of primary interest in this investigation as this is the type of wind shield widely used for environmental noise measurements. Tests were conducted using three different 90 mm wind shields with characteristics as per Table 1. Figure 2 compares the measurements for the three tests.

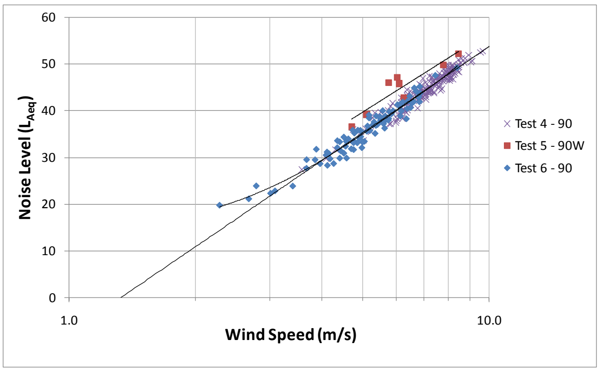

Figure 2. Comparison of three 90 mm wind shields, one of which (Test 5) had wires running over the surface of the shield. Data for 30 second averaging time.

The trend lines fitted to the above data points follow a linear logarithmic relationship, with the exception of the curved 4^{th} order polynomial fitted to the Test 6 data. The 4^{th} order polynomial is fitted to the Test 6 data to demonstrate that it appears that noise measurements below 3 m/s have been affected by background noise and/or the noise floor of the equipment. Noise data below 3 m/s for the 90 mm wind shield was excluded from the later analysis. Excellent agreement between the trend lines of the Test 4 and Test 6 results is achieved above 4 m/s, confirming the wind tunnel result that two plain professional quality 90 mm wind shields from different manufacturers generate similar levels of wind generated noise. Note that Test 6 was conducted on the same hill as the Test 4 measurements, but three weeks earlier and at a location approximately 100 m from the site used for Test 4. Similar results between the tests suggest that the measurements were not site dependant.

The Test 5 results used the same polyurethane foam wind shield as the Test 4 results but with the addition of a wire cage around the shield which consisted of three wires that were 2 mm in diameter. The Test 5 results lie approximately 4 dB(A) higher than the Test 4 and 6 results, and confirm our previous findings and those of Hessler *et al*. (2008) that irregularities on the surface of the wind shield increase the wind-generated noise. It is therefore recommended that windshields with wires running over the surface and/or bird spikes are not used for environmental noise measurements where high wind speeds are expected.

Comparison of different diameter wind shields

The results of all of the tests with measurements averaged over a 30 second period are presented in Figure 3.

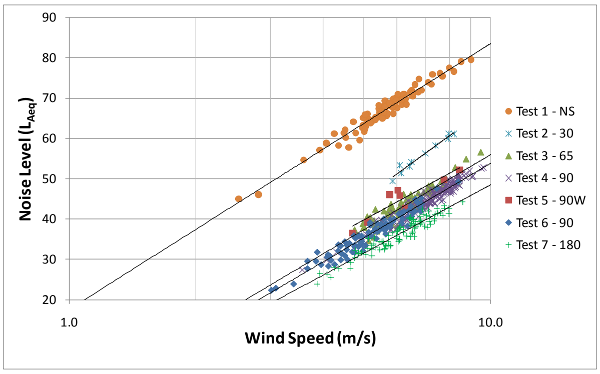

Figure 3. Comparison of L_{Aeq} resulting from all test wind shields using 30 second averages.

Due to the similarity of the two 90 mm results, a combined trend line was fitted to the Test 4 and Test 6 results in the above graph, with the three points below 3 m/s excluded due to the influence of background noise. Figure 3 demonstrates reduced wind-generated noise with increased wind shield diameter, confirming the findings of our previous wind tunnel measurements and the work of Strasberg (1988) and Hessler.

Relationship between wind speed and noise level

The trend lines fitted to the data points were used to determine the relationship between wind speed and self-generated wind noise. The form of the equation used to represent the relationship is as follows:

$$L_{Aeq} = 10 \times \log\left(v^{C_1}\right) + C_2 \quad (2)$$

Where: L_{Aeq} = The A-weighted wind generated equivalent noise level
v = Wind speed at the microphone in m/s
C_1 and C_2 = Constants as per Table 2

Constants for use with the above equation to determine the wind-generated noise level for professional quality wind shields of various diameters are provided in Table 2.

Table 2. Constants for use with Equation (2)

Diameter (mm)	C_1	C_2
No shield	6.59	17.6
65	6.18	-5.9
90	6.14	-7.6
180	5.63	-7.9

A $V^{6.14}$ relationship was therefore measured for the 90 mm wind shield with slightly higher power measured for no wind shield and slightly lower power measured for the larger wind shield. Only a limited amount of time was spent collecting data for both the 30 mm diameter and the 90 mm diameter wind shield with wire cage (Test 2 and 5). Due to the lack of data points for those tests, no constants for predicting the level of wind-generated noise are provided. Table 3 provides a summary of the wind-generated noise levels at various wind speeds predicted using Equation (2).

Table 3. A-weighted wind induced noise level at selected wind speeds (m/s).

	Wind Speed (m/s) / L_{Aeq} (re: 20 μPa)			
Diameter (mm)	*2.5*	*5*	*7.5*	*10*
No shield	44	64	75	84
65	19	37	48	56
90	17	35	46	54
180	15	31	41	48

SUITABILITY OF RELATIONSHIP FOR USE OVER LONGER TIME PERIODS

To determine the suitability of Equation (2) for predicting the 10 minute wind induced noise level on a microphone, the predicted noise level was compared to the measured noise level for all 10 minute consecutive blocks of data recorded during the testing. Predictions were undertaken using the matching 10 minute 6th power averaged wind speeds calculated using Equation (1), and also a normal 10 minute average wind speed for comparison. The total number of 10 minute periods available for the analysis was 20 with 11 of those being for 90 mm wind shields and the remainder being divided between the no wind shield, 65 mm wind shield and 180 mm wind shield tests. Table 4 shows the accuracy of the model. This model showed a similar level of accuracy for all types of wind shield.

Table 4. Accuracy of model for predicting 10 minute L_{Aeq} from 1 second average wind speeds.

	Error of predicted vs. measured level (10 minute L_{Aeq}, dB(A))		
	Mean	*Standard deviation*	*Maximum error*
v_{av} from Equation (1).	+0.1	0.4	0.9
10 minute average speed.	-2.1	0.7	3.5

Table 4 demonstrates that there is a very good level of accuracy when using the model combined with 6th power averaged wind speeds to predict the 10 minute equivalent noise level from wind-induced noise on the microphone. Accuracy when using a standard 10 minute average wind speed is comparatively poor.

SUITABILITY OF RELATIONSHIP FOR DETERMINING L_{A90} LEVELS

For wind farm noise measurements, the ability of the model to predict the L_{A90} noise level from wind speed at the microphone is of primary importance. This is because noise measurements of both the pre-existing background and post–construction wind farm noise levels are determined using L_{A90} levels.

Prediction of the L_{A90} noise level was complicated by the resolution of the anemometer when measuring one second average wind speeds, which was 0.59 m/s. If the lowest 10th percentile of the wind speeds was used for the prediction, there is potential for the error in the wind speed to be ½ the anemometer resolution, which would be 0.295 m/s. The lowest 10th percentile wind speed measured during the 10 minute periods was 3.34 m/s and highest 6.33 m/s. A 0.295 m/s wind speed error would result in a 2.5 dB(A) error in the predicted noise level for the 3.34 m/s data.

In an attempt to overcome the problem of anemometer resolution, the wind speed was calculated by assuming a normal distribution of wind speeds and using the mean and standard deviation of the 1 second wind speeds to determine the probable lowest 10th percentile wind speed. From Kreyszig (1999), the probable 10th percentile speed can be predicted from the mean and standard deviation using the following equation:

$$v_{10\ \mathrm{prob}} \approx \mu - 1.28 \times \sigma \qquad (3)$$

Where: $v_{10\ \mathrm{prob}}$ = The probable lowest 10th percentile wind speed
μ = Mean wind speed during the 10 minute period
σ = Standard deviation of wind speed during the 10 minute period

Table 5 shows the accuracy of Equation (2) when used to predict the L_{A90} noise level using various wind speeds.

Table 5. Accuracy of Equation 2 for predicting 10 minute L_{A90} from 1 second average wind speeds.

	Error of predicted vs. measured (10 minute L_{A90}, dB)		
Wind Speed	*Mean*	*Standard deviation*	*Maximum error*
$v_{10\ \mathrm{prob}}$ from Equation (3).	+0.1	0.8	1.4
10th percentile wind speed.	+0.1	1.4	2.8
10 minute average speed.	+7.8	1.6	10.9

Table 5 demonstrates that the probable lowest 10th percentile wind speed can be used to predict the L_{A90} wind-generated microphone noise level with a good level of accuracy. Equation (2) when used in combination with Equation (3) therefore provides sufficient accuracy to determine whether the L_{A90} measurements have been adversely affected by wind generated noise on the microphone.

Table 5 also indicates that while the measured lowest 10th percentile of the wind speeds provides a reasonable level of accuracy, the error is almost twice that resulting from the use of the probable 10th percentile speed. As could be expected, the average wind speed at the microphone is demonstrated to be not suitable for predicting the L_{A90} noise level.

COMPARISON AGAINST PREVIOUS WORK

Figures 4 to 7 compare the results of this investigation against previously derived relationships for wind-induced microphone noise. The other studies included in these figures and details of the tests are provided in Table 6.

Figures 4 to 7 demonstrate that the previously measured wind tunnel results provide higher reported noise levels, while results in still air provide lower reported levels. The exception is Hessler's result for the 175 mm diameter wind shield at 5 m/s, which appears to be a significant outlier in that data, given all other data points lie 3 to 5 dB(A) above our results. It is suspected that the higher levels reported by the wind tunnel tests are due to increased turbulence in the incident flow and/or wind generated noise in the wind tunnel, which like microphone-induced noise, would be expected to increase with a 6^{th} power relationship to speed. It is believed that the lower results calculated using the Strasberg model result from the lack of turbulence in the incident flow.

Table 6. Other results compared to the findings of this investigation.

Author	*Details*
Strasberg	Reported values are calculated by summing $1/3^{rd}$ octave results calculated levels from Strasberg's relationship, which was derived based on measurements of four different authors. Those measurements were all made by moving a microphone through still air. No turbulence was therefore incident on the wind shield during the tests.
Rion	Results read from graphs in Rion technical data for the WS-02 and WS-10 wind shields. No details given but number of data points on graphs suggests that results are provided from wind tunnel testing.
Hessler	Results provided by Hessler in tabular form, for wind shields tested in a wind tunnel.

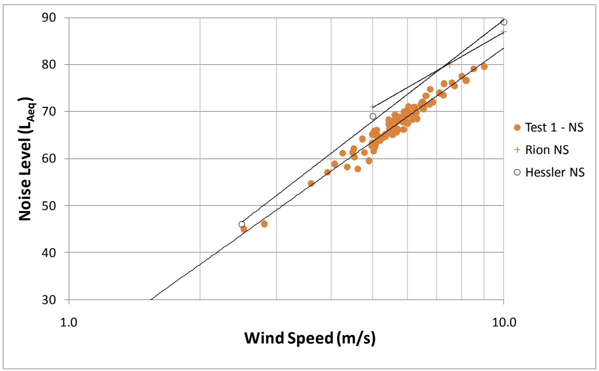

Figure 4. Comparison of results for no wind screen against previously reported wind tunnel measured levels.

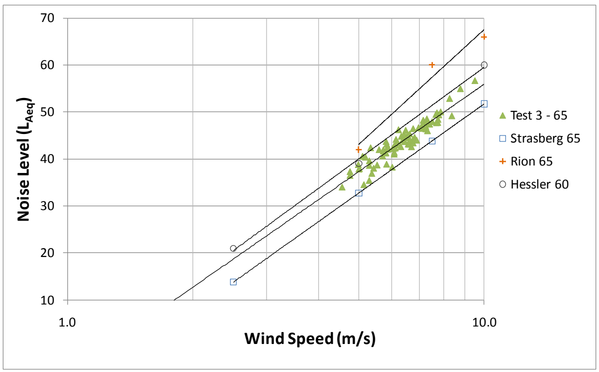

Figure 5. Comparison of results for 65 mm diameter wind screen against previously reported wind tunnel and still air noise levels (Hessler result for 60 mm screen).

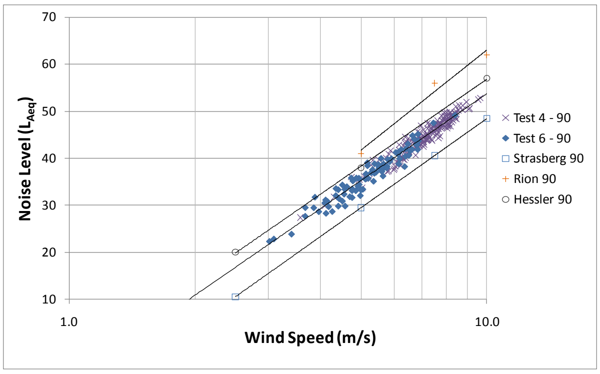

Figure 6. Comparison of results for 90 mm diameter wind screen against previously reported wind tunnel and still air noise levels.

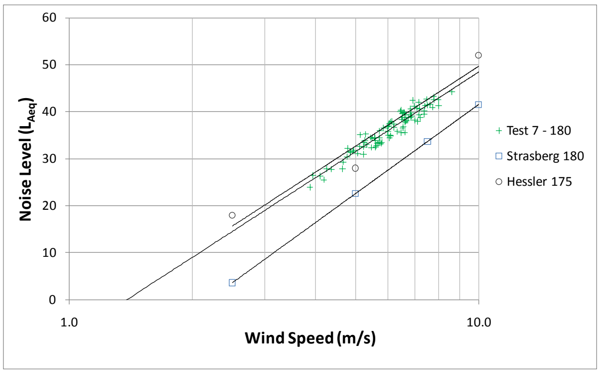

Figure 7. Comparison of results for 90 mm diameter wind screen against previously reported wind tunnel and still air noise levels (Hessler result for 175 mm wind shield).

CONCLUSION

When undertaking background noise measurements at residences surrounding wind farms, it is necessary to ensure that the measured noise levels are the result of noise from ambient wind-generated noise rather than wind-induced noise on the microphone. This investigation was undertaken with the aim of developing an approach that could be used to predict the L_{A90} self noise level which results from wind at the microphone.

This study confirms our previous findings from wind tunnel measurements that showed professional quality wind shields of the same diameter but different manufacturers generate very similar levels of wind induced noise. On this basis, a model for predicting the level of wind-induced noise on the microphone as a function of the wind speed for several wind shield diameters has been developed.

Comparisons between the measured L_{Aeq} noise level and previously reported levels indicate that the level of wind-induced noise under atmospheric turbulence is greater than that measured by moving a microphone through still air, but less than that measured using wind tunnel measurements. While still air measurements and wind tunnel measurements provide ease of comparison of the relative performance of two wind shields, it appears that models developed from those measurements are not suitable for predicting noise levels in atmospheric flow.

This paper demonstrates that both L_{A90} and L_{Aeq} levels resulting from wind-induced noise can be accurately predicted using the developed model.

REFERENCES

van den Berg, G.P. 2006, 'Wind induced noise in a screened microphone', *J. Acoust. Soc. Am.* **119** (2), pp 824-833.

Chong T.P., Joseph, P.F. and Davies P.O.A.L. 2008. 'Design and characterisation of a quiet, low turbulence open jet blow down wind tunnel in ISVR, Southampton, UK' Technical *Report 57774, University of Southampton ISVR http://eprints.soton.ac.uk/57774/*

Corcos G.M. 1963, 'Resolution of pressure in turbulence.' *Journal of the Acoustical Society of America* **35**, pp. 192–199.

Curle N 1955 'The Influence of Solid Boundaries upon Aerodynamic Sound' *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences* **231**(1187), pp505-514.

EPA South Australia 2003, *Wind farms – Environmental Noise Guidelines*, February 2003.

EPA South Australia 2009 *Wind farms – Environmental Noise Guidelines*, July 2009.

Hessler G. F., Hessler D. M., Brandstätt P. and Bay K. 2008, 'Experimental study to determine wind-induced noise and windscreen attenuation effects on microphone response for environmental wind turbine and other applications', *Noise Control Eng. J.*, **56** (4), pp. 300-309.

Kreyszig, *Advanced Engineering Mathematics 8th edition*, Wiley, New York, 1999.

Leclercq D., Cooper J. and Stead M., 2008, 'The use of microphone windshields for outdoors noise measurements', *Acoustics 2008, Geelong, Australia.*

Leclercq D., Doolan C. and Reichl J., 2007, 'Development and Validation of a Small-Scale Anechoic Wind Tunnel', *14th International Congress on Sound and Vibration, Cairns, Australia.*

Pearse J. R. and Kingan M.J. 2006, 'Measurement of sound in airflow', *The Thirteenth International Congress on Sound and Vibration, Vienna, Austria, July 2-6, 2006.*

RION, *'Wind screens and their use' Technical report 202,* Tokyo, (undated).

RION, *'Technical notes, Sound level meter, NL-21 / NL-31 no. 32042 06-06',* Tokyo, (undated).

Standards Australia 2010, AS4959:2010 Acoustics- Measurement, prediction and assessment of noise from wind turbine generators, Sydney, 2010.

Standards New Zealand 1998 'NZS 6808:1998 Acoustics- The assessment and measurement of sound from wind turbine generators' 1998.

Standards New Zealand 2010, NZS 6808:2010 Acoustics- Wind farm noise, Wellington, 2010.

Schewe G. 1983. 'On the structure and resolution of wall-pressure fluctuations associated with turbulent boundary layer flow.' *Journal of Fluid Mechanics.* **134** : 311-328.

Strasberg, M. 1988, 'Dimensional analysis of windscreen noise', *J. Acoust. Soc. Am.* **83** (2), pp 544-548.