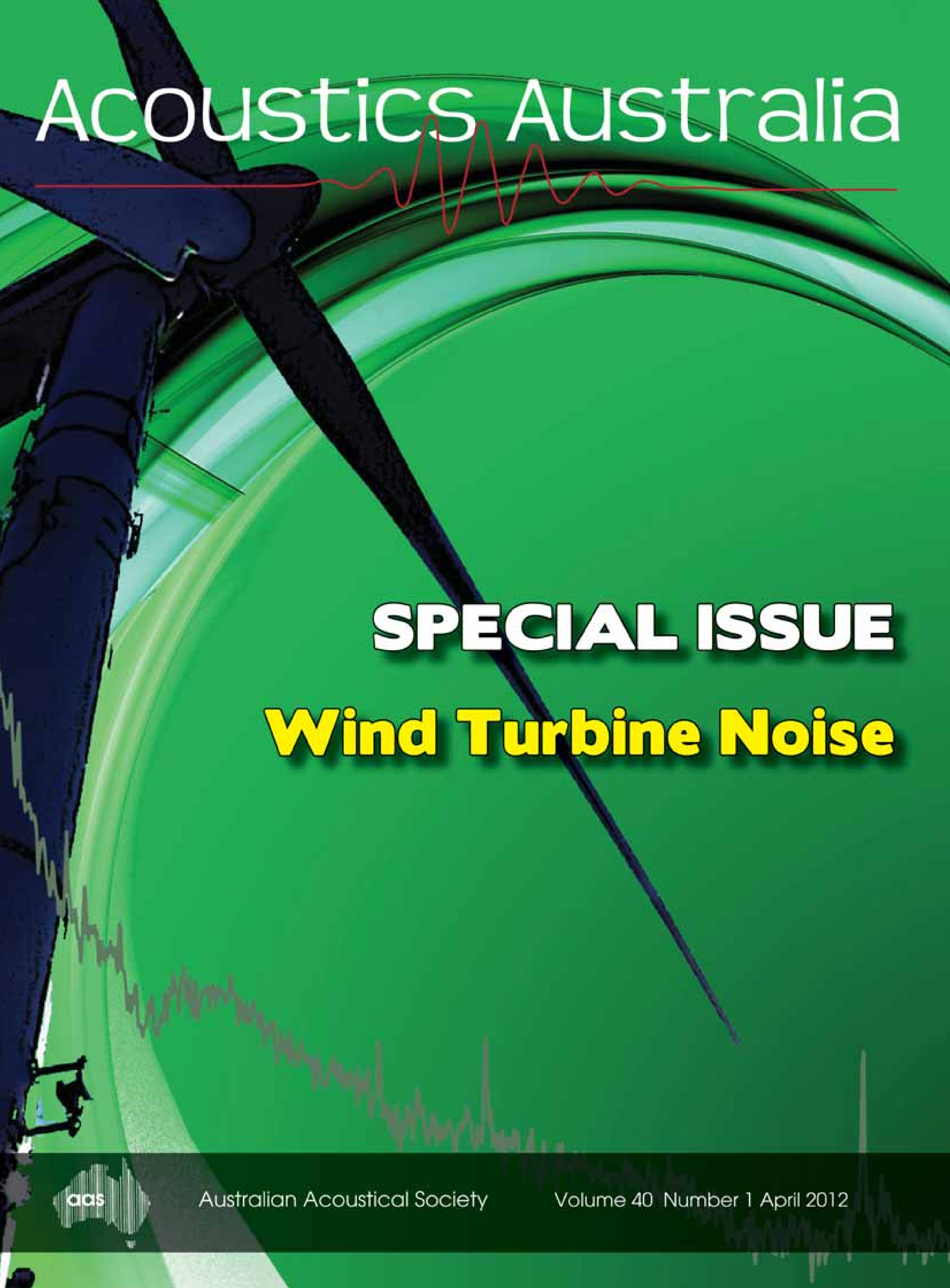
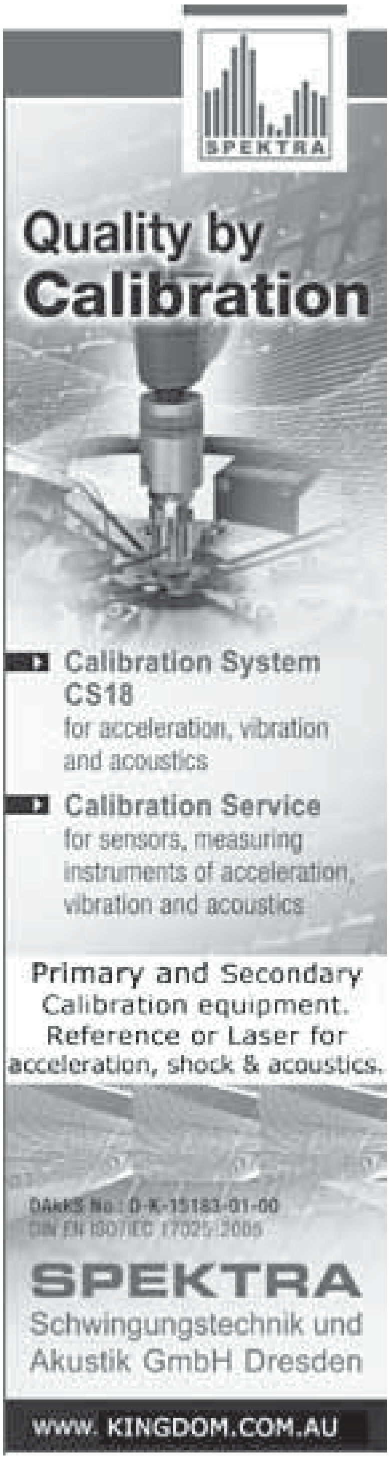
Acoustics Australia



SPECIAL ISSUE

Wind Turbine Noise

Australian Acoustical Society
Volume 40 Number 1 April 2012



3263M8
3097A
3225M23/24
High output
3224A1

Acoustics Australia

Acoustics Australia
General Business
(subscriptions, extra copies, back issues, advertising, etc.)
Mrs Leigh Wallbank
P O Box 70
OYSTER BAY NSW 2225
Tel (02) 9528 4362
Fax (02) 9589 0547
wallbank@zipworld.com.au

Acoustics Australia
All Editorial Matters
(articles, reports, news, book reviews, new products, etc)
The Editor, Acoustics Australia
c/o Nicole Kessissoglou
School of Mechanical and
Manufacturing Engineering
University of New South Wales
Sydney 2052 Australia
+61 401 070 843 (mobile)
AcousticsAustralia@acoustics.asn.au
www.acoustics.asn.au

Australian Acoustical Society
Enquiries see page 94

Acoustics Australia is published by the Australian Acoustical Society
(A.B.N. 28 000 712 658)
ISSN 0814-6039

Printed by
Cliff Lewis Printing
91-93 Parraweena Rd,
CARINGBAH NSW 2229
Tel (02) 9525 6588
Fax (02) 9524 8712
email: matt@clp.com.au
ISSN 0814-6039

Vol. 40, No. 1 April 2012

PAPERS

TECHNICAL NOTES

Cover design: Helena Brusic

Noise Loggers

Norsonic

Sound Meters & Analysers

Low Cost Real-Time 1/1 & 1/3

Remote access

Nor-136
OHS
Vibration

Nor-140
Analyser

Nor-277 Tapping Machine
- Remote Operation
- Battery & Mains
- Low weight
- Compact

1/1 & 1/3 Real-Time Loggers

BELCUR PTY. LTD.

Ph: 07 3820 2488 : 0418 491 409
belcur@optusnet.com.au
www.norsonic.com
93 Cumberland Drive, Alex Hills, Qld 4161

clp

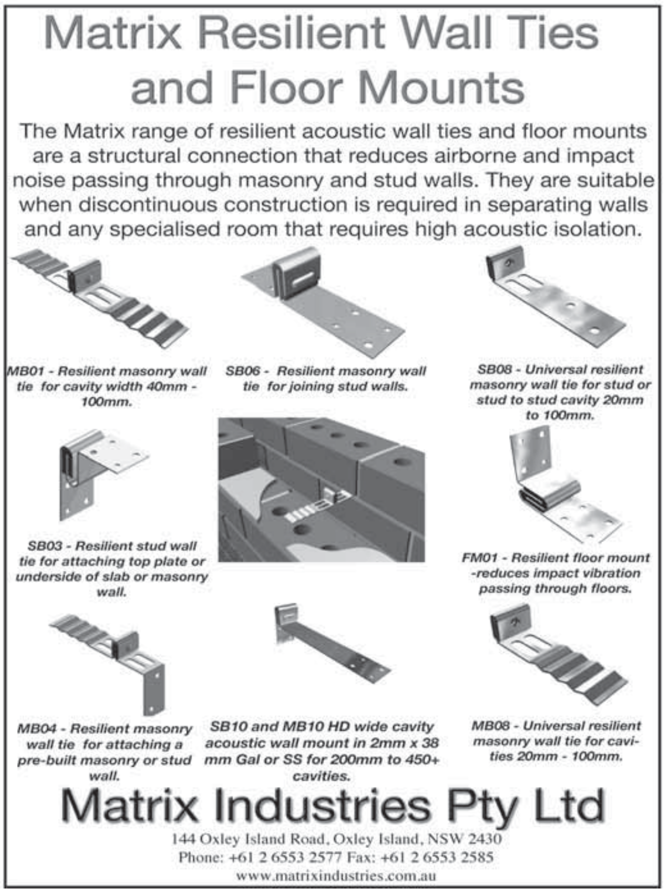
cliff lewis printing

Specialists in Scientific Printing and Publishing

MORE THAN JUST PRINTING

- **Art and Design**
- **Branding Design**
- **Stationery**
- **Binding & Finishing**
- **Promotional Material**

t (02) 9525 6588 f (02) 9524 8712
e printing@clp.com.au
www.clp.com.au
91-93 Parraweena Road, Taren Point, NSW 2229



Matrix Resilient Wall Ties and Floor Mounts

The Matrix range of resilient acoustic wall ties and floor mounts are a structural connection that reduces airborne and impact noise passing through masonry and stud walls. They are suitable when discontinuous construction is required in separating walls and any specialised room that requires high acoustic isolation.

MB01 - Resilient masonry wall tie for cavity width 40mm - 100mm.

SB06 - Resilient masonry wall tie for joining stud walls.

SB08 - Universal resilient masonry wall tie for stud or stud to stud cavity 20mm to 100mm.

SB03 - Resilient stud wall tie for attaching top plate or underside of slab or masonry wall.

FM01 - Resilient floor mount -reduces impact vibration passing through floors.

MB04 - Resilient masonry wall tie for attaching a pre-built masonry or stud wall.

SB10 and MB10 HD wide cavity acoustic wall mount in 2mm x 38 mm Gal or SS for 200mm to 450+ cavities.

MB08 - Universal resilient masonry wall tie for cavities 20mm - 100mm.

Matrix Industries Pty Ltd
144 Oxley Island Road, Oxley Island, NSW 2430
Phone: +61 2 6553 2577 Fax: +61 2 6553 2585
www.matrixindustries.com.au

MESSAGE FROM THE PRESIDENT

We start the year with a special and bumper edition of Acoustics Australia based on the theme of wind turbine generators, wind farms and low frequency noise. This special edition evolved from our recent annual conference Acoustics 2011 Gold Coast topic of interest – Wind Turbine Acoustics and the workshop on Wind Turbines and Low Frequency Noise that was chaired by Dr Norm Broner. Norm has co-edited this edition, was instrumental in driving the papers submitted and we thank him for his dedication and work in this area.

Whilst on the subject of dedication and service I am acutely aware that several divisions committees are struggling with achieving quorums at AGM's, sourcing technical meeting speakers and topics, and with poor attendance. Please assist your local divisions and their respective committees, they devote their time and effort to these tasks and respectfully should be paid in kind. From my experience, it is a worthwhile positive experience along with the diversified membership that you meet. We also have a wide variety of interesting technical presentations, and site visits which also can be used for time towards continuing professional development.

Our General Secretary, Richard Booker, has advised that as of mid March 2012 there were still a significant number of members (around 18%) who are still in arrears with their membership subscriptions for 2011-2012. Our yearly subscriptions are not onerous compared with other societies and institutions, and we rely on these subscriptions to operate the Society and produce a world class acoustics journal. To avoid late fees please attend to your subscriptions in a timely manner.

I would like to thank Marion Burgess who on behalf of AAS:

- Attended the Standards Australia AGM on 18 November 2011. There are a number of outcomes from this AGM that affect the AAS and our members on the standard committees and these are currently being addressed.
- Is representing us at the next WESPAC board meeting prior to the Hong Kong Acoustics 2012 WESPAC conference in May 2012

I refer to the recent Enews email issued 22 March 2012 by Engineers Australia in which their chief executive, Stephen Durkin, states the following:

- *Engineers Australia has been monitoring the proceedings of the Queensland Floods Commission of Inquiry on behalf of its membership to establish facts of the events surrounding the floods.*
- *We are currently analysing the 654-page Final Report to understand the legal and policy ramifications of its recommendations for engineering professionals.*
- *Engineers have a critical role to play in protecting the community, especially in times of crisis. We demand that our members adhere to Engineers Australia's Code of Ethics and perform their jobs in accordance with the highest standards.*

Regarding the above last item, in particular, as a member of the AAS, we too have a Code of Ethics that must be adhered to and it is a timely reminder to reflect on these when performing our duties. Our code of ethics can be easily accessed on our website at *http://www.acoustics.asn.au/joomla/codeethics.html*

It is with great sadness and sorrow that we were advised that Vale Warren Renew recently passed away. Warren was a member of the Queensland Division since its founding and before that was Member of the Queensland group in the NSW Division from the early 1970s. Warren was a member of the foundation Division Committee and with Bob Hooker represented the Division on Federal Council. On behalf of the society I would like to take this opportunity to pass on our gratitude for Warren's services and sincere condolences to his family. Warren's obituary is provided on page 87 of this issue.

I noticed the recent final call email for abstracts for this year's Australian Acoustical Society's national conference: Acoustics 2012 Fremantle, to be held at The Esplanade Hotel, Fremantle, Western Australia, from 21 to 23 November. The theme of the conference is *Acoustics, Development and the Environment*. Late November in Fremantle is a delightful time of year, and the Esplanade Hotel is right in the heart of this vibrant place. Come and join us for what should be an excellent conference.

Peter Heinze

MESSAGE FROM THE GUEST EDITOR

It started out as an idea by the organising Committee for a workshop at the annual Acoustical Society Conference on the Gold Coast in November last year, and turned into a very successful and well attended workshop on Wind Turbine and Low Frequency Noise. Given the success of the workshop, I thought it would be a great idea to take it one step further and devote a special edition of Acoustics Australia to the issue of Wind Turbine and Low Frequency Noise, especially as the question of Wind Turbines and possible health effects has received much press attention over the last year or two. So I set about contacting various people to contribute and here we are. I thank those who responded positively for their contributions and for putting in the effort to get the papers written in time for our press deadline. I thank those people who contributed by reviewing papers and providing constructive comments so as to improve the quality of the papers in this edition. And I want to give a special thanks to Nicole Kessissoglou, our Editor, who put in a tremendous effort to make sure that the copy met all the requirements for manuscripts and, in particular, for ensuring that the many references in the various papers met the requirements of Acoustics Australia. I would be very happy if people would engage the Authors via a Letter to the Editor in the next edition of Acoustics Australia. Congratulations to all and I hope you enjoy reading this special issue.

Norm Broner

WIND TURBINE NOISE MECHANISMS AND SOME CONCEPTS FOR ITS CONTROL

Con J. Doolan, Danielle J. Moreau and Laura A. Brooks
School of Mechanical Engineering, The University of Adelaide, Adelaide, SA 5005, Australia

The aerodynamic noise production mechanisms of modern horizontal axis wind turbines are reviewed. An engineering analysis of the time and frequency scales from three noise sources, leading edge turbulence interaction noise, trailing edge noise and blade-tower interaction noise is presented. The analysis shows that noise sources are present from low-frequencies (1-4 Hz) to over 500 Hz for a representative wind turbine. The results of the analysis are used to explain amplitude modulation observed during noise measurements at a European wind farm. Daytime noise measurements close to a South Australian wind farm are also presented that show amplitude modulation. The paper concludes with a description of conceptual ideas for the control of wind turbine noise.

INTRODUCTION

Climate change policies have forced governments around the world to mandate large increases in wind power. Consequently, wind power is now one the fastest growing energy sources, with worldwide generation predicted to increase from 150 TWh in 2008 to 1068 TWh (per annum) by 2030 [1]. In Australia, wind energy production is set to increase from 4 TWh in 2007-8 to over 40 TWh by 2030.

Wind energy increases will mean that many more wind turbines will be installed, inevitably closer to more people and their residences. Noise from wind turbines is a serious and controversial issue and it can be expected to become more of a concern as wind power production is increased. Surveys [2] show that noise from wind turbines is annoying to people and that it is perceived to be more annoying than other forms of industrial noise at the same level. To accommodate the expected increase in the number of installed wind farms and to reduce public disquiet, there needs to be more research and development into how wind turbine noise is generated and how it can be controlled.

The purpose of this paper is to review the aeroacoustic source mechanisms that are on a wind turbine blade and possible methods for reducing their strengths. An engineering analysis is performed that gives an indication of the frequencies that contain most of the energy for each type of source. Some recently published results on wind farm noise will be discussed that suggest that the noise from multiple wind turbines can interact, creating intermittent regions of increased noise amplitude. Daytime noise measurements taken several hundred meters from a South Australian wind farm are also presented. These measurements show noticeable amplitude modulation that is similar to that of European data. An explanation for the noise phenomena is suggested in this paper along with some conceptual ideas for its control.

WIND TURBINE AERODYNAMIC NOISE GENERATION MECHANISMS

The major noise sources on a wind turbine are located at the gearbox and the fast moving outer blade tip region [3]. Gearboxes on modern turbines are now very quiet [4] and therefore the dominant noise sources are located on the blade. These noise sources are aeroacoustic in origin and in order to understand them, a review of blade aerodynamics is first necessary.

Figure 1 shows an idealised picture of a wind turbine outer blade tip moving through air. The major aerodynamic phenomena that influence noise are shown. Ahead of the blade is atmospheric (or other) turbulence. When the blade interacts with these turbulent eddies, unsteady lift is generated by the blade. The unsteady lift creates a dipole-like sound source located at the blade leading edge [5]. This is called inflow or leading-edge interaction noise and has a dipole-like directivity pattern.

The flow of air over the blade surface creates a boundary layer, due to the viscous shear present between the blade and the air. The flow conditions on large wind turbine means this boundary layer will usually transition to a turbulent state by the time the air reaches the trailing edge. Turbulence by itself is a very inefficient radiator of sound [6], but when turbulent eddies pass a sharp edge (such as the trailing edge of a wind turbine blade), the acoustic waves created by turbulence are reinforced via an edge diffraction mechanism [7], making them much more efficient. This is known as trailing edge noise [8] and is the major noise source on a wind turbine [4, 9, 10].

An important quality of trailing edge noise is its directivity pattern, which is different from a monopole or dipole. Figure 2 illustrates the directivity pattern of trailing edge noise, assuming that the frequency of sound emitted from the trailing edge is high enough so that the airfoil can be considered a semi-infinite half-plane. Most of the sound is radiated forward of the blade (in what is known as a cardioid directivity pattern), in the direction of rotation, while little is radiated behind. This explains the "swish" character of wind turbine noise whereby an observer on the ground will periodically receive fluctuations in acoustic energy as the blade rotates. Here, "swish" is defined as the amplitude modulation of broadband aerodynamic noise created by the blades at the blade passing frequency, which is usually about 1 Hz [11]. The received acoustic signal has both a high frequency broadband character (due to turbulence in the blade boundary layer) and a low frequency amplitude modulation (due to the combination of the directivity function and convective amplification of sound due to blade rotation). It is not clear whether reports of "thumping" noise [12] at large distances are due to swish or another effect such as blade tower interaction.

The interaction of the rotor blade with the tower can also be an important source of noise. In the early development of wind power, downwind turbines were common and produced high levels of noise associated with the interaction of the tower wake with the rotor blades. This form of noise is generated in a similar way to the leading edge interaction with turbulent eddies, though in this case, the eddies are created by the tower itself. Modern horizontal axis wind turbines place the rotor upstream of the tower, thus eliminating the wake-rotor interaction. However, the blades still pass through a region of perturbed flow upstream of the tower [3], creating unsteady lift and hence noise.

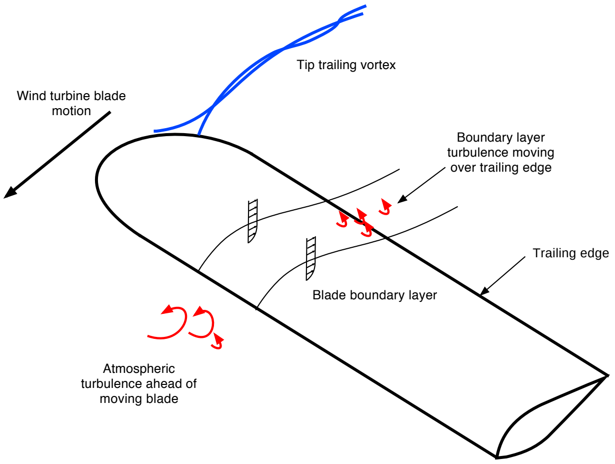


Figure 1. The flow over a wind turbine blade tip

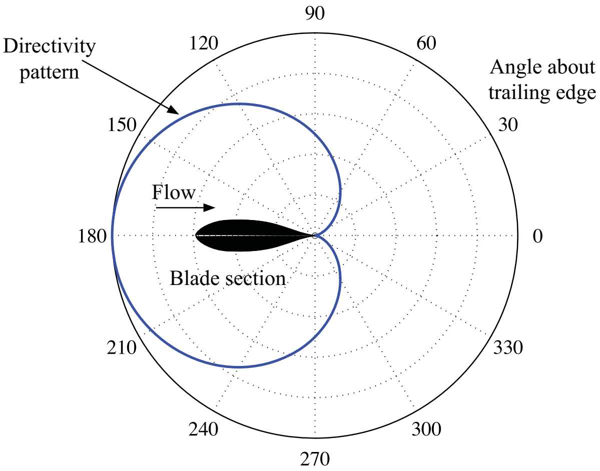


Figure 2. Trailing edge noise directivity (high frequency case)

There are two other, important noise sources that should be mentioned in this brief review. The first is airfoil tip noise, which is generated by flow over the blade tip resulting in a trailing vortex system (see Fig. 1). This form of noise generation is similar to trailing edge noise as it involves the interaction of turbulence with an edge. It is not believed to be as significant as the trailing edge source [4]; however, more work needs to be done in this area.

The other noise source to be considered is airfoil tonal noise [13]. Here, discrete vortices form either in the boundary layer or wake and create intense tonal noise, with or without a self-reinforcing feedback loop [14]. Tonal noise occurs at low-to-moderate Reynolds numbers (approximately 50,000 to 250,000), hence is not usually a problem for large wind turbines that operate at higher Reynolds numbers. Small wind turbines (≤10 kW) may operate at conditions where tonal noise constitutes a major part of the noise source energy. A summary of the wind turbine noise sources discussed here is given in Table 1.

Table 1. Summary of wind turbine noise sources

Type	Directivity	Mechanism
Leading-edge interaction noise	Dipole	Atmospheric turbulence impinging on rotor trailing edge
Trailing edge noise	Cardioid	Boundary layer turbulence passing over rotor trailing edge
Blade tower interaction	Dipole	Rotor blade passing through flow perturbed by tower
Tip noise	Cardioid	Turbulance interacting with rotor tip
Airfoil tonal noise	Cardioid	Vortex shedding and/or resonant feedback loop on rotor blade boundary layer

FREQUENCY AND TIME SCALES

This section will discuss the frequency and time scales associated with the major aerodynamic noise sources on a horizontal axis wind turbine. These are broadband noise associated with turbulence leading-edge interaction, airfoil trailing edge noise and impulsive noise associated with the blade-tower interaction. To perform the analyses, the wind turbine used by Oerlemans and Schepers [11] was used. This turbine is a GE 2.3 MW prototype test turbine with a rotor diameter of 94 m and a tower height of 100 m. For a wind speed of 9.75 m/s and a rotational speed of 14.7 RPM, an empirical model [15] was used to estimate the boundary layer height at the trailing edge (needed to estimate trailing edge noise frequencies). Assuming a tip chord of 1.5 m, the trailing edge boundary layer height was estimated to be 24 mm at the tip of the blade (maximum radius).

Broadband Energy

Broadband energy is created by the interaction of turbulence with the leading and trailing edges. Turbulence leading-edge interaction noise is dominated by the spectrum of the inflow turbulence in the atmospheric boundary layer. The peak energy [3] for this type of noise is contained at a frequency

$$f_{peak} = \frac{StV_{tip}}{h - 0.7R} \tag{1}$$

where the Strouhal number is $St = 16.6$, h is hub height, V_{tip} is the rotor tip speed and R is the blade radius. Using the wind turbine of Oerlemans and Schepers [11], it can be expected that peak energy will occur at approximately 18 Hz.

Airfoil trailing edge noise is directly related to the surface pressure spectrum at the trailing edge [8]. There are many well-known empirical models that allow an estimate of the spectral energy distribution beneath the airfoil boundary layer. A recent and well-validated model is the one by Goody [16]. Using this model, we are able to estimate the frequency at which most of the turbulent energy in the boundary layer is converted to fluctuating surface pressure and hence far-field noise.

Goody [16] shows that surface pressure spectra under boundary layers can be scaled using the boundary layer height and that the peak energy is contained approximately a decade either side of a frequency given by the following relationship

$$\frac{\omega\delta}{U_e} \sim 1 \qquad (2)$$

where $\omega = 2\pi f$, f is frequency, δ is boundary layer height at the trailing edge and U_e is the velocity external to the boundary layer at the trailing edge. Using Eq. (2), the trailing edge noise generated by the blades is expected to have most energy centred at about 465 Hz. This is in broad agreement with the time-averaged noise measurements of Oerlemans and Schepers [11], which show most acoustic energy from the trailing edge of a wind turbine occurs within the 160-1500 Hz frequency range. Below 160 Hz, it is expected that the effects of trailing edge noise will diminish and the effects of turbulence leading edge noise to become more important.

Blade-Tower Interaction

Impulsive noise may be generated by the interaction of the blades with the perturbed flow upstream of the tower. Figure 3 illustrates the phenomenon. The flow over the tower creates a region of non-uniform flow upstream of the tower, represented by the curved streamlines in Fig. 3. As the rotor blade passes through this perturbed flow region, the angle of attack changes on the blade, causing a fluctuation in lift force. This fluctuation in lift force creates radiated sound with a time scale associated with the size of the perturbed flow region upstream of the tower.

To estimate the time scales associated with blade-tower interaction (BTI) a first-order model was created. The model uses potential flow theory to estimate the flow field upstream of the tower. This is a valid use of potential flow theory as no boundary layer separation occurs in this region and inviscid effects dominate the flow. Using the flow field estimate, the variation of angle of attack with time is estimated for a blade section passing though the perturbed flow region. This angle of attack history is then converted into a transient lift data record using thin airfoil theory. Using the theory of Curle [17] and assuming a compact source, the source strength can be estimated by taking the time derivative of the lift. Using this method, a first-order estimate of BTI noise source strength, appropriately non-dimensionalised, is

$$\frac{\dot{L}D_T}{V_{tip}qcl} = 2\pi\dot{\alpha}\,\frac{D_T}{V_{tip}} \qquad (3)$$

where $\dot{L}$ is the time derivative of Lift, D_T is the tower diameter, q is the dynamic pressure of the flow approaching the blade tip, c is the blade chord, l is the span wise region of the blade under analysis (assumed to be the outer 20% of the rotor blade) and $\dot{\alpha}$ is the time derivative of the blade angle of attack.

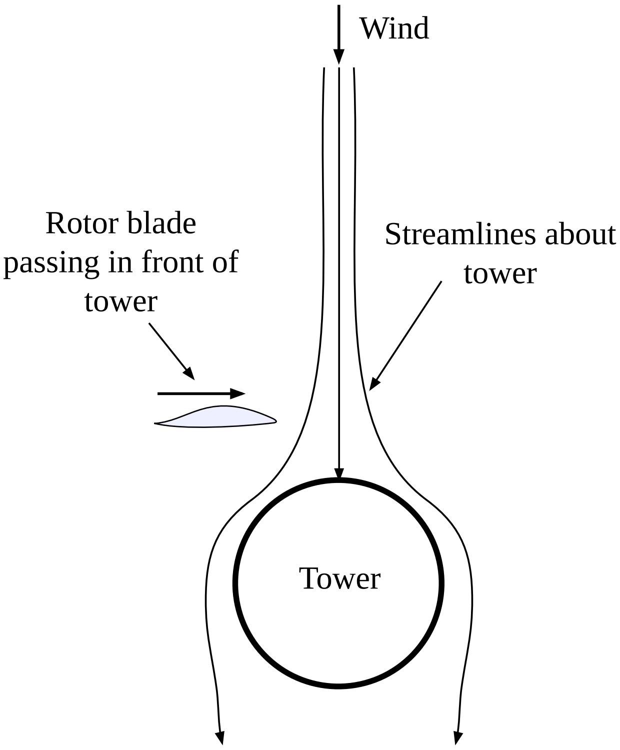


Figure 3. Blade tower interaction

Using the turbine described previously, an understanding of the time and frequency scales associated with the BTI can be determined. Figure 4 shows the variation of the strength of the BTI noise source during one complete revolution of the turbine. Time is shown in a non-dimensional form using the tower diameter and tip speed to determine an appropriate normalising time scale. The noise source calculation assumes the diameter of the tower $D_T = 4$ m and the rotor disc is positioned 4 m upstream of the tower. The calculation was also performed for the blade tip region of the rotor.

As shown in Fig. 4, three pulses are generated during each revolution. The creation of each pulse occurs when a blade passes the tower and interacts with the perturbed flow region. Such a repetitive impulsive noise source will contain a variety of frequency components. The autospectrum of the impulsive BTI noise source signal is shown in Fig. 5. The spectrum is shown in non-dimensional units on both axes. The spectral decomposition of the BTI noise shows multiple frequency components. The most energy is contained at $fD_T/V_{tip} = 0.12$ or 2.2 Hz and multiple components from $fD_T/V_{tip} = 0.04$ (0.8 Hz) to $fD_T/V_{tip} \sim 0.6$ (11 Hz).

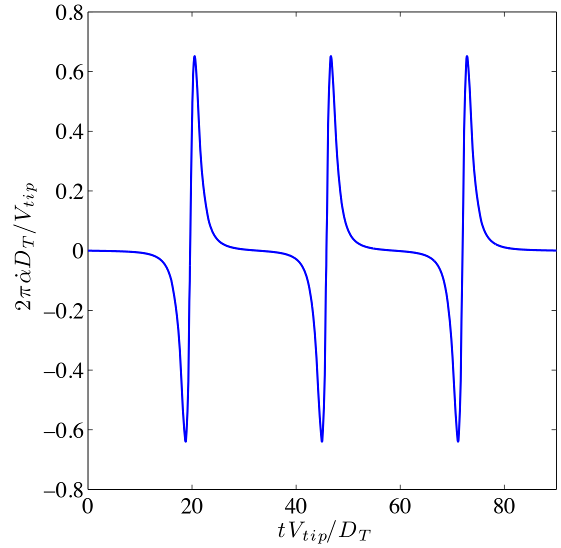


Figure 4. Time variation of BTI noise source strength over one revolution of the GE prototype wind turbine

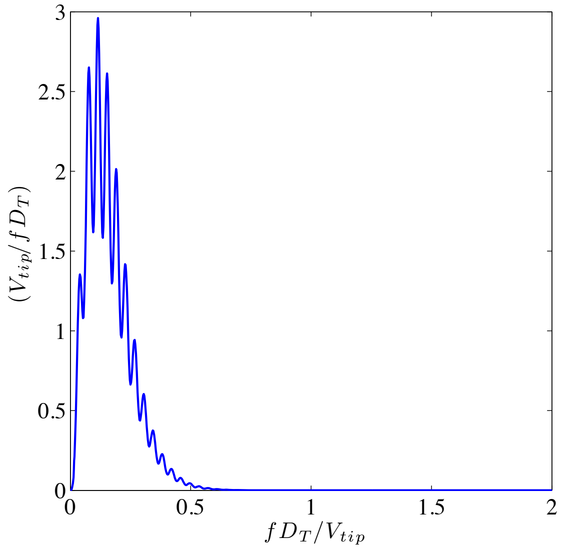


Figure 5. Autospectrum of the BTI noise source signal

WIND TURBINE NOISE MEASUREMENTS

The preceding analysis gives an indication of the frequency scales that we can expect from three dominant wind turbine aerodynamic noise sources. Note that there are more possible sources and these may also have significant contribution to the observed noise, but this paper will concentrate on blade swish and BTI to explain observed behaviour.

Broadband noise at relatively high frequency is the dominant component of blade swish. Although modulated at the blade passing frequency (~1 Hz), blade swish cannot be considered a low frequency noise source. Rather, it is an amplitude modulated broadband source with dominant energy at about 500 Hz (for the example turbine in this paper). Swish has been recorded from wind turbines for many years [11, 18] and can be attributed to noise generated at the trailing edge of the outer part of the turbine and its forward looking directivity pattern coupled with blade rotation.

The analysis above also shows that a low frequency noise source is also present due to the BTI and turbulence leading-edge interaction mechanisms. However, the analysis is only sufficient to predict the dominant frequencies. Determination of the strength of these noise sources will depend on many factors that include the aerodynamic coupling of the blade and tower, viscous effects on the blade, the dimensions of the turbine and tower as well as the aeroelastic properties of the rotor and atmospheric turbulence levels. The analysis provides assistance to those taking noise measurements and in the interpretation of existing data.

Some observations may be explained by the proposed models described here. Recent measurements and observations taken at a European wind farm [12] show a marked difference between day and night. During a summer day, the level of noise from the wind farm was low or not perceivable, even in strong winds (on the ground). On "quiet nights", residents at distances of 500-1000 m from the wind farm observed "pile-driving" noise at a rate coinciding with the blade passing frequency. An observer at 1900 m described the noise as an "endless train". Within the wind farm (close to the turbines) audible swish-like noise was observed day and night however, no thumping or pile-driving noise was audible.

To explain some of these observations, Van den Berg [12] pointed out that the state of the atmosphere at night is different to that in the day. In fact, when the atmosphere becomes stable at night the wind at ground level (and at 10 m which is the reference height used to characterise the atmospheric boundary layer) can be relatively low while at hub height, it can be very high. In fact, the hub height wind speed was shown to be 2.6 times higher at night than what would be expected if the standard day-time atmospheric model was used. This created 15 dB more noise from the turbine than would be expected for the same wind speed at 10m height during the day. As the ground level wind speed is small, there are low levels of background noise as well thus enhancing the ability of an observer to perceive noise. As wind turbines grow in capacity, this effect can be expected to become greater due to the required increase in tower height to accommodate large radius rotors.

Using A-weighted noise measurements taken over a 50 ms time-base, Van den Berg [12] was able to show that the noise level fluctuated at a rate of about 1 Hz at a residence's home 750 m from the wind farm. The amplitude of this fluctuation varied between 1 and 5 dB at various times throughout the measurement period. It was inferred that this variation was due to periods of time when noise emission from multiple wind turbines in the farm become in or out of phase. Van den Berg [12] states that this is the cause of the impulsive noise observed outside of the wind farm. Residents expressed that the noise is more annoying at night when the rotor speed is high, thus linking the stability of the atmosphere to annoyance.

The analysis of the previous section is now used to explain these observations. The time varying measurements are A-weighted and therefore are dominated by noise with frequencies that are linked to trailing edge noise. The amplitude modulation observed is hence not due to the interaction with the tower but is due to the unique directivity associated with the trailing edge source. The reinforcement effects observed by Van den Berg [12] are still caused by multiple turbines except that the sound is emitted directly from the trailing edge rather than from BTI, as suggested by Van den Berg in Ref. [19].

This is not to suggest that the BTI source is not important. In the same way as the broadband swish noise can be reinforced and become unexpectedly high outside of a wind farm, it is not unreasonable to expect that the same may be true for BTI noise. Currently, there is no methodology or dataset available that can allow researchers to accurately quantify BTI noise. However, high levels of low-frequency BTI noise may couple with structural resonances of homes and workplaces, creating audible noise that may have an annoying character. As wind turbines become larger, the BTI noise source can be expected to become stronger. A similar argument may be applicable to turbulence leading-edge interaction noise as well, albeit with dominant energy levels at higher frequencies.

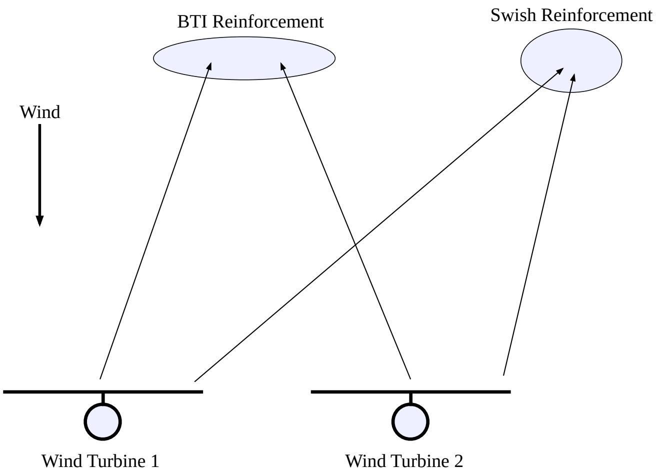


Figure 6. Plan view of two wind turbines with possible zones of noise reinforcement

The reinforcement of trailing edge and BTI noise sources may create regions about the wind farm where noise fluctuation amplitudes are high. As a means to explain wind farm noise reinforcement, a simple schematic showing two wind turbines in plan view is displayed in Fig. 6. It shows noise propagating upwind of the turbines only (other directions are omitted for clarity) and regions where broadband swish noise and BTI noise may be reinforced. Of course, the sound will couple with atmospheric propagation effects making the actual sound paths more complicated than is represented in the figure, but conceptually the idea is the same. Note that BTI noise signals, as described in this paper, may cancel each other as well reinforce as they are pulses of temporally coherent sound; however, the broadband noise signals are incoherent random signals and may only reinforce and not cancel each other. If this model is correct, it may explain why some residents become annoyed, both inside and outside a home. While broadband swish noise may annoy people outside, its high frequency components may be attenuated inside a home. However, if BTI reinforcement occurs at the same location, noise from BTI-excited structural vibration may also be apparent inside the home. While much more work is required to understand BTI and swish reinforcement, the model presented provides a framework for understanding and addressing public concerns about wind turbine noise.

Preliminary wind turbine measurements in South Australia

To investigate amplitude modulation of operational wind turbines, a series of daytime measurements were taken at a South Australian wind farm. Acoustic data from a line of 7 turbines (6 of which were operative) were recorded on a November afternoon in 2011 at a sampling frequency of 51.2 kHz using a Brüel and Kjær 4190 ½ inch free-field microphone connected to a National Instruments Data Acquisition system (NIDAQ 9234). The microphone was located at broadside to the wind farm at a distance of several hundred metres. The microphone was covered in a foam windsock, was held in a microphone stand at 0.75 m height and was directed towards the nearest turbine.

Conditions were sunny with very little cloud cover. The microphone was located downwind of the wind farm. Wind speed was not measured directly; however, a wind speed of 17 km/h (4.72 m/s) was recorded at the closest Bureau of Meteorology weather station on the afternoon of the measurements. Noise from the wind farm was clearly audible.

Acoustic data were bandpass filtered to 500-5000 Hz. A 12-second long time series of the measured data is shown in Fig. 7. The signal amplitude is observed to fluctuate temporally, with elements of periodicity apparent.

The A-weighted sound pressure level (SPL) of the signal is shown in Fig. 8, which was calculated by separating the signal into 125 ms long segments, performing a fast Fourier transform on each segment then applying an A-weighted filter and integrating to obtain a mean energy (equivalent to the time weighting FAST setting on a sound level meter). The single SPL value from each time segment was then plotted in Fig. 8, yielding an A-weighted SPL as a function of time. It can be seen that the periodicity in the signal amplitude becomes more apparent and these periodic amplitude fluctuations are observed to dominate the signal. The expected signal maxima and minima corresponding to a 1.28 second period are shown in the figure, and although not every point corresponds to a maxima or minima, the trend is apparent. The 1.28 second period is within 1.2% of the wind turbine blade pass frequency estimated from video footage, supporting the hypothesis that the amplitude fluctuations are due to amplitude modulation at the blade passing frequency. Figure 8 also shows, for comparison, acoustic data recorded on the same afternoon (and using the same methodology) at a location further from the wind turbine farm where wind turbine noise was not audible. By comparing the two data sets, it is apparent that both the amplitude of noise within the 500-5000 Hz range, and the amplitude of any temporal fluctuations are significantly smaller in this second measurement.

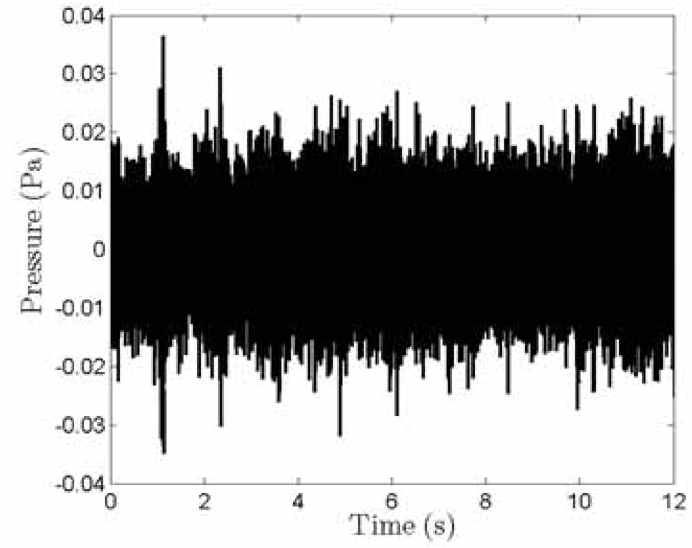


Figure 7. Time series of acoustic data

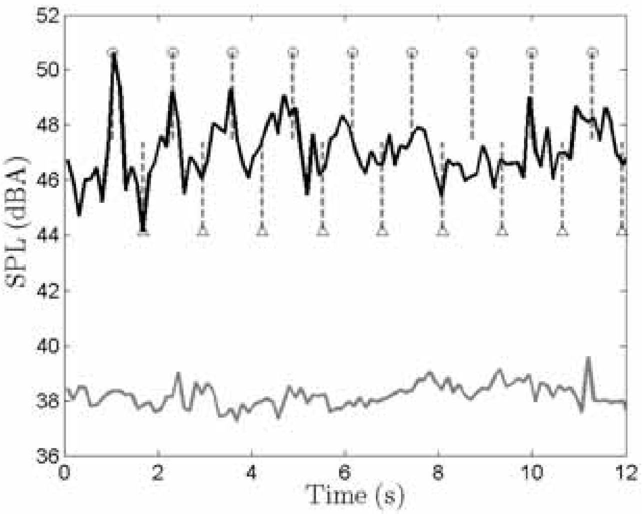


Figure 8. A-weighted SPL with 125 ms FFTs (FAST): near-turbine measurements (black) and measurements (not simultaneous) at a nearby location where wind turbines were not audible (grey). Circles and triangles with dashed lines represent expected signal maxima and minima corresponding to blade pass frequency, respectively

WIND TURBINE NOISE CONTROL CONCEPTS

This section of the paper will outline methods of controlling both broadband swish and BTI noise.

Passive Control Methods

The most efficient means of controlling trailing edge noise is to reduce the strength of its source. One of the most direct methods for doing this is to alter the blade shape in order to influence the nature of the turbulent boundary layer at the trailing edge. Methods of doing this vary between ad-hoc design changes to computationally demanding aeroacoustic shape optimisation [20, 21]. Recently, Jones et al. [22] developed an optimisation procedure using a semi-empirical model of trailing edge noise to develop new, low noise airfoil designs. One design achieved a 2.9 dB OASPL noise reduction (over the original NACA 0012 shape used to start the optimisation process) whilst also reducing drag. It can be expected that much quieter airfoil designs will be developed as noise prediction methods become more accurate and efficient.

Another important passive noise control technique for trailing edge noise is the use of trailing edge serrations. These are saw-tooth extensions placed on the trailing edge. As originally pointed out by Howe [23], the serrations present a trailing edge at an angle to the stream wise flow direction thus reducing the efficiency of the edge sound source. Theoretically, serrations are able to reduce noise by a large amount. However, in practice, serrations do not reduce noise as much as theory suggests [9, 24, 25] and this may be due to the production or re-orientation of turbulence by the serrations themselves. Porous trailing edge inserts [26] are also promising noise reducing devices, but may have limited applicability due to dirt accumulation in the pores, requiring regular costly maintenance.

While shape modifications or inserts may provide an effective means of trailing edge (broadband swish) noise control, passive means of BTI noise are limited. One answer is to increase the distance between the rotor tip and tower. The current spacing between the rotor tip and tower has probably been maximised by the manufacturer. Increasing this distance will require extensive redesign of the gearbox and nacelle and could introduce more problems such as shortened mechanical life, vibration and noise.

Active Control Concepts

Swish and BTI reinforcement occurs due to in-phase noise production on multiple wind turbines. As each turbine rotates in the same direction and experiences close to the same wind speed and direction they will turn at very nearly the same angular velocity. If the azimuthal phase of a group of wind turbines is nearly the same, then we would expect that their sound would be produced at nearly the same time and propagate in a similar manner. Given that broadband swish has a forward propagating directivity, then zones of high amplitude modulation of trailing edge noise are expected. BTI noise has the directivity of a dipole, hence an array of in-phase BTI sources will create alternate zones of reinforcement and cancellation.

Active phase desynchronisation is a concept that can potentially alleviate this situation. By monitoring the phase of each blade in a wind farm, small adjustments to the rotor blade pitch or brake can be made to alter the blade's phase and ensure that noise reinforcement does not occur at a particular receiver location or locations, such as homes. While this seems a simple and cost effective solution to the problem, it may be difficult to implement without more knowledge of how the noise sources are produced, their strengths and how they propagate in the atmosphere.

SUMMARY AND OUTLOOK

This paper has reviewed the major sources of aerodynamic noise on modern horizontal wind turbines. A brief analysis of the time and frequency scales of two dominant noise sources for a modern wind turbine was presented. Broadband airfoil trailing edge noise for the case studied was shown to have most of its energy at approximately 500 Hz. Its directivity ensures that trailing edge noise from a wind turbine will have its amplitude modulated with time at the blade passing frequency. While the amplitude modulation occurs at low frequency, it cannot be considered a low frequency noise source. Blade-tower interaction (BTI) noise was analysed using a first order model and its frequency content was found to have maximum energy at 2.2 Hz.

Some measurements from a modern European wind farm were reviewed. These results strongly suggest that noise from multiple wind turbines in a wind farm can reinforce each other and create impulsive “pile-driving” like sound, considerable distances from the wind farm. The published results are A-weighted; hence are dominated by noise from the broadband swish (trailing edge) component. Recent measurements taken close to a South Australian wind farm confirm that amplitude modulation is present under Australian daytime conditions. It is speculated BTI noise may also be reinforced in the same manner and create zones of high-level low-frequency sound. Passive and active control concepts were presented with active phase desynchronisation a promising method for controlling both forms of noise.

More research is needed to understand both swish and BTI noise sources before effective control methods can be pursued. BTI noise remains the least well studied and some controversy surrounds the issue of whether it is a significant noise source. Only more detailed measurements and understanding of how it is generated and propagates will provide meaningful answers.

REFERENCES

[1] Geoscience-Australia and ABARE, *Australian energy resource assessment*, Technical report, Australian Government, Canberra, Australia, 2010.

[2] E. Pedersen and K.P. Waye, “Perception and annoyance due to wind turbine noise—a dose–response relationship”, *Journal of the Acoustical Society of America* **116**(6), 3460-3470 (2004)

[3] S. Wagner, R. Bareiss and G. Guidati, *Wind turbine noise*, Springer Verlag, 1996

[4] S. Oerlemans, P. Sijtsma and B. Mendez Lopez, “Location and quantification of noise sources on a wind turbine”, *Journal of Sound and Vibration* **299**, 869–883 (2007)

[5] W.K. Blake, *Mechanics of flow-induced sound and vibration*, Vol. 2, Academic Press, New York, 1986

[6] M.J. Lighthill, “On sound generated aerodynamically: General theory”, *Proceedings of the Royal Society of London A* **221**, 564–587 (1952)

[7] J.E. Ffowcs-Williams and L.H. Hall, “Aerodynamic sound generation by turbulent flow in the vicinity of a scattering half plane”, *Journal of Fluid Mechanics* **40**(4), 657–670 (1970)

[8] M.S. Howe, “A review of the theory of trailing edge noise”, *Journal of Sound and Vibration* **61**(3), 437-465, (1978)

[9] S. Oerlemans, M. Fisher, T. Maeder, and K. Kögler, “Reduction of wind turbine noise using optimized airfoils and trailing-edge serrations”, *AIAA Journal* **47**(6), 1470-1481 (2009)

[10] P. Migliore and S. Oerlemans, “Wind tunnel aeroacoustic tests of six airfoils for use on small wind turbines”, *Journal of Solar Energy Engineering* **126**, 974-985 (2004)

[11] S. Oerlemans and J.G. Schepers, “Prediction of wind turbine noise and validation against experiment”, *International Journal of Aeroacoustics* **8**(6), 555–584 (2009)

[12] G.P. Van den Berg, “Effects of the wind profile at night on wind turbine sound”, *Journal of Sound and Vibration* **277**, 955–970 (2004)

[13] E. Arcondoulis, C.J. Doolan, A. Zander, and L.A. Brooks, “A review of trailing edge noise generated by airfoils at low to moderate Reynolds number”, *Acoustics Australia* **38**(3), 129–133 (2010)

[14] D.J. Moreau, L.A. Brooks and C.J. Doolan, “On the aeroacoustic tonal noise generation mechanism of a sharp-edged plate”, *Journal of the Acoustical Society of America* **129**(4), EL154-EL160, 2011.

[15] T. Cebeci and P. Bradshaw, *Momentum transfer in boundary layers*, McGraw Hill, 1977

[16] M. Goody, “Empirical spectral model of surface pressure fluctuations”, *AIAA Journal* **42**(9), 1788–1794 (2004)

[17] N. Curle, “The influence of solid boundaries on aerodynamic sound”, *Proceedings of the Royal Society of London A*, **231**, 505–514 (1955)

[18] H.H. Hubbard, F.W. Grosveld and K.P. Shepherd, “Noise characteristics of large wind turbine generators”, *Noise Control Engineering Journal* **21**, 21-29 (1983)

[19] G.P. Van Den Berg, “The beat is getting stronger: the effect of atmospheric stability on low frequency modulated sound of wind turbines”, *Noise Notes* **4**, 15–40 (2005)

[20] A.L. Marsden, M. Wang, J.E Dennis and P. Moin, “Trailing-edge noise reduction using derivative-free optimization and large-eddy simulation”, *Journal of Fluid Mechanics* **572**, 13–36 (2007)

[21] T. Lutz, A. Herrig, W. Wurz, M. Kamruzzaman and E. Kramer, “Design and wind-tunnel verification of low-noise airfoils for wind turbines”, *AIAA Journal* **45**(4), 779-785 (2007)

[22] R.F. Jones, C.J. Doolan and M. Teubner, “Minimization of trailing edge noise by parametric airfoil shape modifications”, *Proceedings of the 17th AIAA/CEAS Aeroacoustics Conference (32nd AIAA Aeroacoustics Conference)*, AIAA 2011-2782, Portland, Oregon, USA, 6-8 June 2011

[23] M.S. Howe, “Aerodynamic noise of a serrated trailing edge”, *Journal of Fluids and Structures* **5**(1), 33–45 (1991)

[24] D.J. Moreau, L.A. Brooks and C.J. Doolan, “Flat plate self-noise reduction at low-to-moderate Reynolds number with trailing edge serrations”, *Proceedings of Acoustics 2011*, Gold Coast, Australia, 2-4 November 2011

[25] M. Gruber, P. Joseph, and T.P. Chong, “Experimental investigation of airfoil self noise and turbulent wake reduction by the use of trailing edge serrations”, *Proceedings of the 16th AIAA/CEAS Aeroacoustics Conference (31st AIAA Aeroacoustics Conference)*, AIAA 2010-3803, Stockholm, Sweden, 7-9 June 2010

[26] T. Geyer, E. Sarradj and C. Fritzsche, “Measurement of the noise generation at the trailing edge of porous airfoils”, *Experiments in Fluids* **48**(2), 291–308 (2010)

ON MEASURING AND DETERMINING WIND TURBINE NOISE EMISSIONS AT DISTANT SENSITIVE RECEPTOR LOCATIONS – A CHALLENGE

George F. Hessler Jr.
Hessler Associates, Inc., Haymarket, VA USA, George@HesslerAssociates.com

Paul D. Schomer
Schomer and Associates, Inc., Champaign, ILL USA, Schomer@SchomerAndAssociates.com

Determining noise emissions attributable solely to wind turbine/s at potentially sensitive receptor locations far from the turbines is a technical challenge indeed. If the project is successfully designed acoustically, the wind turbine source is barely audible during the day or night with relatively moderate winds and not distinguishable at all during high winds. We must try to separate wind turbine emissions from the prevailing background environment and from sounds created by the same wind that drives the turbines. This paper suggests a methodology that measures surrounding turbine emissions simultaneously at the standard IEC-61400-11 distance to document background-free emissions for input into a relatively simple propagation model to calculate true turbine emissions at the distant receptor location of interest. An example is given from an actual site where turbine noise emissions could be accurately measured at the receptor location for comparison to model calculations.

INTRODUCTION

Measuring wind turbine noise emissions is unique, unlike any other power generation source because measurements must be made in the presence of wind. Other generation sources are customarily measured in quiescent or near quiescent meteorological conditions that of course are impossible for wind turbines. Measuring in windy conditions is problematical and introduces component sources that must be accounted for in the measured total sound pressure arriving at the microphone at the potentially sensitive location of interest. These are:

1. Wind induced pseudo microphone noise
2. Residual background sound from normal environmental sources
3. Background sound induced by wind (turbulence over the surface and grass, foliage and tree rustle)
4. Noise emissions from the wind turbine/s.

SOURCES OF NOISE AT FAR-OFF SENSITIVE RECEPTOR LOCATIONS

Figure 1 illustrates the measured flow induced pseudo noise using two diameter wind screens. A larger diameter is always better for any given porosity, and note there can be a 10+ dB improvement in measurement capability just by windscreen selection. This data is given in an experimental windscreen study at an aero-acoustic wind tunnel in Germany [1]. It should

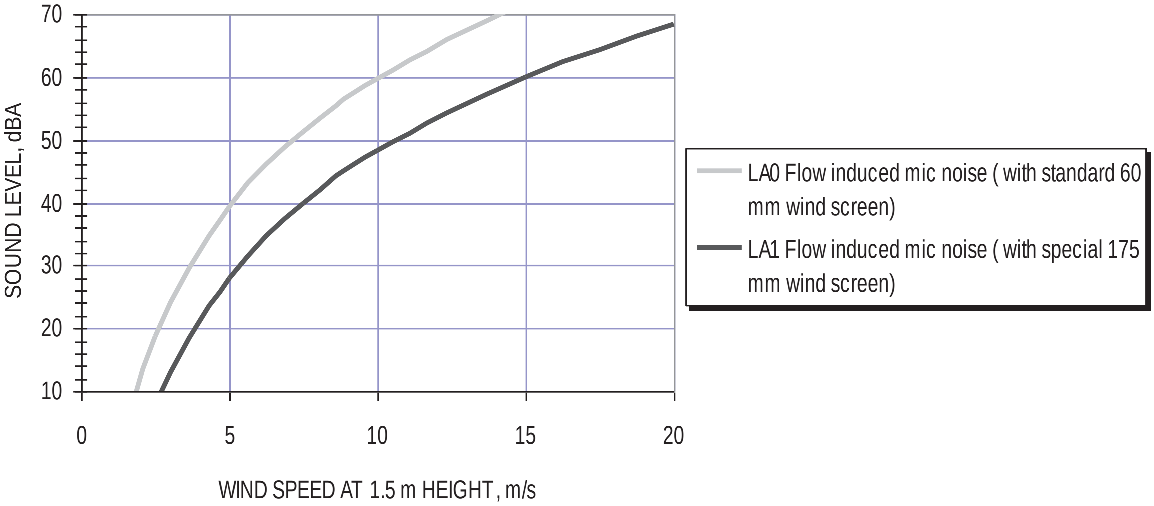


Figure 1. Measured pseudo microphone noise using two sizes of windscreens with identical porosity

be noted that controlled flow in a laboratory is less turbulent and steady than outdoor wind and actual pseudo noise may be higher than shown under field conditions.

Figure 2 shows the two components of background noise that makeup the total measurable level in a moderately windy environment. The short dashed line is the residual level usually from far-off unidentifiable traffic or industrial sources, while the long dash line is wind induced sounds. Wind source sound follows a 10^6 power slope as an aerodynamic source. The combination of the two components yields the background level as a function of wind speed.

Figure 3 is a typical shape of wind turbine noise emissions versus wind speed. When we combine all these sources in Figure 4, it is easy to see that the only measurable sound level at a point far from the turbines may not represent turbine emissions at all except in a small select range where the total can be corrected for background. We also show that a small standard windscreen can give a totally erroneous answer, and the larger size windscreen may still produce a component source in the measurement, particularly at higher speed.

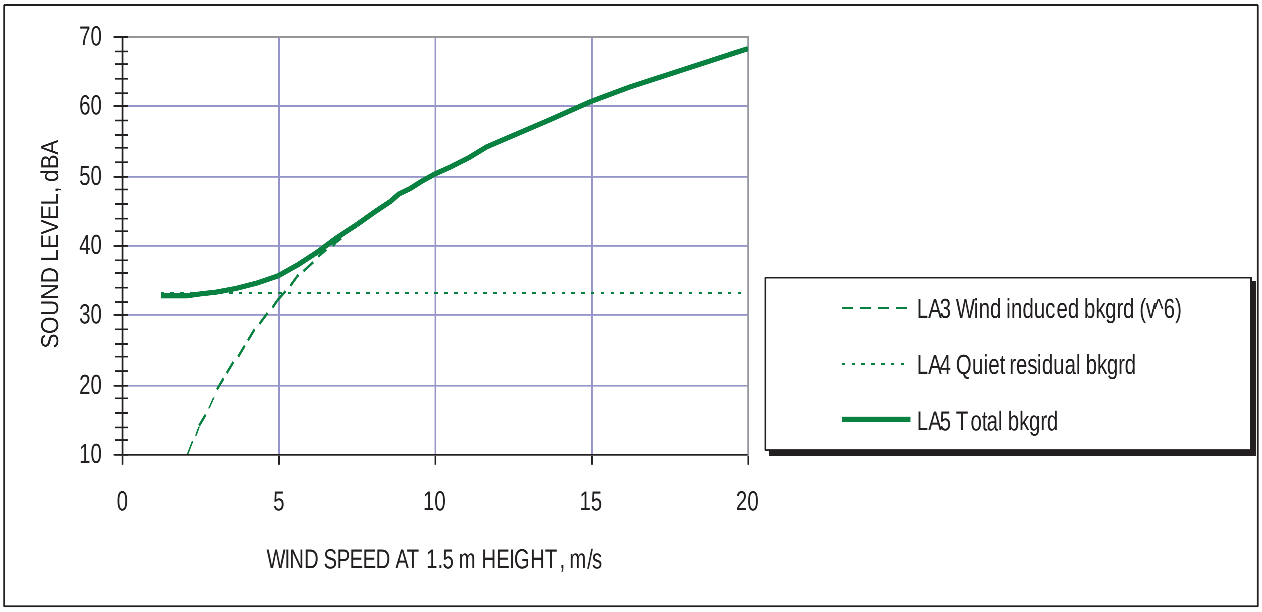


Figure 2. Residual background noise, wind induced sources and total background noise

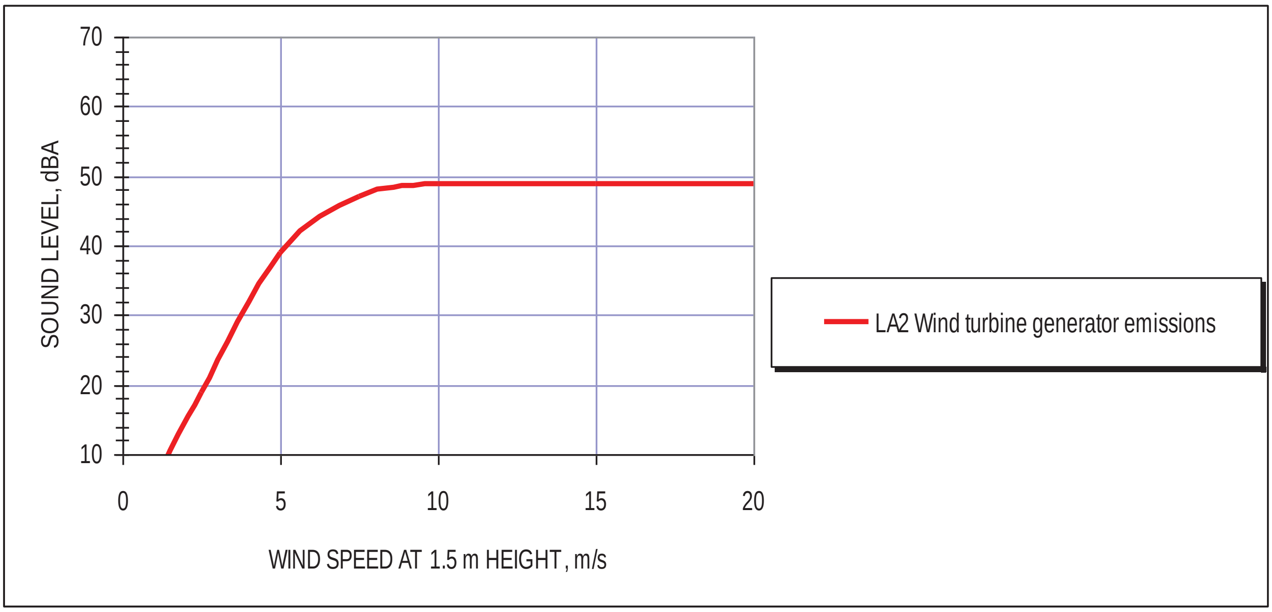


Figure 3. Wind turbine noise emissions as a function of wind speed

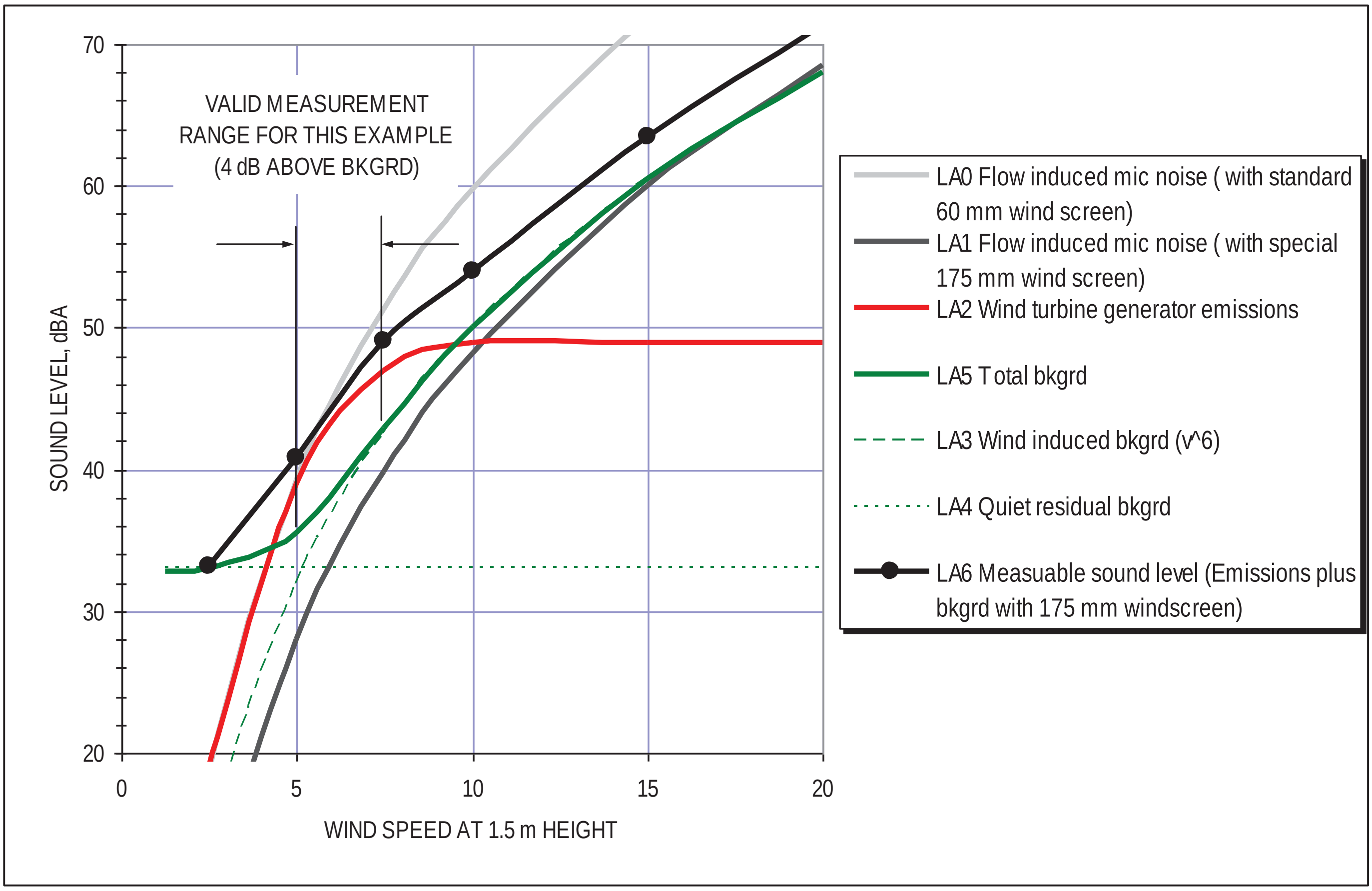


Figure 4. Combined sources of noise at a far-off sensitive receptor location

Background effects can be accounted for to a degree at observed and monitor testing with a cooperative owner by periodically turning off the closest and other surrounding turbines for say 10 or 20 minute periods and then restarting. For distances far from large facilities it may be necessary to shut down the entire facility. ON and OFF data can be compared and if the background sound is 3 or 4 dB or more below the total background may be subtracted. This works well at moderate speed but not so well at high speed and/or full load as there will be little change in level if the measurement is dominated by pseudo and wind induced background. Figure 4 also illustrates how easy it is to arrive at an accurate but incorrect answer. It should be made clear that Figures 1 to 4 are for illustrative value and do not represent data at any particular site.

PROPOSED MEASUREMENT METHODOLGY

Most of the measurement difficulties described above could be eliminated by selecting a measurement location closer to the turbine/s where one measures *only* turbine emissions, exclusive of background. This close-in alternate location is a time-honored successful technique and is suggested by South Australian EPA Noise Policy measurement standards for single sources under investigation. Here we develop and demonstrate the use of the close-in technique for multiple source wind turbine arrays.

A specific ideal location is prescribed in IEC 61400-11 [2] as one hub height plus one blade length away. At this location, there is no ground effect and background sound has little significance. Figure 5 shows a typical measurement with time at this location taken to show any background influence at shut off intervals and to keep the measurement location downwind. It is clear that only turbine emissions are being measured. The data spikes during shutdown are technician sounds aligning the instrumentation. The measurement for the proposed methodology could be on a reflective ground plane surface or on a tripod one to two meters above the surface as required.

We propose an in-situ test set-up as shown in Figure 6 for an array of multiple wind turbine sources. Measurements are carried out at the four closest turbines surrounding or closest to the location of interest. The measurements would be done simultaneously and note that they could be up, down or cross wind, accounting for any turbine noise directivity effects.

PROPOSED MODELLING TO DETERMINE WTG EMISSIONS

It remains to extrapolate the IEC distance results to the point of interest, L_{pi}. The data can be computed for each turbine by the following equation and then summed logarithmically to arrive at the wind turbine emissions exclusive of background and microphone effects:

$$L_{pi} = 20\log(d_{iec}/d_i) + A_a + A_g + C \qquad (1)$$

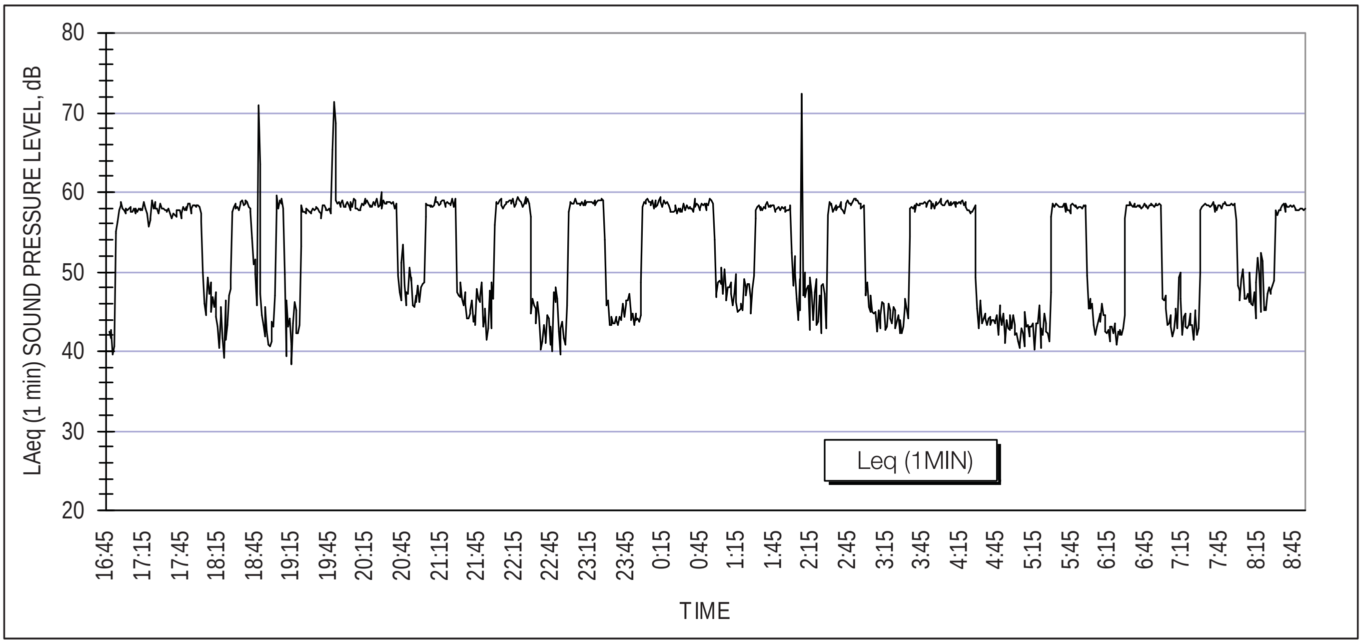


Figure 5. Typical raw data at the standard IEC 61400-11 test distance of hub height plus one blade length away

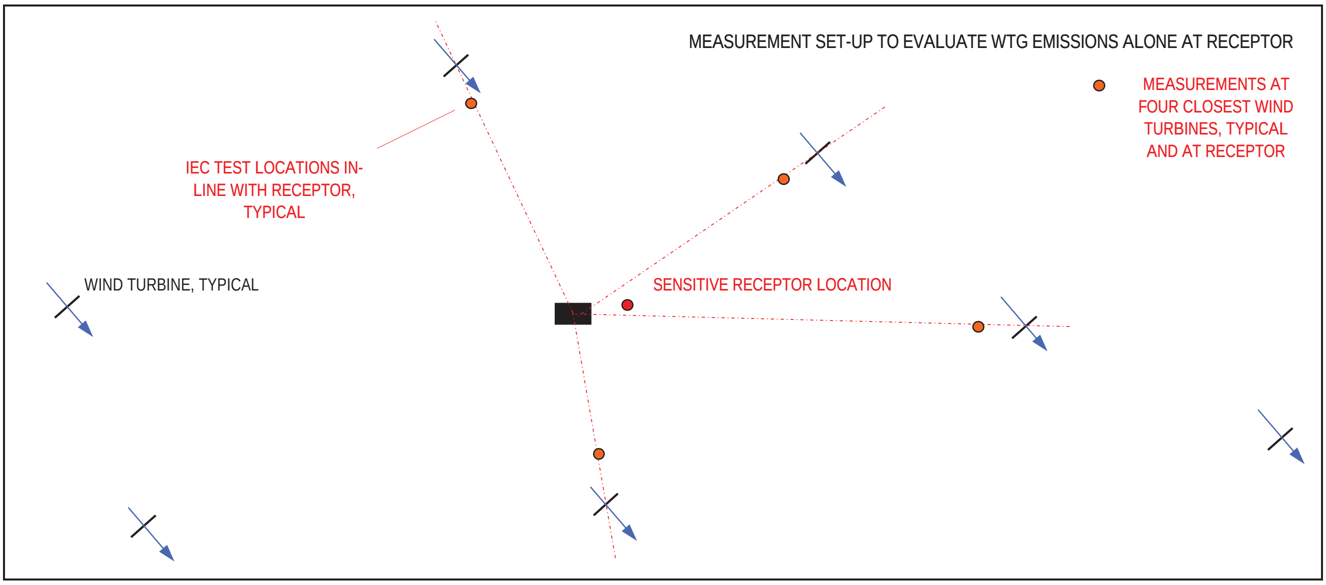
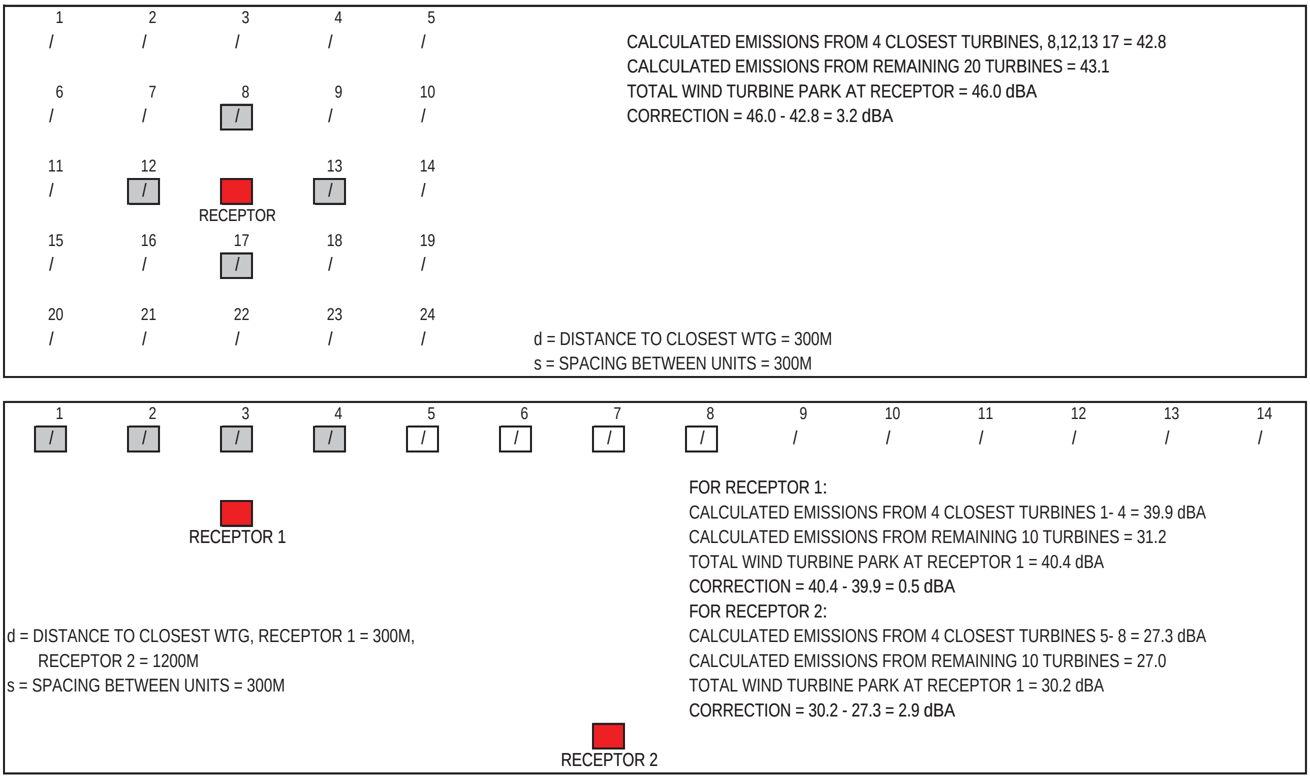


Figure 6. Proposed test set up for quantifying turbine emissions at a sensitive far-off receptor

The subscript i from 1 to 4 are for each turbine location. The IEC test distance is denoted d_{iec} and d_i is the distance from ith turbine to the sensitive location. A_a and A_g are for air absorption and ground effects both calculated by ISO-9613 part 2 algorithms. The quantity C is a correction factor to account for the balance of the wind farm turbines that may contribute to the measured level in addition to the four closest turbines. It can be shown that C would range from a small fraction to about 3 dBA depending on the layout of the wind project. In general, C would increase as one moves farther from the array. Figure 7 gives the computation results for correction C. The upper scenario is unlikely and perhaps unfortunate for the receptor and would certainly be the worst case. The lower scenario illustrates two extremes for a close and distant row of turbines.

Equation (1) comes from ISO 9613 and can be implemented in a simple A-weighted model or be done as a function of frequencies in octave bands. We suggest an octave band measurement and model for certification purposes and a simple A-wt model for information-only purposes. The modelling is very *minimal* and essentially we are simply *extrapolating* sound pressure from one distance to another in the same direction.

Experience shows that the quantity Ag is particularly important for wind turbines that have peak noise emissions at around 500 Hz. Ag depends almost exclusively on the ground surface *near* the point of interest measurement receiving location – see Figure 8. Using a ground absorption coefficient from 0.5 to 1 for "soft" surfaces has shown very good modelling results over long term sampling times.



CALCULATED EMISSIONS FROM 4 CLOSEST TURBINES, 8,12,13 17 = 42.8
CALCULATED EMISSIONS FROM REMAINING 20 TURBINES = 43.1
TOTAL WIND TURBINE PARK AT RECEPTOR = 46.0 dBA
CORRECTION = 46.0 - 42.8 = 3.2 dBA

d = DISTANCE TO CLOSEST WTG = 300M
s = SPACING BETWEEN UNITS = 300M

FOR RECEPTOR 1:
CALCULATED EMISSIONS FROM 4 CLOSEST TURBINES 1- 4 = 39.9 dBA
CALCULATED EMISSIONS FROM REMAINING 10 TURBINES = 31.2
TOTAL WIND TURBINE PARK AT RECEPTOR 1 = 40.4 dBA
CORRECTION = 40.4 - 39.9 = 0.5 dBA
FOR RECEPTOR 2:
CALCULATED EMISSIONS FROM 4 CLOSEST TURBINES 5- 8 = 27.3 dBA
CALCULATED EMISSIONS FROM REMAINING 10 TURBINES = 27.0
TOTAL WIND TURBINE PARK AT RECEPTOR 1 = 30.2 dBA
CORRECTION = 30.2 - 27.3 = 2.9 dBA

d = DISTANCE TO CLOSEST WTG, RECEPTOR 1 = 300M,
RECEPTOR 2 = 1200M
s = SPACING BETWEEN UNITS = 300M

Figure 7. Computation results of correction C for use in equation (1)

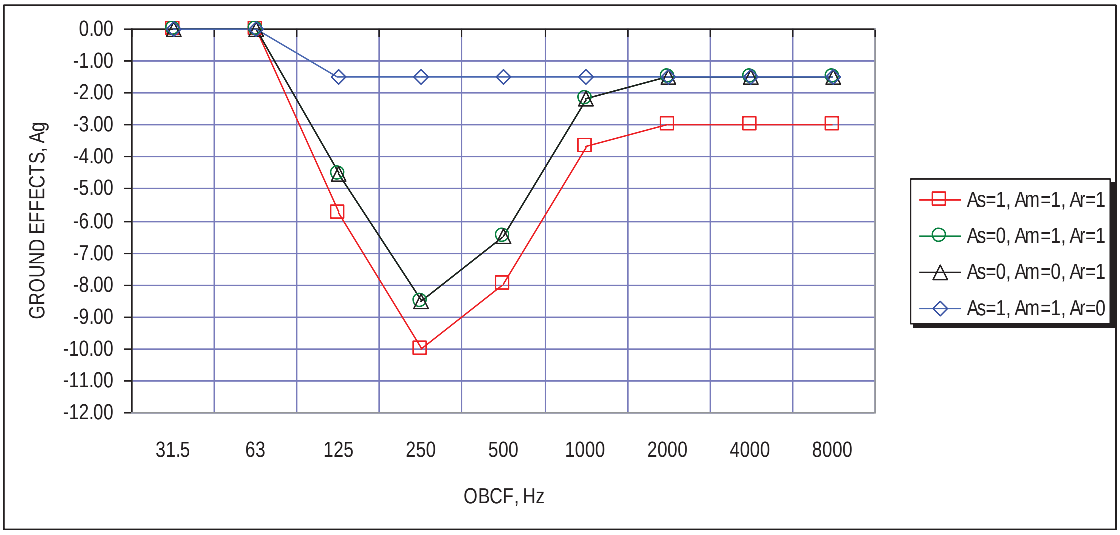


Figure 8. Computation of ISO 9613 ground effects where A is the chosen absorption coefficient for source, mid and receiving areas

A SAMPLE PROPAGATION MODEL

A sample simple A-weighted noise model is given in Table 1 for three residences relatively close to the turbines in accordance with ISO 9613 with the exception of the addition of correction C. Measurements at these locations were dominated by turbine noise so the site serves to compare the measured levels with the proposed methodology. The agreement is good and the emission levels deduced from IEC measurements appear a little conservative compared to actual measurements at the sensitive locations. A nice feature of this method is that the model can be extended (the blue text in Table 2) to see the benefit of shutting down just the closest turbine. In this example, the noise reduction ranged from 2.4 to 8.0 dBA due to the proximity of the surrounding turbines.

It should be noted that the data shown in the model for the IEC distance (58 dBA) comes from a single turbine test and not from the four closest turbines. This test methodology was developed well after this project was completed but this projects data is the best representative data available for the model. Results would be slightly lower if measured at each turbine since some would be upwind and cross wind rather than all downwind – a major advantage of the method. Nevertheless, the model is sufficiently accurate to show the potential value of the proposed method as intended.

CONCLUSIONS

A measurement and analysis methodology is proposed where noise emissions solely attributable to wind turbines can be measured accurately without background or pseudo noise concerns and then simply extrapolated to more distant sensitive receptor locations of interest. This avoids the difficulty of extracting the turbine emissions from total direct measurement at the same location of interest, a nearly impossible task. It is hoped the measurement and analysis method will be tried by other investigators towards the ultimate goal of standardisation.

REFERENCES

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

[2] International Electrotechnical Commission IEC 61400-11, *Wind turbine generator systems – Part 11: Acoustic noise measurement techniques*, Edition 2.1, 2006-11

Table 1. Sample A-weighted noise model

SIMPLE A-WTD MODEL BASED ON ISO 9613, PART 2 ALGORITHMS										
	INPUTS IN RED			ISO 9613 PROPAGATION VALUES				CORR. C	CALC.	MEAS
Lp AT IEC POINT	HUB HT.	ROTOR DIA.	DISTANCE	DIST	AIR ABS	GROUND	MIC MOUNT	C	LA	LA
SITE M							Y/N			
58	80	80	252	-4.9	-.8	.0	-3.0	.5	49.8	
58	80	80	340	-7.5	-1.1	-.5	-3.0	.5	46.4	
58	80	80	377	-8.4	-1.2	-1.0	-3.0	.5	45.0	
58	80	80	402	-8.9	-1.3	-1.2	-3.0	.5	44.1	
							CALCULATED LEVEL		53.0	50-52
SITE N										
58	80	80	654	-13.1	-2.1	-2.6	-3.0	.7	37.8	
58	80	80	579	-12.1	-1.9	-2.3	-3.0	.7	39.4	
58	80	80	780	-14.7	-2.5	-3.0	-3.0	.7	35.5	
58	80	80	949	-16.4	-3.0	-3.3	-3.0	.7	33.0	
							CALCULATED LEVEL		43.1	42-44
SITE D										
58	80	80	302	-6.4	-1.0	.0	-3.0	1.8	49.4	
58	80	80	629	-12.8	-2.0	-2.5	-3.0	1.8	39.4	
58	80	80	767	-14.5	-2.5	-3.0	-3.0	1.8	36.9	
58	80	80	943	-16.3	-3.0	-3.3	-3.0	1.8	34.2	
							CALCULATED LEVEL		50.1	48-50

DIMENSIONS IN METERS MIC MOUNT: CORRECTION FOR MICROPHONE MOUNTED ON GROUND PLANE OR ON TRIPOD AT 1-2 M ABOVE GRADE

Table 2. Sample A-weighted noise model with abatement extension

SIMPLE A-WTD MODEL BASED ON ISO 9613, PART 2 ALGORITHMS											NOISE REDUCTION BY SHUTTING DOWN SINGLE CLOSEST WTG	
	INPUTS IN RED			ISO 9613 PROPAGATION VALUES				CORR. C	CALC.	MEAS		
Lp AT IEC POINT	HUB HT.	ROTOR DIA.	DISTANCE	DIST	AIR ABS	GROUND	MIC MOUNT	C	LA	LA		
SITE M							Y/N					
58	80	80	252	-4.9	-.8	.0	-3.0	.5	49.8		.0	
58	80	80	340	-7.5	-1.1	-.5	-3.0	.5	46.4		46.4	
58	80	80	377	-8.4	-1.2	-1.0	-3.0	.5	45.0		45.0	
58	80	80	402	-8.9	-1.3	-1.2	-3.0	.5	44.1		44.1	
							CALCULATED LEVEL		53.0	50-52	50.1	2.9
SITE N												
58	80	80	654	-13.1	-2.1	-2.6	-3.0	.7	37.8		37.8	
58	80	80	579	-12.1	-1.9	-2.3	-3.0	.7	39.4		.0	
58	80	80	780	-14.7	-2.5	-3.0	-3.0	.7	35.5		35.5	
58	80	80	949	-16.4	-3.0	-3.3	-3.0	.7	33.0		33.0	
							CALCULATED LEVEL		43.1	42-44	40.7	2.4
SITE D												
58	80	80	302	-6.4	-1.0	.0	-3.0	1.8	49.4		.0	
58	80	80	629	-12.8	-2.0	-2.5	-3.0	1.8	39.4		39.4	
58	80	80	767	-14.5	-2.5	-3.0	-3.0	1.8	36.9		36.9	
58	80	80	943	-16.3	-3.0	-3.3	-3.0	1.8	34.2		34.2	
							CALCULATED LEVEL		50.1	48-50	42.1	8.0

DIMENSIONS IN METERS MIC MOUNT: CORRECTION FOR MICROPHONE MOUNTED ON GROUND PLANE OR ON TRIPOD AT 1-2 M ABOVE GRADE

SOURCES OF WIND TURBINE NOISE AND SOUND PROPAGATION

Renzo Tonin
Renzo Tonin & Associates (NSW) Pty Ltd, PO Box 877, Strawberry Hills, NSW 2012
rtonin@renzotonin.com.au

The mechanism of noise generation by wind turbines is a subject not yet fully understood. A large number of complex flow phenomena occur, each of which generate sound in particular frequency bands. The purpose of this paper is to provide a brief description of the current state of technology in respect of noise generation from a wind turbine in a complex meteorological atmosphere and reliable methods of noise prediction to sensitive receptors.

INTRODUCTION

According to the recent report of an Australian Senate Committee inquiry into noise from wind farms, in 2009 there were 85 wind farms in Australia the majority of which were installed in Victoria, South Australia and Western Australia. South Australia accounts for 48 percent of the total generating capacity of wind turbines [1].

Wind farms are located in rural areas where they have the capacity to be intrusive if not properly planned and managed. Objection to a wide range of adverse amenity impacts (including noise) from wind farms has prompted the formation of community groups opposing wind farms in a similar way to those which were formed in opposition to aircraft and motorways. According to the inquiry report, there is a sense of distrust by those community groups of wind farm developers, government authorities and the legal system resulting in a belief by some people that "there is something mysterious about wind farm noise" and "that government and developers are covering something up" [Ref 1, para 2.22 page 9].

At a technical level, there is no doubt that noise from wind turbines is a complex issue. It is the objective of this paper to describe the mechanisms of noise generation from wind turbines as they are currently known.

ANATOMY OF A WIND TURBINE

The energy of the wind is converted into mechanical energy by turning blades attached to a hub and rotor. The rotor is connected to a generator which converts mechanical energy into electrical energy [2].

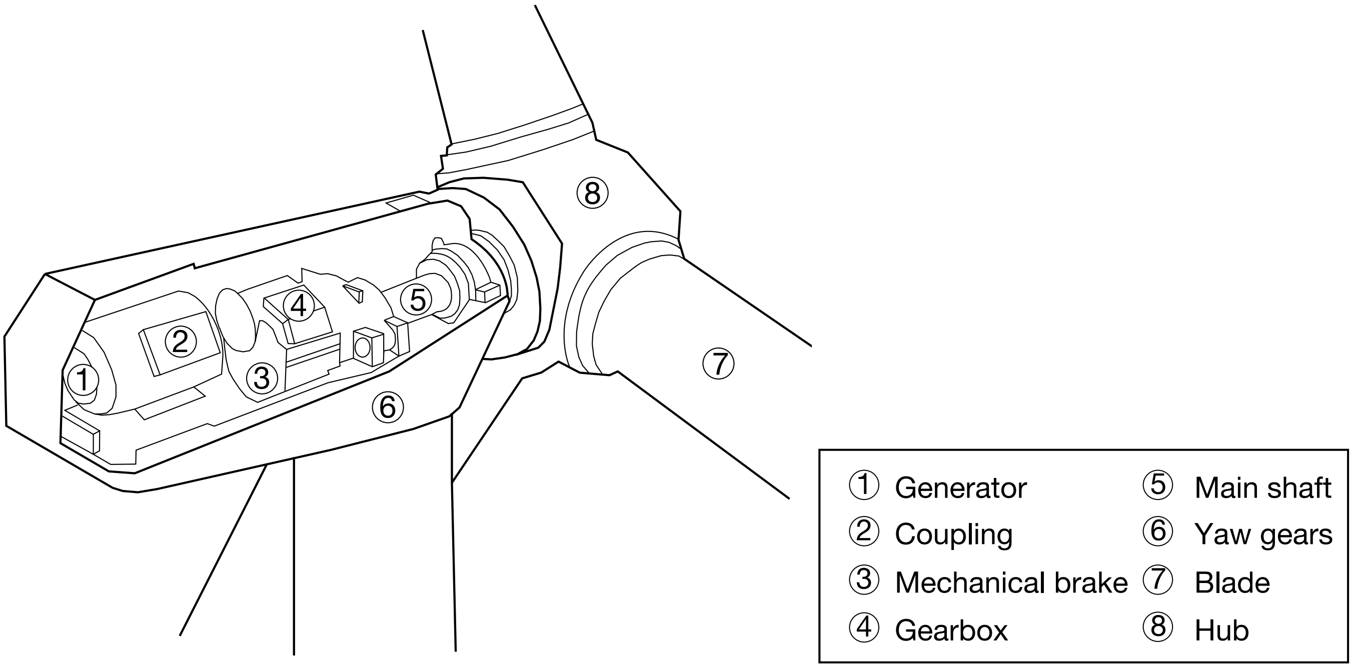


Figure 1. Typical construction of a wind turbine nacelle and arrangement of blades

The conventional 'horizontal axis wind turbine' (referring to the axis on which the blades and hub rotate) consists of four main elements: nacelle, rotor, tower and footing.

1. *Nacelle*: Meaning 'small boat' in French, the nacelle sits on top of the tower and houses the gearbox and generator (see Figure 1). The hub connecting the blades is attached to it at one end. Nacelles are of varying sizes, depending mainly on the design and size of the generator, and may weigh between 20 and 70 tonnes. The nacelle revolves horizontally on the tower ('yawing') to allow the rotor to face the wind regardless of its direction.
2. *Rotor*: The rotor consists of a hub and blades with a shaft connecting them to the gearbox and generator. Most turbines have three blades, commonly made of carbon fibre, plastic, fibreglass or epoxy, which are aerodynamically designed for maximum energy generation and minimum noise. Fixed-speed turbines automatically adjust their blade angle to maintain constant rotation speed in all wind conditions. Variable-speed turbines rotate faster as the wind speed increases, and use power electronics to ensure correct voltage and frequency of output. Blades may exceed 40 metres in length, giving a rotor diameter of 80 to 120 metres.
3. *Tower*: Towers are typically between three and five metres in diameter at the base and taper to about two metres at the top. Their height varies with the size of the generator and the length of the blades and may be as high as 120 metres. The height is necessary to gain access to higher and less variable wind speeds than those at ground level. All modern wind farms use tubular steel towers. Earlier overseas developments used steel lattice towers [3].
4. *Footing*: Footings are generally a concrete slab below ground, 7-12 metres or more in diameter, and 1-2 metres in depth. The base is topped with a circular plinth which contains the turbine tower 'holding down' bolts. Once the footing is installed and the tower erected, the excavation is back-filled and the area landscaped to the base of the tower.

Wind turbines are either fixed-speed machines or more commonly variable speed. Fixed-speed turbines idle (turn slowly) until a “cut-in” wind speed is reached, typically 4 to 5 m/s (metres per second) measured at the hub. “Cut-in” is the point at which the generator starts to produce electricity. Beyond that point, the rotors quickly reach constant operating speed of 15 to 30 revolutions per minute. The control system of the turbine maintains the operating speed by constantly adjusting the pitch of the blades in response to changes in wind speed.

Variable speed turbines allow more efficient conversion of energy from the wind with hub speeds varying from about 14 to 18 revolutions per minute. The conversion of a variable electrical output to a fixed line frequency and amplitude is accomplished by electronics.

All turbines automatically stop rotating when they reach a “cut-out” wind speed, typically 25 m/s measured at the hub. Whether fixed or variable speed, all wind turbines are designed to maintain a reasonable stable quality of power output regardless of variations in wind speed.

WIND TURBINE SOUND CHARACTERISTICS

The combination of noise sources from a wind turbine can generally be described as a mechanical noise (such as a car running or a train in continuous motion) combined with an aerodynamic swishing sound (described as like a stick being swung through the air quickly). There are four types of sound generated by wind turbine operation: tonal, broadband, low frequency/infrasound, and impulsive:

1. Tonal: Tonal sound is defined as sound at discrete frequencies. It is caused by components such as meshing gears, non-aerodynamic structural resonances, or unstable flows over holes or slits or a blunt trailing edge. Tonal sound is not usually a problem in modern turbines as evidenced by examination of numerous test certification documents from manufacturers such as Vestas, RE Power and GE.
2. Broadband: This is sound characterized by a continuous distribution of sound pressure with frequencies greater than 100 Hz. It is caused by the interaction of boundary layer turbulence with the trailing edge of the turbine blades and is also described as a characteristic "swishing" or "whooshing" sound [4]. The variation in sound level and character is called “modulation” or “amplitude modulation” and is probably the most predominant source of noise in modern wind turbines.
3. Low Frequency/Infrasound: Low frequency sound contains frequencies in the range 20 to 100 Hz and is mostly associated with downwind rotors (turbines with the rotor on the *downwind* side of the tower which are no longer common). It is caused when the turbine blade encounters localized air stream disturbance from the tower [5]. Infrasound is sound with frequencies below 20Hz [6] and is generated to some extent by air turbulence impinging on the blade leading edge but probably more so by flow perturbation over the blade as it passes in front of the tower, however the true sources of infrasound are yet to be proven [4].
4. Impulsive: This sound is described as regular short acoustic impulses or a “thumping” sound occurring at the rate of about one per second (the blade passing frequency). It is caused by the interaction of wind turbine blades with disturbed air flow around the tower of a downwind machine. It has also been observed to occur in modern upwind rotors [7]. It may also be the low frequency components remaining in the acoustic signal after sound propagation through the atmosphere has attenuated the high frequency components. However, the precise mechanism of impulsive noise is in dispute.

SOURCES OF WIND TURBINE NOISE

The total noise generated by a wind turbine is made up of several components, broadly grouped as mechanical noise and aerodynamic noise. Whenever the wind speed is below “cut-in”, the blades rotate very slowly or are stationary and “parked” and consequently there is minimal noise generated. When the turbine is operating between wind speeds of approximately 4m/s and 30m/s measured at hub height, the sound power level monotonically increases, a typical example of which is shown in Table 1.

Table 1. Sound power level for Vestas V90-3.0MW (80m Hub)

U_s m/s	4	5	6	7	8	9
Lw dB(A)	97.9	100.9	104.2	106.1	107.0	106.9

U_s m/s is the wind speed in m/sec at a standardised anemometer height of 10m. Lw is sound power level re 10^{-12} watts.

Mechanical Noise

Sources of mechanical noise include the following:

- Gearbox
- Generator
- Yaw Drives
- Cooling Fans
- Auxiliary Equipment (e.g., hydraulics), and
- Application of parking brakes

Since the emitted sound is associated with the rotation of mechanical and electrical equipment, it tends to be tonal although it may have a broadband component. For example, pure tones can be emitted at the rotational frequencies of shafts and generators, and the meshing frequencies of the gears. However, in modern turbines (other than the brief application of parking brakes in some turbines), mechanical noise is not usually audible above aerodynamic noise.

Aerodynamic Noise

Aerodynamic noise associated with the passage of air over the blades is typically the most important component of wind turbine acoustic emissions. A large number of complex flow phenomena occur, each of which generate sound in particular frequency bands. Aerodynamic sound level generally increases with rotor speed.

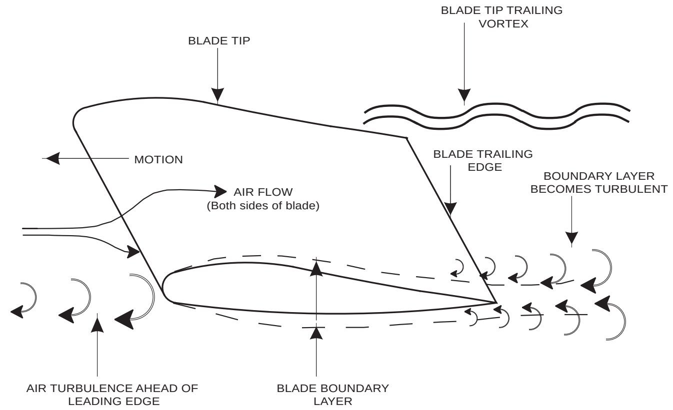


Figure 2. Aerodynamic noise sources associated with wind turbine blade (blade shown cut to reveal cross-section)

By reference to Figure 2, the various aerodynamic sound generation mechanisms may be grouped as follows:

1. *Trailing Edge Noise*: The flow of air over the turbine blade creates a boundary layer attached to its upper and lower surfaces typically 25mm thick. The flow transitions to a turbulent state as it reaches the trailing edge of the blade and sound is generated by the interaction of the turbulence eddies with the trailing edge. This is the major source of noise in modern wind turbines with most of the energy in the frequency range 250-1000Hz [4]. A very important observation by Doolan [4] is that trailing edge noise has a cardiod directivity characteristic associated with dipole aerodynamic sources with its predominant lobe oriented towards the leading edge of the blade. In other words, there is an inherent directivity associated with aerodynamic noise emitted from wind turbines which has not to date received much attention in the literature. On the downward movement of the blades, the change in orientation of the asymmetric directivity pattern associated with the trailing edge noise source described earlier, results in a frequency modulation which is colloquially described as a "swish" [8-10]. Associated with the "swish" is an amplitude modulation of the sound at the blade passing frequency. The swish amplitude is defined as the difference between the minimum and maximum dB(A) sound level during one revolution of the blades [8].
2. *Impulsive Noise*: As stated in the various noise guidelines and standards referred to later in this paper, there is a level of "swish" which is a normal characteristic of wind turbines. However, an increased level of amplitude modulation is reported as a "thumping sound" by several investigators [8] and is referred to in this paper as "impulsive noise" to distinguish it from a normal level of amplitude modulation or "swish" as described above. However, it is important to note that the term "amplitude modulation" in the various standards and guidelines pertaining to wind farm noise includes what is referred to here as "impulsive noise". Although various possible causes for impulsive noise have been suggested such as blade noise directivity, blade-tower interaction, variation of wind speed over the rotor and interaction between the noise from two or more turbines, the mechanism is not well understood [8]. A study by Salford University concluded that of 155 wind farm sites surveyed, only four exhibited instances of impulsive noise generation and at those sites, impulsive noise occurred for 7-15% of the time which was managed by operational means [11]. A study of three other wind farms in the UK which were reported to have a low frequency noise problem concluded that the cause of annoyance was amplitude modulation especially at night [12].

   To date, there is no clear indication of the conditions that are responsible for impulsive noise and therefore its occurrence cannot be predicted. In the interim, as a precautionary measure, if the effect is associated with high shear winds and enhanced propagating conditions then this could be examined at the planning phase of a development. For example, the adoption of a principle that a relatively high level of wind shear (a coefficient greater than about 0.4) together with a high frequency of occurrence of temperature inversion (% occurrence of classes F+G greater than about 30%) are *prima-facie* conditions for which there is likely to be a risk of occurrence of impulsive noise.
3. *Inflow Turbulence Sound*: This source of noise is due to turbulence in the air stream ahead of the leading edge of the blade interacting with the blade surface. This also has a characteristic dipole directivity pattern but unlike trailing edge noise the frequency generated is around 18Hz [4].
4. *Blade Tip Noise*: This is generated by flow past the blade tip

generating a vortex stream in a similar way to trailing edge noise. However, it is understood to be not as significant a source as trailing edge noise.

5. *Blade-Tower Interaction*: This is an impulsive sound caused by the interaction of the blades with the perturbed up-stream flow caused by the tower. The flow of air around the tower is disturbed (or separated) up-stream of the tower causing the blades to experience a change in lift force and a corresponding production of noise. The frequencies associated with this source are generally infrasonic. The magnitude of the noise level is understood not to be significant for modern wind turbines.

IEC 61400-11 WIND TURBINE SOUND POWER MEASUREMENT

The noise output of a wind turbine generator is universally determined from controlled site tests in accordance with international standard IEC 61400-11 "Wind turbine generator systems – Part 11: Acoustic noise measurement techniques" [6]. The procedure involves measurement of sound levels up close to the turbine and calculating the sound power level of the turbine at integer wind speeds referenced to a 10m high anemometer mast (as in Table 1). Measurements are taken with a microphone fixed to a circular board placed on the ground to reduce the wind noise generated at the microphone and to minimise the influence of different ground types. Measurements of sound pressure levels and wind speeds are made simultaneously over short periods of time and over a wide range of wind speeds. The wind speed is measured at a height z (which may differ from the standard anemometer height of 10m).

As explained later in this paper, the wind speed increases with height above ground, the rate of increase in part depending upon the height of obstructions on the ground such as buildings and vegetation. The height of obstructions on the ground is measured by the surface roughness length z_0. Values of z_0 typically range from 10mm for open flat land to 300mm for suburbs or land with densely planted trees such as forest. The international standard corrects the measured wind speed at height z to specific reference conditions. The reference condition for terrain is a roughness length of 50mm (typical of open vegetated farming land) and the reference condition for the wind speed height is the standard anemometer height of 10m. The standardization is accomplished by use of the following equation:

$$U_s = U_z \left[\frac{\ln\left(\frac{z_{ref}}{z_{0ref}}\right) \ \ln\left(\frac{H}{z_0}\right)}{\ln\left(\frac{H}{z_{0ref}}\right) \ \ln\left(\frac{z}{z_0}\right)} \right] \tag{1}$$

where U_s is the corrected wind speed under reference conditions which is correlated with the sound power level of the turbine, U_z is the measured wind speed at anemometer height z, z is the measurement anemometer height, z_{ref} is the standard anemometer reference height of 10m, z_{0ref} is the reference roughness length of 50mm, z_0 is the roughness length at the measurement site, and H is the rotor hub height.

The standardising procedure enables the sound power level of wind turbines measured under different environmental conditions to be directly compared with each other under reference conditions. However, in applying the quoted sound power level of turbines to a new project site, one cannot simply assume those sound power levels relate to the 10m anemometer wind speeds measured at the project site because the roughness length could be different to the reference conditions. One would need to use a variation of equation (1) to recalculate U_s for the project site (U_s') with the appropriate roughness length z_0' applicable to the project site. In the author's experience, this has not been common practice when assessing noise from new projects as it was presumably assumed that project sites can be equated to "open vegetated farming land" having a roughness length of 50mm. Furthermore, as discussed below in this paper, the wind speed gradient does not only depend upon the terrain roughness length but also on meteorological conditions. Therefore, the recalculated value of U_s' for the project site may not necessarily apply to all meteorological conditions. If instead the reference wind speed for sound power level measurements is quoted at hub height rather than at the 10m standard anemometer height this avoids those complications. This is the preferred method recommended in current wind standards and guidelines.

The quantification of noise characteristics is also described in the standard such as tonality, infrasound, low-frequency noise, impulsive noise, amplitude modulation and any other characteristics (such as bangs and screech). Caution should however be used in applying those noise characteristics measured close to the turbine as they may not apply at larger distances. The reason is that characteristics such as impulsive noise and amplitude modulation may not be evident close to the turbine due to the directional properties of aerodynamic noise referred to earlier. Also, testing during the daytime may avoid the incidence of amplitude modulation and impulsive effects if they occur at night in high wind shear situations.

WIND SPEED PROFILE

The effect of wind speed profile and atmospheric stability on wind turbine sound propagation has been studied and reported extensively by van den Berg [7]. In a non-complex terrain up to a height of about 200 m above ground level, wind speed is not constant but usually increases with height. The reason is that wind close to the ground is influenced by the roughness of the ground surface and therefore experiences friction resulting in the formation of a boundary layer over this height range. The wind profile is reasonably well approximated as a power-law of the form:

$$U_z = U_r \left[\frac{z}{z_r}\right]^{\varepsilon} \tag{2}$$

where U_z is the scalar mean wind speed at height z above ground level, U_r is the scalar mean wind speed at some reference height Z_r, commonly 10 m, and ε is the power-law exponent. The power-law exponent ε typically varies from about 0.1 on a sunny afternoon to about 0.6 during a cloudless night. The larger the power-law exponent, the larger the vertical gradient in the wind speed. Although the power-law is a useful engineering approximation of the average wind speed profile, actual profiles will deviate from this relationship.

Site-specific values of the power-law exponent may be determined for sites with two levels of wind data by solving equation (2) for ε:

$$\varepsilon = \left[\frac{\mathrm{1n}(U_z) - \mathrm{1n}\ (U_r)]}{\mathrm{1n}(Z) - \mathrm{1n}\ (Z_r)} \right] \qquad (3)$$

The wind profile power-law exponent is a function of stability, surface roughness and the height range over which wind speeds are determined. Stability refers to the state of the atmosphere close to the ground. An unstable atmosphere occurs when the ground heats the lower air during the day and the upper air remains cold. This is an unstable situation because the hot air, being less dense, is prone to rise and to be replaced with the upper cold air which, being denser, gravitates downwards to replace it. This vertical motion and mixing of air destabilizes the horizontal air-flow pattern and causes the wind speed to be less variable with height. At sunset, the ground cools quickly and the adjacent air also cools. The warmer air, being less dense, gradually disperses to the higher altitudes. The vertical mixing described above subsides and the situation now becomes stable (warm air at the upper levels and cold air at the lower levels). This is referred to as a temperature inversion. In a stable atmosphere, horizontal air-flow becomes laminar (i.e. moves essentially horizontally over the ground) and, in the absence of vertical disturbances, is capable of developing a strong horizontal shear gradient with the upper air moving faster than the lower air. However, strong winds may disperse a temperature inversion due to mixing effects.

Surface roughness is also a factor affecting the power-law exponent. In general terms, the rougher the ground surface (for example forest compared to open grass), the greater will be the power-law exponent. As stability and surface roughness vary depending upon wind direction and season of the year, they should be determined independently for each of those time categories. Typical values of power-law exponent which occur in various stability situations are given in Table 2 [13,14]. The atmospheric stability classifications A-G in Table 2 are termed the Pasquill-Gifford classification.

Table 2. Typical default power-law exponents ε for urban and rural wind profiles

Stability Class	Typical Occurrence	Urban Exponent	Rural Exponent
A	Unstable. Sunny day with light winds	0.15	0.07
B	Mildly unstable	0.15	0.07
C	Weakly unstable	0.20	0.10
D	Neutral: Overcast conditions regardless of wind speed	0.25	0.15
E	Weakly stable	0.30	0.35
F	Stable: Clear sky, light winds and moderate temperature inversion present	0.30	0.55
G	Extremely unstable: Found in arid rual areas. Strong temperature inversion present	>0.30	>0.55

Figure 3 shows, by way of example, the variation in wind speed with height for three typical cases indicated in Table 2, that is A, D and E. On a sunny day with light winds (Class A), the wind speed does not vary significantly with height. The wind speed at the standard anemometer height of 10m does not differ substantially from the wind speed at a hypothetical turbine hub height of 70m. On a clear night (Class E), the wind speed at the turbine hub height may be substantially higher than at 10 metres, in this case it is twice the value measured at the standard anemometer height. However, the power-law exponent should be calculated from wind speed data for each specific site.

It should now be clear that the rotor blades sweep through a wind that changes speed with height above ground level and having a gradient dependent upon meteorological conditions and the nature of the landscape and so the mechanisms producing aerodynamic noise previously described are found to be in cyclic synchronism with that complex airflow pattern. This interaction of machine and its environment is what makes turbine noise a unique noise source.

EFFECT OF WIND SPEED PROFILE ON SOUND PROPAGATION

Sound is convected by the wind, that is, the wind carries the sound with it. Sound travels at a speed of approximately 340m/sec and so in a 5m/sec wind at a given height (in the same direction as the sound) it will travel at a speed of 345m/sec. If the wind speed increases with height, then sound “rays” at a higher altitude will travel faster than sound “rays” close to the ground. The net result is that the “rays” bend towards the ground. Those rays which would have dispersed into the air and thus would not have been audible are bent towards the ground and amplify the sound traveling along the ground. This enhances the sound level when the wind blows from the source to the receiver. When the wind blows from the receiver to the source, one may think in terms of the wind “blowing the sound rays” away and hence the sound is attenuated. The degree to which the sound is enhanced or attenuated is affected by the power-law exponent. The greater the power-law exponent, the greater the wind effect. Hence, on sunny days (Class A), for the same wind speed measured at the standard 10m height, the effect of wind is not as great as on clear nights (Classes E-G).

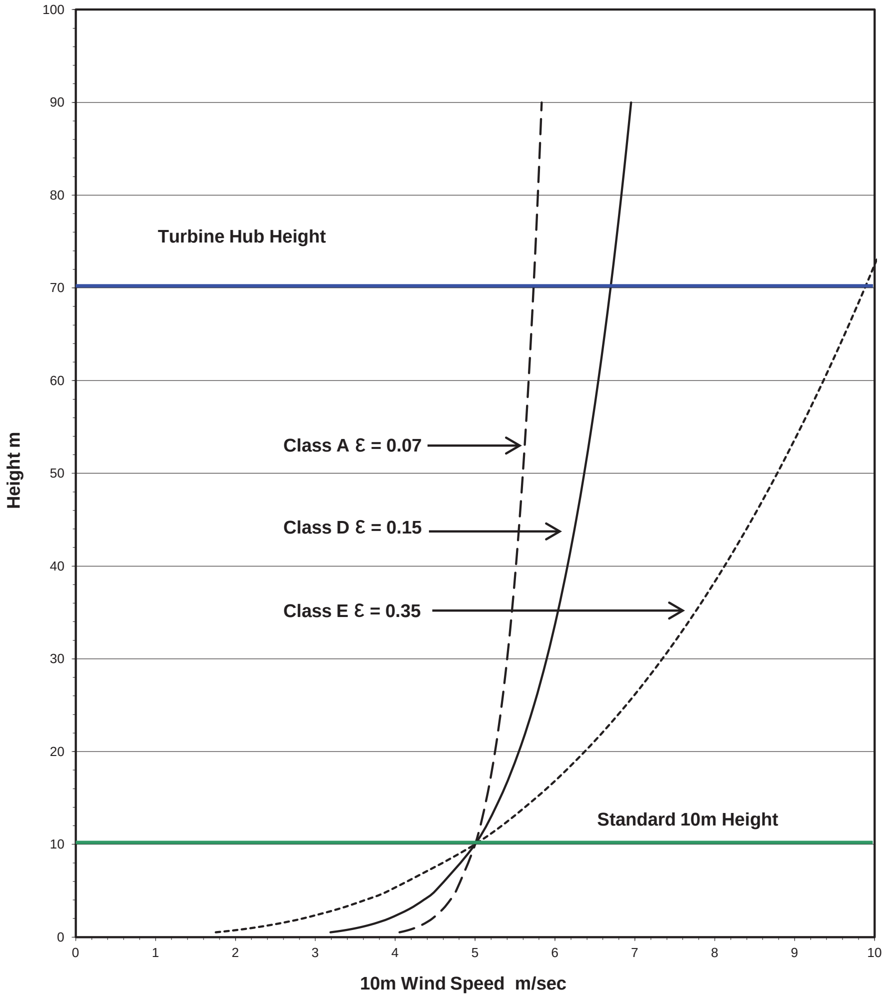


Figure 3. Wind speed profiles with equal speed of 5m/sec at 10m height (above ground level)

VERTICAL TEMPERATURE GRADIENT

During the day, the air temperature generally decreases with height as a consequence of the ground heating the lower air and not the upper air. This is termed a “temperature lapse” and, for the reasons discussed above, is an unstable situation. At night, the reverse occurs and the ground cools quickly, in turn cooling the lower air whilst the higher air remains warm due to its poor thermal conductivity. This is termed a “temperature inversion” and, again for the reasons stated above, is a stable situation. When overcast, the effect of cloud cover is to make the air generally constant in temperature and this is termed a “neutral” situation. The stability of the air is expressed in terms of the Stability Category A-G which was previously introduced in Table 2. Categories A-C, for example are classed as a temperature lapse, Category D is a neutral situation and Categories E-G are temperature inversions as shown in Table 3 [14].

Table 3. Stability categories based on vertical temperature gradient

Stability Class	Typical Occurrence	Vertical Temp Gradient C°/100m
A	Unstable. Sunny day with light winds	<-1.9
B	Mildly unstable	-1.8
C	Weakly unstable	-1.6
D	Neutral: Overcast conditions regardless of wind speed	0
E	Weakly stable	1.5
F	Stable: Clear sky, light winds and moderate temperature inversion present	3.0
G	Extremely unstable: Found in arid rual areas. Strong temperature inversion present	≥ 4

EFFECT OF VERTICAL TEMPERATURE GRADIENT ON SOUND PROPAGATION

Sound travels faster in warmer air. If the temperature increases with height (ie. in a temperature inversion), then sound "rays" at a higher altitude will travel faster than sound "rays" close to the ground. The net result is that the "rays" bend towards the ground. As for the discussion above in the case of wind, those rays which would have dispersed into the air and thus would not have been audible are bent towards the ground and amplify the sound traveling along the ground. This enhances the sound level when there is a temperature inversion. However, unlike wind, the enhancement occurs in all directions no matter where the receiver is located relative to the source. If the temperature decreases with height (ie. in a temperature lapse), the sound "rays" are convected upwards and hence the sound is attenuated. The degree to which the sound is enhanced or attenuated is affected by the vertical temperature gradient. The greater the gradient, the greater the effect. Hence, on sunny days (Class A), sound is generally reduced and on clear nights (Classes E-G) the sound is enhanced. The combined effects on noise of a wind speed gradient and temperature gradient are additive.

NOISE PREDICTION MODELS

There are three principal methods used in Australian codes and guidelines for the prediction of noise levels from wind turbine sites [15-17], namely, the simple geometrical model, ISO9613-2 and CONCAWE. The factors affecting sound propagation are:

- Distance
- Air absorption
- Ground effect (because the ground is not a perfect reflector and the effect of sound reflection and refraction from the ground is dependent on the source height, terrain cover, ground properties and frequency)
- Blocking of sound by obstructions and uneven terrain
- Weather effects (wind speed and the variation of wind speed or temperature with height), and
- Shape of the land (certain land forms can focus sound).

Simple Geometric Model

A simple model based on the more conservative assumption of hemispherical sound propagation over a reflective surface including air absorption is recommended in Australian Standard AS4959 as follows [18]:

$$Lp = Lw - 10\log(2\pi R^2) - \alpha R \qquad (4)$$

where Lw is the sound power level of the turbine (dB re 10^{-12} watts), R (metres) is the distance between the source and the receptor, and the term αR takes into account the absorption of sound as it passes through the air. α is expressed in octave band frequencies and is given in Table 4.

Table 4. Atmospheric absorption coefficient α dB/m

Octave Band Freq Hz	63	125	250	500	1k	2k	4k	8k
α dB/m	.0001	.0004	.0011	.0023	.0041	.0087	.0264	.0937

The total sound pressure level produced by multiple wind turbines is calculated by logarithmic summation of the sound pressure levels from each turbine at a specific location. The ETSU review of a model similar to that described in the standard concluded that the predicted levels lie within about 1-2dB(A) of the levels measured in the presence of a 6m/sec positive wind vector (10m height) between source and receiver [19]. Other evidence however suggests that the model may not be conservative in specific topography [20].

If the receptor is located indoors, then the sound is reduced a further 10 dB(A) for a typical residence with open windows. With windows closed the decrease is typically 15 dB(A) or more, depending upon the glazing thickness and the window type. However, this relates only to the dB(A) scale. Much lower values of outdoor-to-indoor sound attenuation have been measured for infrasound, in some instances close to zero attenuation [21].

ISO 9613-2

The ISO 9613 noise prediction model is described in Part 2 of the international standard. It is part empirically based and part theoretically based. It calculates noise levels under conditions favourable to the propagation of noise. Favourable conditions are defined to be a 1m/s to 5m/s component of wind speed blowing from the source to the receiver or a well developed moderate temperature inversion. The ISO model also includes the effects of terrain, excess attenuation due to ground effects and acoustic screening.

The accuracy of output from the ISO model was validated by ETSU [19]. The project aimed to quantify the variation in noise level experienced at varying distances from an omni-directional loudspeaker noise source located between 15m to 30m above ground level on three different sites representing 'flat', 'rolling' and 'complex' topography. At each site, sound pressure levels were continuously monitored at up to 15 locations around the noise source over periods of up to 6 weeks. The measurement locations extended from less than 50m to over 900m from the noise source. Simultaneous measurements of important meteorological parameters were also undertaken including wind speed, wind direction, wind shear, temperature, temperature gradient, atmospheric pressure and rainfall.

Under conditions of a 6m/s positive vector wind speed (10m height) on flat, rolling and complex terrain sites, the accuracy was found to be within 1.5dB(A). The only observed exceptions occurred in the presence of marginal or partial acoustic screening, and also where the ground falls away significantly between the source and receiver.

In order to account for these situations, it was proposed in the report that the excess attenuation attributable to barriers should be limited to no more than 3dB(A). This is because it has been observed experimentally that the presence of a positive component of wind from the source to the screened receiver significantly reduces the effective barrier performance.

Where the ground falls away significantly between the source and receiver, such that the mean propagation height is at least 1.5 times that over flat ground and particularly where the ground falls away steeply from the receiver, it was recommended that 3dB(A) be added to the calculated sound pressure level. This correction factor is based on experimentally measured levels. It accounts for the reduction in excess ground attenuation due to the increased height of propagation.

Provided the suggested correction factors are applied to the output of the ISO 9613 model, the report states that agreement is achieved to within 2dB(A) of noise levels measured under practical 'worst case' conditions at distances of up to 1,000 metres from a noise source. Also, based on the observed scatter of measured sound pressure levels under these same conditions, it concluded that the one standard deviation spread of data above the calculated levels will be below 1dB(A), even at the furthest distances from the source. It therefore concluded that an 85% level of confidence can be placed on the noise levels measured in practice not exceeding the calculated level by more than 1dB(A). The accuracy of the model at distances beyond 1,000 metres at which, in Australia at least, most residential dwellings will usually be located, is under investigation [eg. reference 23].

CONCAWE

The CONCAWE prediction method was developed for use in predicting noise from power stations and validated in areas of relatively flat terrain [22]. As a consequence of the large deviations noted in the model predictions for wind farm noise, the ETSU study [19] did not recommend use of the model. Recent studies of the model in Australia confirm that it is accurate under some circumstances but not in others [23].

CONCLUSIONS

The fact that wind turbines interact with the environment which propagates the sound they generate makes this source of noise unique amongst other autonomous mechanical noise sources. This paper has provided an introduction into the complex mechanisms involved and a simple view of the current state of understanding of the technology relating to the generation and propagation of wind turbine noise.

REFERENCES

[1] The Senate Community Affairs References Committee, *The social and economic impact of rural wind farms*, Australian Senate June 2011, http://apo.org.au/node/25321

[2] *NSW Wind Energy Handbook 2002*, Sustainable Energy Development Authority of NSW (SEDA)

[3] P. Gipe, *Wind turbine tower trends*, http://www.wind-works.org/articles/TowerTrends.html (Last accessed on 18 March 2012)

[4] C. Doolan, "Concepts for the control of wind turbine noise", *Proceedings of Acoustics 2011*, Gold Coast, Australia, 2-4 November 2011

[5] J. Jakobsen, "Infrasound emission from wind turbines", *Journal of Low Frequency Noise, Vibration and Active Control* **24**(3), 145-155 (2005)

[6] International Electrotechnical Commission IEC 61400-11, *Wind turbine generator systems – Part 11: Acoustic noise measurement techniques*, edition 2.1 2006-11

[7] G.P. van den Berg, "Effects of the wind profile at night on wind turbine sound", *Journal of Sound and Vibration* **277**, 955-970 (2004)

[8] S. Oerlemans and J.G. Schepers, "Prediction of wind turbine noise and validation against experiment", *International Journal of Aeroacoustics* **8**(6), 555-584 (2009)

[9] D. Bowdler, "Amplitude modulation of wind turbine noise", *Acoustics Bulletin* **33**(4), July/August 2008, pp. 31-35

[10] *Wind turbine sound and health effects: An expert panel review*, American Wind Energy Association and Canadian Wind Energy Association, 2009, http://www.awea.org/learnabout/publications/upload/awea_and_canwea_sound_white_paper.pdf (Last accessed 18 March 2012)

[11] A. Moorhouse, M. Hayes, S. von Hünerbein, B. Piper and M. Adams, *Research into aerodynamic modulation of wind turbine noise: Final report*, University of Salford, Contract No NANR233, 2007

[12] *The measurement of low frequency noise at three UK wind farms*, Hayes McKenzie Partnership Ltd. for the UK Department of Trade and Industry (DTI), Contract No. W/45/00656/00/00, 2006

[13] United States Environmental Protection Agency, *Meteorological monitoring guidance for regulatory modeling applications*, EPA-454/R-99-005, 2000

[14] NSW Industrial Noise Policy, Appendix E - *Methods for determining the frequency of temperature inversions*, Environment Protection Authority, 2000

[15] NSW Department of Planning and Infrastructure, *Draft NSW Planning Guidelines: Wind Farms, 2011*

[16] South Australia Environment Protection Authority, *Wind farms environmental noise guidelines*, 2009 http://www.epa.sa.gov.au/xstd_files/Noise/Guideline/windfarms.pdf

[17] Victoria uses New Zealand Standard NZS 6808:2010 *Acoustics – Wind farm noise*

[18] Australian Standard AS 4959:2010 *Acoustics – Measurement, prediction and assessment of noise from wind turbine generators*

[19] J.H. Bass and A.J. Bullmore, *A critical appraisal of wind farm noise propagation*, Report No. 058/RES/2521, Issue 1, Energy Technology Support Unit (ETSU) W/13/00385/00/REP, 2000

[20] T. Evans and J. Cooper, "Comparison of predicted and measured wind farm noise levels and implications for assessments of new wind farm", *Proceedings of Acoustics 2011*, Gold Coast, Australia, 2-4 November 2011

[21] R.D. O'Neal, R.D. Hellweg Jr. and R.M. Lampeter, "Low frequency noise and infrasound from wind turbines", *Noise Control Engineering Journal* **59**(2), 135-157 (2011)

[22] CONCAWE, *The propagation of noise from petroleum and petrochemical complexes to neighbouring communities*, ATL Report No 4/81, 1981

[23] J. Cooper, T. Evans and L. Najera, "Comparison of compliance results obtained from the various wind farm standards used in Australia", *Proceedings of Acoustics 2011*, Gold Coast, Australia, 2-4 November 2011

COMPARISON OF PREDICTED AND MEASURED WIND FARM NOISE LEVELS AND IMPLICATIONS FOR ASSESSMENTS OF NEW WIND FARMS

Tom Evans[1] **and Jonathan Cooper**[2]
[1]**AECOM, Level 28, 91 King William Street, Adelaide, SA 5000**
[2]**Resonate Acoustics, 97 Carrington Street, Adelaide, SA 5000**

To maximise the energy output of wind farms whilst still meeting the relevant noise regulations, it is important that an accurate environmental noise prediction method be used during the planning stage. This paper presents a comparison of predicted noise levels from four commonly applied prediction methods against measured noise levels from the operational wind farm conducted in accordance with the applicable guidelines in South Australia. The results indicate that the methods typically over-predict wind farm noise levels but that the degree of conservatism appears to depend on the topography between the wind turbines and the measurement location.

INTRODUCTION

An environmental noise assessment is an important component of the planning stage for new wind farms located near to noise sensitive receivers. Noise criteria defined by regulatory authorities will often constrain the layout and number of turbines within the wind farm.

A key part of the assessment is the environmental noise prediction method used to predict wind turbine noise levels at nearby sensitive receivers. A prediction method that under-predicts noise levels, even marginally, could lead to turbines being shut down during the operational phase in order to achieve compliance with the noise criteria. Conversely, a prediction method that over-predicts noise levels could result in available land for wind energy production being under-utilised.

This paper presents a comparison of predicted noise levels from commonly applied noise prediction methods against measured operational wind farm noise levels from 13 sites at six wind farms. Noise levels from each of the sites have been analysed in accordance with the South Australian *Wind Farms Environmental Noise Guidelines* (SA Guidelines) [1].

In order to minimise the effect of other factors that could result in a difference between predicted and measured noise levels, predictions have been carried out using:

- measured sound power levels for the installed turbines
- topographical contours for each wind farm
- GPS-determined co-ordinates for measurement sites
- hub height measured wind speeds.

Similarly, the measurement sites and analysis processes have been selected to minimise the contribution of background noise to the measured noise levels.

The findings of this paper complements those of the authors' other paper in this issue [2]. The noise measurement and analysis process, outlined briefly in this paper, is discussed in more detail in the other paper.

PREVIOUS INVESTIGATIONS

A number of investigations into the accuracy of environmental noise prediction methods for wind farms have been undertaken both in Australia and internationally, with key ones discussed briefly in this section.

Bass et al. [3] conducted a study into the development of a wind farm noise propagation prediction model by measuring noise levels from a loudspeaker of known sound power level across three different sites. The loudspeaker was situated at a height between 15 to 30 metres above ground, with measurements conducted up to 900 metres away. It was concluded that the prediction model defined by International Standard ISO 9613-2:1996 [4] provided “impressive” accuracy between the predicted and measured noise levels but that this could be improved through the application of corrections depending on topographical conditions. Following this, Bullmore et al. [5] conducted measurements around three European wind farm sites and found the ISO 9613-2 prediction method provided an upper limit of measured noise levels under downwind conditions. This modelling assumed either completely reflective ground or 50% absorptive ground depending on the particular site.

A comparison of measured and predicted noise levels for two wind farms as part of the Portland Wind Energy Project has also recently been carried out [6]. For this assessment, post-construction L_{95} noise levels were measured in accordance with New Zealand Standard NZS 6808:1998 [7] and compared to the sum of the predicted noise levels and the average pre-construction background noise levels. It was found that the ISO 9613-2 prediction method, using 50% absorptive ground, provided the best correlation to the measurement data across the two wind farms. However, the paper identified potential concerns regarding the contribution of background noise levels to the overall measured noise levels.

A number of standards and guidelines also provide recommendations on prediction methods to be used for wind farms. NZS 6808:1998 and the updated 2010 version [8] both outline acceptable methods. A stakeholder review of NZS 6808:1998 [9] concluded that:

> *In cases where the distances between turbines and receivers are significant and have significant terrain features, the ISO9613 model produces more accurate results. As typical setbacks to NZ wind farms are 800 metres or more, ISO9613 would appear to most accurately predict measured sound levels.*

The SA Guidelines recommend the use of either the ISO 9613-2 or CONCAWE [10] prediction methods.

The discussed previous studies have typically focussed on comparing individual attended measurements (under known conditions) with predicted noise levels, or on assessing whether prediction methods provide an upper limit for any measured noise level at the site. This limits the ability to directly compare the results from these studies with the compliance measurement procedures typically carried out for Australian wind farms, as these procedures involve determination of an average noise level across a number of data points at each integer wind speed.

While the Portland Wind Energy Project study was carried out based on the NZS 6808:1998 assessment methodology, this method has only been used within Victoria and has recently been superseded by the NZS 6808:2010.

In our study, measured noise levels from wind farms in South Australia and Victoria have been determined in accordance with the SA Guidelines, or the earlier 2003 SA Guidelines [11] which use the same measurement process. This requires determination of an average measured noise level under all downwind periods. For future wind farms assessed in this manner, it is important that the accuracy of the environmental noise prediction method be understood to both improve the planning of the wind farm and to address concerns about noise prediction accuracy.

SITE DESCRIPTIONS

Six wind farm locations and 13 measurement sites have been selected for comparison in this paper as measurements collected at these sites appear to be controlled by noise from the wind turbines across a reasonable wind speed range.

The measurement sites were selected based on their higher than typical exposure to noise from the wind farms, or due to the low background noise levels at the site. They are typically representative of the closest receivers to wind farms in South Australia, although several of the measurement sites were not actually at a residence. However, one measurement site has been selected that is located approximately 3,000 metres from the nearest turbine.

For commercial reasons, the names and locations of the wind farms have not been disclosed and the wind farms will be designated as Wind Farm A through to F. The turbines at the farms are rated between approximately 1.5 MW and 2 MW. Based on compliance monitoring conducted at each site, all of these wind farms are in compliance with the environmental noise criteria.

Wind Farm A

Wind Farm A involves a line of turbines stretching about 10 kilometres along the top of a range of hills. The turbines are spaced approximately 400 metres apart. Three noise measurement sites have been considered as part of this comparison (A1, A2 and A3). Each site is located between 800 and 1000 metres from the nearest turbine, and situated 50 to 70 metres lower than the base height of that turbine.

The ground between Sites A1 and A2 and the nearest turbine to each site slopes steadily down from the turbine, with a slight rise in the ground relative to the straight line between the turbine base and the measurement site within about 100 metres of the receiver location. The ground between Site A3 and the nearest turbine slopes sharply down from the turbine initially, reaching a height of 5 metres above the measurement point less than 400 metres from the turbine before sloping gently for the remainder of the distance.

Wind Farm B

Wind Farm B also involves a line of turbines stretching about 10 kilometres along the top of a range of hills. The turbines are spaced approximately 300 metres apart. Four noise measurement sites have been considered as part of this comparison (B1, B2, B3 and B4). B1, B2 and B3 are located approximately 1,000 to 1,500 metres from the nearest turbine, with B4 located approximately 3,000 metres away. All sites are situated 130 to 200 metres lower than the base height of the nearest turbine.

The ground between Sites B1 and B3 and the nearest turbine to each site initially slopes sharply down from the turbine to the measurement site, with an 80% decrease in elevation before the midpoint between is reached. The topography between Site B4 and the nearest turbine is similar to that of B1 and B3, but the 80% decrease in elevation occurs within 800 metres of the turbine (approximately 25% of the total horizontal distance to the measurement point). The ground between Site B2 and the nearest turbine slopes relatively evenly down for the entire distance, with a slight concave nature to the slope.

Wind Farm C

Wind Farm C involves a group of turbines distributed over about 20 square kilometres, and spaced approximately 350 metres apart. Three measurement sites have been considered as part of this comparison and have been designated C1, C2 and C3. The measurement sites are located between 300 and 700 metres from the nearest turbine.

The ground around the wind farm is relatively flat, with no change in elevation from the turbine base to the measurement site greater than 10 metres.

Wind Farms D, E and F

Wind Farms D and E both involve turbines arranged in a line, while the turbines at Wind Farm F are arranged into a group. One noise measurement site has been selected for each wind farm and designated D1, E1 and F1 respectively. The distance from each site to the nearest turbine is 300 metres for D1, 1,200 metres for E1 and 700 metres for F1.

The ground between the nearest turbines and the measurement site at each of these wind farms is relatively flat, with no change in elevation from the turbine base to the measurement site greater than 10 metres.

Summary

Table 1 provides a general description of the topography for each site. At none of the measurement sites was the line of sight from receiver to the nearest turbine hubs and blades (controlling the overall noise levels) interrupted by the local topography.

MEASURED NOISE AND SOUND POWER LEVELS

Environmental Noise Measurements

A-weighted $L_{90,10min}$ noise levels from the wind farms were measured at each site over a period of three to four weeks. Both the measurements and subsequent data analysis were undertaken in accordance with the 2009 SA Guidelines [1]. The measured noise levels were correlated with wind speeds for the period, measured at the most representative hub height meteorological mast. A single 'measured' noise level value for each integer wind speed was determined by fitting a polynomial regression line to the data.

Only those measured noise levels that coincided with wind directions within 45° of the worst case wind direction (i.e. the direction from the nearest wind turbine to the measurement site) were considered for the analysis. Measurements that were obviously affected by extraneous noise sources or that did not coincide with wind speeds between the cut-in and cut-out of the turbines were excluded from the analysis. At eleven of the locations, over 500 valid data points remained in the worst case wind direction. At the other two locations (C1 and C2) approximately 200 valid data points remained although these were confined mainly to the small range of wind speeds where measured sound power data for the installed turbines was available.

A significant issue that can affect measurement results from operational wind farms is the contribution of the background noise environment. While this can be somewhat overcome by subtracting the measured pre-construction noise levels, Delaire and Walsh [12] showed this method is susceptible to error as background noise levels can change across seasons and years. The pre- and post-construction measurement locations may also be different, another possible inaccuracy with this method. To address this, each measurement site was selected such that it was as far away as possible from potential sources of background noise (e.g. trees, occupied dwellings), and such that the noise level at the site was typically controlled by turbine noise. In addition, only wind speeds where the L_{A90} noise level appears to be consistently controlled by turbine noise were considered in our analysis. These wind speeds have been selected based on analysis of the measurement data and supported by observations made on site during the measurements. Wind speeds where there was a significant spread in the measured noise levels were excluded, as observations on site indicated this variation was the result of extraneous noise sources affecting measured levels.

As an example, Figure 1 presents measurement results for Site B3, indicating a wind speed range of 4 to 12 m/s where the measured noise level is controlled by turbine noise. This is evident due to the small spread of the measurement data when compared to wind speeds above 12 m/s where background noise causes significant variation between measured noise levels at the same integer speed. At lower wind speeds, there are also a number of measurements where the turbine clearly cut-out due to low wind speed during the measurement period. These have been excluded from further analysis. For each measurement site, between three and six integer wind speeds were identified as being in the turbine-controlled wind speed range.

Table 1. General description of topography

Site	Topographical description	Approximate distance to nearest turbine
A1	Steady downward slope	1000 m
A2	Steady downward slope	800 m
A3	Concave downward slope	800 m
B1	Concave downward slope	1500 m
B2	Slight concave downward slope	1000 m
B3	Concave downward slope	1000 m
B4	Concave downward slope	3000 m
C1	Flat	600 m
C2	Flat	300 m
C3	Flat	700 m
D1	Flat	300 m
E1	Flat	1200 m
F1	Flat	700 m

Sound Power Level Measurements

Sound power levels for typically two of the turbine models installed at each site were measured in general accordance with International Standard IEC 61400-11 Edition 2.1 [13]. Minor deviations from IEC 61400-11 Edition 2.1 at each site were not considered likely to affect the measured sound power levels. There was generally little difference between the measured sound power levels for different turbines at the same site but the average measured sound power level has been used for this comparison.

The measured sound power levels were compared against the measured compliance noise levels at each of the sites. At every site, the change in measured compliance noise level across the turbine-controlled wind speed range demonstrated good correlation with the change in sound power level across that range. This suggests that there is no noticeable change in the propagation of noise from the turbines to the measurement locations due to changes in the wind speed.

Figure 2 compares the measured noise levels for Site B3 against the measured sound power levels (reduced by approximately 60 dB) for the turbines at that wind farm. Similar results were obtained for all of the measurement sites.

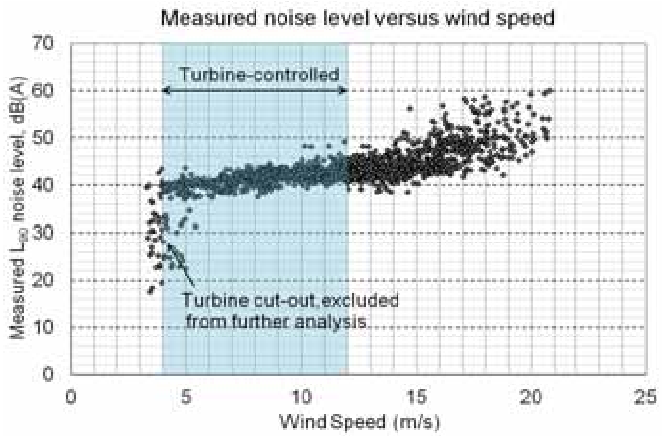


Figure 1. Example of measured noise levels versus wind speed with turbine-controlled wind speed range

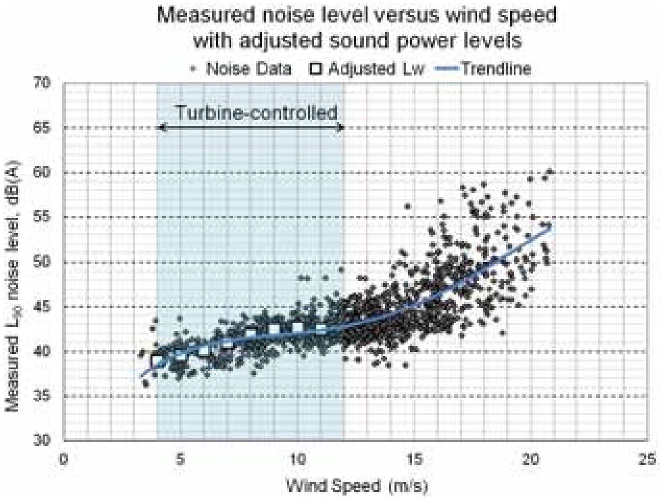


Figure 2. Comparison of measured noise levels and measured sound power levels

ENVIRONMENTAL NOISE PREDICTION METHODS

ISO 9613-2

The ISO 9613-2 prediction method, as implemented in the SoundPLAN Version 7.0 software (produced by Braunstein + Berndt GmbH), has been selected for comparison with the measured noise levels in this paper. It is recommended by both NZS 6808:2010 and previous investigations as providing appropriate accuracy for predictions of wind farm noise levels. ISO 9613-2 states a prediction accuracy of ± 3 dB for sources of heights up to 30 metres above ground and for distances up to 1000 metres from the source. However, outside of these conditions, no indication of accuracy is provided.

Two different ground absorption values (G=0 and G=0.5) have been adopted for the ISO 9613-2 method. No meteorological correction factor has been applied, such that the predicted levels can be considered to reflect the typical downwind noise level.

CONCAWE

The CONCAWE prediction method, as implemented in the SoundPLAN Version 7.0 software, has also been selected. It was developed based on sources of heights up to 25 metres above ground and is typically applied up to distances of 2,000 metres from the source.

Predictions with the CONCAWE method have been carried out assuming worst case meteorological conditions (Weather Category 6) apply from all wind turbines to each measurement site. Completely absorptive ground (G=1) has been assumed as the use of reflective ground has previously been found to result in significant over-predictions with the CONCAWE methodology [9]. The air absorption values specified by ISO 9613-2 have been used for the CONCAWE predictions.

NZS 6808:1998 method

The simplified hemispherical prediction method outlined in NZS 6808:1998 has been widely used in Australia and New Zealand, has also been used in this paper. The method is independent of topography and the noise level (L_R) at a height of 1.5 metres and distance R from each turbine is calculated based on Equation (1):

$$L_R = L_W - 10\log(2\pi R^2) - \alpha_a R \qquad (1)$$

L_W is the sound power level of the turbine and α_a is the attenuation of sound due to air absorption in dB(A)/m. Two different air absorption values have been used to calculate noise levels using this method:

- a constant value of 0.005 dB(A)/m as recommended by NZS 6808:1998
- the octave band air absorption values outlined in ISO 9613-2.

Nord2000 method

The Nordic environmental noise prediction method, referred to herein as the Nord2000 method, has been validated for the prediction of wind turbine noise [15]. This method, as implemented in the SoundPLAN Version 7.0 software, has been selected for comparison. The Nord2000 method represents the only prediction method used where the wind speeds have been altered accordingly to predict noise levels at each speed within the turbine-controlled wind speed range. This is as the Nord2000 method allows for specific wind speeds to be input at particular heights, which can vary the propagation. Other inputs specific to the Nord2000 prediction method included:

- average roughness length of 0.05 metres
- downwind conditions
- average temperature gradient of +5 K/km (temperature inversion), with standard deviation of 1 K/km
- turbulence constants: C_V^2 of 0.012 $m^{4/3}s^{-2}$ and C_T^2 of 0.0008 Ks^{-2}
- average ambient pressure measurements for the meteorological masts at each site
- flow resistivity for the site of 80 $kNsm^{-4}$
- medium roughness class.

Further information on each of these inputs and how they affect the predicted noise levels from the Nord2000 method can be found in the *Nordic Environmental Noise Prediction Methods, Nord 2000 Summary Report* [15].

Additional Model Inputs

Each noise model within the SoundPLAN software included the measured sound power levels for the installed turbines, topographical ground contours, turbine co-ordinates provided by the site operator and measurement site co-ordinates determined using a handheld GPS unit. The search radius in the SoundPLAN calculation module was set to 20 kilometres.

At Wind Farms A and B where the topography varied considerably between turbine and receiver, one metre elevation contours were used to develop the digital ground model. For Wind Farms C, D, E and F, 10 metre contours were used as this was the most accurate topographical data available. However, given the relatively flat nature of these sites, this was considered unlikely to affect the predictions. For the simpler NZS 6808:1998 method, only the measured sound power levels and the turbine and receiver co-ordinates were used as additional inputs. Based on the 2009 SA Guidelines, an average temperature of 10°C and average humidity of 80% was assumed for each site.

COMPARISON BETWEEN MEASURED AND PREDICTED NOISE LEVELS

Table 2 summarises the average difference between the predicted and measured noise levels at each site. A positive difference indicates over-prediction of the noise levels, while a negative difference indicates under-prediction. The differences have been averaged across the turbine-controlled wind speed range for the site, but the variation between differences at each wind speed is typically less than 0.2 dB(A) due to the good agreement between the change in measured sound power levels and the change in measured noise levels. The results indicate that, except for concave topographies, nearly all of the prediction methods over-predict wind farm noise levels at receivers when the measured levels are assessed in accordance with compliance methodology specified by the SA Guidelines.

Based on the comparison for the thirteen different measurement locations, it appears that topography plays an important role in the accuracy of predicted noise levels. This is most clearly evident at Wind Farm A where measurement sites A2 and A3 are located on different sides of the same small group of wind turbines. The only significant difference between the two sites is the topography from the nearest turbines to the measurement site.

As an example of the effect of topography, the ISO 9613-2 method with 50% absorptive ground is typically within ±1 dB(A) of the measured noise levels at Wind Farms C, D, E and F where the topography is relatively flat. Yet at Wind Farm B, where the topography is concave between the nearest turbines and receivers, this method can under-predict noise levels by up to 4 dB(A).

Considerable under-predictions appear to occur only at sites with concave slopes, with the NZS 6808:1998 (constant αa) and ISO 9613-2 (G=0.5) methods typically under-predicting by 2 to 5 dB(A). The exception is at B4, where the NZS 6808:1998 (constant α_a) method resulted in an under-prediction of approximately 15 dB(A). This is considered to be an effect of the significant distance to the measurement site (over 3,000 metres) at which the assumption of constant air absorption across the entire frequency range does not hold.

However, the relatively commonly used ISO 9613-2 (G=0) method only marginally under-predict noise levels at these locations. This finding is consistent with that of Bass et al. [3] who stated with reference to the ISO 9613-2 method:

> *Where the ground falls away significantly between the source and receiver ... it is recommended that 3 dB(A) be added to the calculated sound pressure level.*

IMPLICATIONS FOR ASSESSMENTS OF NEW WIND FARMS

Effects of Topography

The comparison between measured and predicted noise levels suggests that the topography between the turbines and the assessment location can be an important factor in the accuracy of particular prediction methods. The difference in accuracy of a particular method between a site with a steady slope to the nearest turbine and one with a concave slope can be 6 to 7 dB(A), even where the turbine hub is still clearly visible from the receiver.

Figure 3 shows the topographical cross-section for Site A2 (steady slope) from the nearest turbine, with the line of direct sight from the turbine hub to measurement site shown in red and the line from the turbine base to the measurement base shown in blue. Figure 4 shows the same cross-section for Site B1 (concave). It is clear that the line of sight from both measurement sites to the turbine is not broken despite the significant variance in the prediction accuracies at both sites.

A number of different factors based on the topographical cross-section have been calculated and compared to the differences between measured and predicted noise levels for each method in order to determine a correction factor that could be applied to predicted noise levels.

For Wind Farms A and B, dividing the area beneath the topographical cross-section by the area beneath the line connecting the turbine base to the measurement base appears to provide a reasonable correlation to the differences obtained

Table 2. Average difference between predicted and measured noise levels at sites (turbine-controlled speeds only)

<table>
<tr><th>Prediction method</th><th colspan="12">Predicted - measured noise levels, dB(A)</th></tr>
<tr><td>Wind Farm A</td><td colspan="4">A1 - Steady</td><td colspan="4">A2 - Steady</td><td colspan="4">A3 - Concave</td></tr>
<tr><td>ISO 9613-2 (G=0)</td><td colspan="4">5.8</td><td colspan="4">5.4</td><td colspan="4">-0.4</td></tr>
<tr><td>ISO 9613-2 (G=0.5)</td><td colspan="4">2.2</td><td colspan="4">2.2</td><td colspan="4">-3.5</td></tr>
<tr><td>CONCAWE (G=1)</td><td colspan="4">6.2</td><td colspan="4">6.5</td><td colspan="4">1.3</td></tr>
<tr><td>NZS 6808:1998 (constant α_a)</td><td colspan="4">2.5</td><td colspan="4">3.1</td><td colspan="4">-1.9</td></tr>
<tr><td>NZS 6808:1998 (ISO 9613 α_a)</td><td colspan="4">6.2</td><td colspan="4">6.5</td><td colspan="4">1.2</td></tr>
<tr><td>Nord2000</td><td colspan="4">3.7</td><td colspan="4">4.5</td><td colspan="4">-0.8</td></tr>
<tr><td>Wind Farm B</td><td colspan="3">B1 - Concave</td><td colspan="3">B2 - Slight concave</td><td colspan="3">B3 - Concave</td><td colspan="3">B4 - Concave</td></tr>
<tr><td>ISO 9613-2 (G=0)</td><td colspan="3">-0.7</td><td colspan="3">1.0</td><td colspan="3">-0.4</td><td colspan="3">-0.3</td></tr>
<tr><td>ISO 9613-2 (G=0.5)</td><td colspan="3">-3.8</td><td colspan="3">-2.4</td><td colspan="3">-3.4</td><td colspan="3">-4.8</td></tr>
<tr><td>CONCAWE (G=1)</td><td colspan="3">-1.2</td><td colspan="3">1.6</td><td colspan="3">0</td><td colspan="3">-5.2</td></tr>
<tr><td>NZS 6808:1998 (constant α_a)</td><td colspan="3">-5.4</td><td colspan="3">-2.5</td><td colspan="3">-2.9</td><td colspan="3">-14.7</td></tr>
<tr><td>NZS 6808:1998 (ISO 9613 α_a)</td><td colspan="3">-0.1</td><td colspan="3">1</td><td colspan="3">-0.4</td><td colspan="3">-1.2</td></tr>
<tr><td>Nord2000</td><td colspan="3">-1.4</td><td colspan="3">0.4</td><td colspan="3">-1.4</td><td colspan="3">-2.2</td></tr>
<tr><td>Wind Farm C</td><td colspan="4">C1 - Flat</td><td colspan="4">C2 - Flat</td><td colspan="4">C3 - Flat</td></tr>
<tr><td>ISO 9613-2 (G=0)</td><td colspan="4">2.9</td><td colspan="4">2.9</td><td colspan="4">2.6</td></tr>
<tr><td>ISO 9613-2 (G=0.5)</td><td colspan="4">1.0</td><td colspan="4">0.1</td><td colspan="4">-0.6</td></tr>
<tr><td>CONCAWE (G=1)</td><td colspan="4">3.5</td><td colspan="4">3.6</td><td colspan="4">2.5</td></tr>
<tr><td>NZS 6808:1998 (constant α_a)</td><td colspan="4">2.5</td><td colspan="4">1.8</td><td colspan="4">0.1</td></tr>
<tr><td>NZS 6808:1998 (ISO 9613 α_a)</td><td colspan="4">3.2</td><td colspan="4">3.4</td><td colspan="4">2.5</td></tr>
<tr><td>Nord2000</td><td colspan="4">1.4</td><td colspan="4">0.6</td><td colspan="4">-0.3</td></tr>
<tr><td>Wind Farm D, E and F</td><td colspan="4">D1 - Flat</td><td colspan="4">E1 - Flat</td><td colspan="4">F1 - Flat</td></tr>
<tr><td>ISO 9613-2 (G=0)</td><td colspan="4">3.2</td><td colspan="4">2.5</td><td colspan="4">2.1</td></tr>
<tr><td>ISO 9613-2 (G=0.5)</td><td colspan="4">0</td><td colspan="4">-1.2</td><td colspan="4">-1.0</td></tr>
<tr><td>CONCAWE (G=1)</td><td colspan="4">3.7</td><td colspan="4">1.8</td><td colspan="4">2.6</td></tr>
<tr><td>NZS 6808:1998 (constant α_a)</td><td colspan="4">1.6</td><td colspan="4">-2.5</td><td colspan="4">-0.6</td></tr>
<tr><td>NZS 6808:1998 (ISO 9613 α_a)</td><td colspan="4">3.2</td><td colspan="4">3.1</td><td colspan="4">3.3</td></tr>
<tr><td>Nord2000</td><td colspan="4">1</td><td colspan="4">0.2</td><td colspan="4">2.0</td></tr>
</table>

with the ISO 9613-2 prediction method. However, this relationship does not hold for the flat topography of the other wind farms.

At this stage, no single topographical correction factor has been identified that can be applied to each of the situations. Additional reliable measurement data from other sites with varying topography is still required to determine an appropriate correction factor for the standard prediction methods.

Uncertainty

The predictions and measurements in this paper have been undertaken in an attempt to reduce potential uncertainty as much as possible. Some of these, such as uncertainty associated with the accuracy of measurement equipment, will be reduced due to the large number of measurements used to determine an overall ‘measured’ noise level. Similarly, slight topographical changes that are not accounted for in the noise models are unlikely to affect predicted noise levels at distances of over 300 metres. Nonetheless, some uncertainty in both the prediction and measurement of noise levels still remains.

A key source of uncertainty relates to the wind shear and variance of wind speed across a wind farm. To minimise this, all wind speeds have been based on hub height wind speeds and taken at a nearby meteorological mast or the nearest turbine to each measurement site. However, some uncertainty remains with regard to the difference between the measured wind speed and the actual wind speed at each wind turbine contributing to the overall measured noise level.

Measurement of the sound power level included calculation of an uncertainty value which is typically less than 1 dB(A) at those speeds considered for this comparison. While this can affect the actual difference between predicted and measured noise levels, most noise assessments undertaken at the planning stage of a new wind farm will use guaranteed sound power levels for turbines provided by the manufacturer. Guaranteed sound power levels are typically higher than actual sound power levels as the uncertainty is sometimes added to them by the manufacturer as a safety factor. For new assessments using guaranteed sound power levels, any prediction method will therefore be more likely to over-predict actual noise levels.

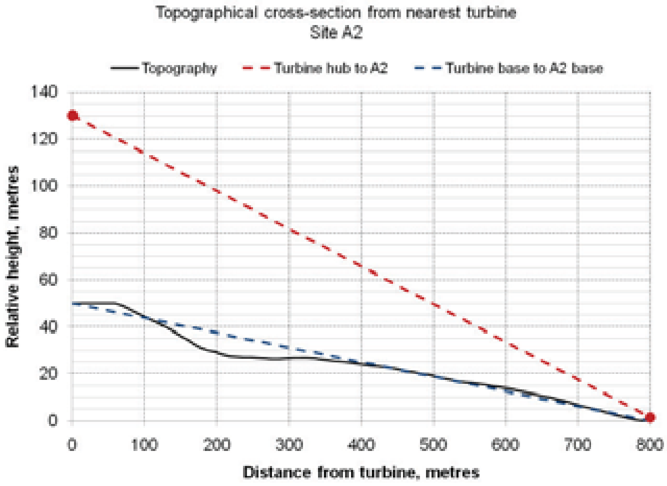


Figure 3. Topographical cross-section from nearest turbine to Site A2 (steady slope)

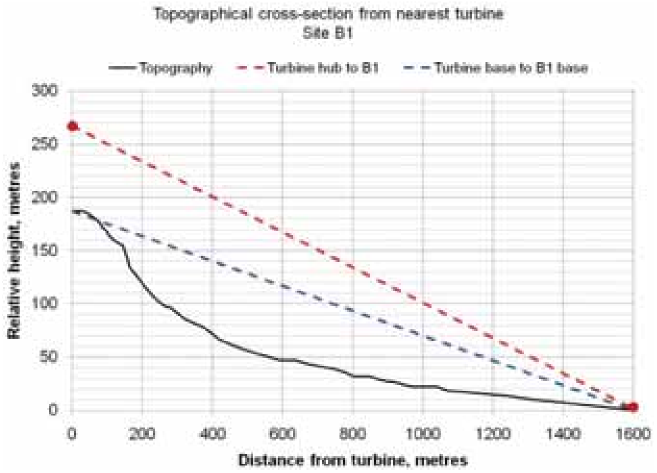


Figure 4. Topographical cross-section from nearest turbine to Site B1 (concave)

The contribution of background noise to the measured noise levels also requires consideration. Although this paper has identified wind speed ranges where turbine noise appears to control overall noise levels, there will still be some contribution to the measured noise levels from background noise. No attempt has been made to correct for the influence of background noise, such that actual turbine noise levels would have been slightly lower than the levels used in this assessment.

Similarly, the noise monitor at Site A3 was located approximately 10 metres from a building structure. This was the only monitor to be located near to a structure, and the measured noise levels may have included a relatively small contribution from reflected noise caused by the presence of the building.

However, any contribution to the measured noise levels from either background noise or reflected noise would lead to an underestimate of over-predictions (and an overestimate of under-predictions) of the different methods. Hence, the analysis provided here may be considered slightly conservative.

Overall Prediction Accuracy

The results in Table 2 indicate that none of the considered prediction methods can be considered suitably accurate for all wind farms. None of the methods appear to appropriately account for effects caused by topographical changes between the turbines and the measurement sites. While the ISO 9613-2 method with completely reflective ground may provide a typical upper limit for the measured noise level across all of the considered sites, it will also significantly over-predict noise levels at sites with flat topography or steady downward slopes.

The CONCAWE method (with G=0) also appears to provide a typical upper limit for the measured noise levels at each site, with the exception of B4 where it under-predicted noise levels by approximately 5 dB(A). B4 is the furthest measurement site from a turbine at a distance of over 3,000 metres and the measured noise levels are in the order of 30 dB(A), considerably below applicable noise criteria. The CONCAWE method therefore seems suitable for predicting noise levels to distances up to approximately 2,000 metres from a wind farm but not for accurately predicting noise levels at distances further than this.

Overall, the comparison of prediction methods in this paper indicates that predicted noise levels for wind farms are generally conservative. None of the measurement results from the sites indicate that the most commonly used methods in South Australia would under-predict noise levels by more than 1 dB(A).

It should also be noted that wind farms represent a relatively rare situation where the noise source is located greater than 60 metres above the ground height. Prediction methods such as CONCAWE and ISO 9613-2 have generally not been developed or tested considering noise sources at these heights, which may explain why they do not appropriately account for topography in this situation.

It is also important to note that the predicted noise levels are A-weighted $L_{eq,10min}$ noise levels which are being compared to measured A-weighted $L_{90,10min}$ noise levels. Our other paper [2] finds that the typical difference between L_{eq} and L_{90} noise levels for wind farms is approximately 1.5 dB(A). This indicates that both the ISO 9613-2 method (with G=0) and the CONCAWE method (with G=1) provide quite accurate predictions of L_{eq} noise levels for wind farms where the topography is relatively flat. Yet for Wind Farms A and B, where the topography varies more significantly, these prediction methods appear to either under- or over-predict L_{eq} noise levels by approximately 2 dB(A).

Recommended Prediction Methods For New Wind Farms

For many other noise sources, exceedances of the noise criteria of 1 to 2 dB(A) are often considered acceptable as humans do not generally perceive a change of 1 to 2 dB(A) in field conditions. However, a 1 dB(A) exceedance of the criteria for a wind farm could often result in a regulatory authority requesting mitigation and it could be considered important should wind farm noise levels be under-predicted by even 1 dB(A) during the planning stage.

Based on the comparisons presented in this paper, the prediction methods that would minimise the risk of a potential exceedance of the criteria would be the ISO 9613-2 method with completely reflective ground or the CONCAWE method with completely absorptive ground and Weather Category 6. However, care should be taken with both of these methods when considering turbines on a raised ridgeline where the ground slopes sharply down from the turbines to the receiver. The analysis in this paper has shown that these methods could under-predict noise levels in this scenario by up to 1 dB(A).

The NZS 6808:1998 method using the ISO 9613 air absorption factors may also be suitable to provide a prediction with minimal risk but is overly conservative on sites with a flat topography or steady downward slope from turbine to receiver.

It is also important to recognise that, in scenarios where the topography is relatively flat or there is a steady slope away from turbines located on a hill, these methods can over-predict noise by up to 6 dB(A) even where line of sight from the receiver location to the turbine hub is not broken. An understanding of the topography is therefore important for any environmental noise assessment of new wind farms.

It appears that the other common prediction methods presented in this paper (NZS 6808:1998 with constant α_a, ISO 9613-2 with 50% absorptive ground and Nord2000) should only be used with due consideration as they can result in considerable under-predictions of noise levels in certain situations.

Due to the relatively large number of possible inputs required for the Nord2000 method to determine meteorological conditions, it may be possible to improve the accuracy of this method through appropriate variation of these inputs. However, this would require further investigation and would also require the environmental noise assessment for a wind farm to analyse much more detailed meteorological data than is currently done.

Other Compliance Assessment Methodologies

The comparison in this paper has focussed on measured wind farm noise levels analysed in accordance with the methodology outlined in the SA Guidelines. For some other Australian and New Zealand wind farms, compliance measurements may also be required to be measured in accordance with NZS 6808:1998 or NZS 6808:2010. These standards require measurement of A-weighted L_{95} and L_{90} noise levels respectively and consider all wind directions. Cooper et al. [2] demonstrated that measured noise levels analysed under these Standards were typically 0 to 2 dB(A) lower than those measured under the 2009 SA Guidelines. This occurred as these other methods consider all wind directions and not only the worst case wind direction, and NZS 6808:1998 also requires measurement of L_{A95}, rather than L_{A90}, noise levels.

The implication of this is that, for wind farms assessed under NZS 6808:1998 or NZS 6808:2010, under-prediction appears unlikely even in the case of a concave slope. Similarly, where the topography is relatively flat around a wind farm or there is a steady downward slope between turbines on a hill and receivers below, the prediction methods considered in this paper would be expected to result in larger over-predictions than shown in Table 2.

Another compliance assessment method that may be used more extensively in the future is that contained in Australian Standard 4959-2010 [16], where the measured average L_{eq} noise level from the wind farm is required to comply with the noise criteria. The Standard assumes that the average L_{eq} noise level from a wind farm will be at least 1.5 dB(A) above the measured L_{90} noise level. The implication of this is that under-prediction of wind farm noise levels would become more likely for flat and concave topographies (unless this 1.5 dB(A) difference is taken into account during the assessment process) should the compliance assessment from AS 4959-2010 be required by regulatory authorities.

CONCLUSIONS

Measured noise levels from 13 measurement sites at six different wind farms have been compared to predicted noise levels using commonly applied noise prediction methods. The measurements and subsequent analysis have been carried out in accordance with the 2009 SA Guidelines. The sites and wind speed ranges have been selected to minimise the influence of background noise on the measured noise levels.

The comparison has indicated that the commonly used ISO 9613-2 (with completely reflective ground) and CONCAWE (with completely absorptive grounds) generally over-predict noise levels from the wind farm. However, the degree of over-prediction appears dependent on the topography around the wind farm. At sites with a relatively flat topography or a steady slope from the turbines to the measurement sites, the over-prediction can be in the order of 3 to 6 dB(A). However, at sites where there is a significant concave slope from the turbines down to the measurement sites, these commonly used prediction methods are typically accurate, with the potential of marginal under-prediction in some cases.

Other commonly used prediction methods, such as the NZS 6808 method with constant air absorption or the ISO 9613-2 method with 50% absorptive ground, can under-predict noise levels in some situations and should only be used with caution.

The implication of this for the assessment of new wind farms is that the topography around the site is an important consideration to estimate the degree of conservatism provided by the prediction method.

At this stage, no clear correction factor based on the topography has been identified that could be reliably applied across any wind farm site to improve the accuracy of noise prediction methods. Additional measured noise levels for wind farms with varying surrounding topography are required in order to improve the available data set.

ACKNOWLEDGEMENTS

We thank the South Australian EPA and our other commercial clients for their support in the preparation of this paper by allowing us to use data gathered for them.

REFERENCES

[1] South Australia Environment Protection Authority, *Wind farms environmental noise guidelines*, 2009

[2] J. Cooper, T. Evans and L. Najera, "Comparison of compliance results obtained from the various wind farm standards used in Australia", *Acoustics Australia* **40**(1), 37-44 (2012)

[3] J.H. Bass, A.J. Bullmore and E. Sloth, *Development of a wind farm noise propagation prediction model*, The European Commission, Joule III, Contract JOR3-CT95-0051, Final Report, 1998

[4] International Organization for Standardization ISO 9613-2:1996, *Acoustics – Attenuation of sound during propagation outdoors Part 2: General method of calculation*

[5] A. Bullmore, J. Adcock, M. Jiggins and M. Cand, "Wind farm noise predictions and comparison with measurements", *Proceedings of the 3rd International Meeting on Wind Turbine Noise*, Aalborg, Denmark, 17-19 June 2009

[6] C. Delaire, D. Griffin and D. Walsh, "Comparison of predicted wind farm noise emission and measured post-construction noise levels at the Portland Wind Energy Project in Victoria, Australia", *Proceedings of the 4th International Meeting on Wind Turbine Noise*, Rome, Italy, 11-14 April 2011

[7] New Zealand Standard NZS 6808:1998 *Acoustics – The assessment and measurement of sound from wind turbine generators*

[8] New Zealand Standard NZS 6808:2010 *Acoustics – Wind farm noise*

[9] Malcolm Hunt Associates and Marshall Day Acoustics, *Stakeholder Review & Technical Comments: NZS 6808:1998 Acoustics – Assessment and measurement of sound from wind turbine generators*, Report prepared for New Zealand Wind Energy Association and EECA, Wellington, New Zealand, 2007

[10] C.J. Manning, *The propagation of noise from petroleum and petrochemical complexes to neighbouring communities*, CONCAWE, ATL Report No 4/81, 1981

[11] South Australia Environment Protection Authority, *Environmental noise guidelines: Wind farms*, 2003

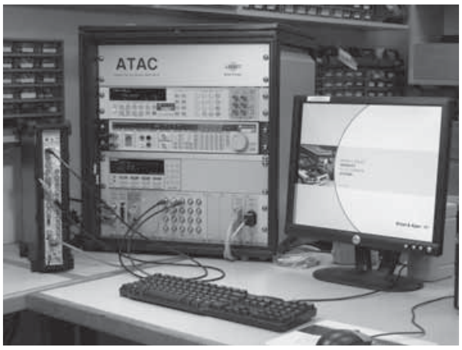
[12] C. Delaire and D. Walsh, "A comparison of background noise levels collected at the Portland wind energy project in Victoria, Australia", *Proceedings of the 3rd International Meeting on Wind Turbine Noise*, Aalborg, Denmark, 17-19 June 2009

[13] International Electrotechnical Commission IEC 61400-11 *Wind turbine generator systems – Part 11: Acoustic noise measurement techniques*, edition 2.1 2006-11

[14] DELTA, *Noise and energy optimization of wind farms – Validation of the Nord2000 propagation model for use on wind turbine noise*, Report PSO-07 F&U project no 7389, Hørsholm, Denmark, 2009

[15] DELTA, *Nordic Environmental Noise Prediction Methods, Nord2000 – Summary Report*, Lyngby, Denmark, 2002

[16] Australian Standard AS 4959:2010 *Acoustics – Measurement, prediction and assessment of noise from wind turbine generators*



COMPARISON OF COMPLIANCE RESULTS OBTAINED FROM THE VARIOUS WIND FARM STANDARDS USED IN AUSTRALIA

Jonathan Cooper[1], Tom Evans[2] and Luis Najera[2]
[1]Resonate Acoustics, 97 Carrington Street, Adelaide, SA 5000
[2]AECOM, Level 28, 91 King William Street, Adelaide, SA 5000

There are a number of standards and guidelines which are used in Australia for the assessment of wind farm noise, most of which provide different methods for measuring compliance once the wind farm is operational. This paper examines the differences that result when assessing compliance against the various compliance measurement and analysis procedures. Compliance measurements from a thirteen receivers at distances of 300 metres to 3 kilometres from six wind farm sites are used in the analysis. Differences of between 1.9 and 4.3 dB(A) are observed between the highest and lowest assessment results obtained at individual receivers, although this range is reduced to 1.9 - 2.7 dB(A) when L_{Aeq} results that appeared to be influenced by extraneous noise are discarded. These results complement the findings of our other paper which compares predicted levels against the compliance measurement results, and together these papers can be used to compare predictions against wind turbine noise levels measured and analysed using the different methodologies.

INTRODUCTION

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

There are a number of standards and guidelines which are used or are intended to be used in Australia for the assessment of wind farm noise. These include, but are not limited to; the South Australian *Wind Farms Environmental Noise Guidelines* 2009 (2009 SA Guidelines) [1], the South Australian *Wind Farms Environmental Noise Guidelines* 2003 (2003 SA Guidelines) [2], Australian Standard 4959:2010 [3], New Zealand Standard 6808:2010 [4], New Zealand Standard 6808:1998 [5], and the currently draft *National Wind Farm Development Guidelines* [6].

A detailed discussion of the slightly different approaches used to set noise criteria for wind farms is beyond the scope of this paper, but the standards and guidelines typically set noise criteria for wind farms to be achieved at sensitive receivers as 40 dB(A) or the background noise level + 5 dB(A), whichever is the greater.

Once noise criteria have been established for a proposed wind farm development it is the acoustic engineer's task to provide detailed wind turbine noise level predictions at the noise sensitive receivers around the site. Following the completion of construction, compliance noise measurements are undertaken at the nearest noise sensitive receivers to confirm compliance with the relevant standard or guideline.

It is important that noise levels are accurately predicted at the design stage. Under-prediction of noise levels may result in failure to meet the noise criteria and the expensive shut down of wind turbines, while overly conservative modelling curtails renewable energy generation and reduces the size, and potentially the financial viability, of wind farm developments.

The standards and guidelines used to assess wind farm developments provide different methods for measuring and analysing operational noise levels at the completion of construction. These differences between the measurement methods result in differences in the measured noise level and can therefore potentially affect whether or not compliance with the noise criteria is achieved.

Compliance measurements from thirteen measurement locations surrounding six wind farm sites are used in the analysis. When selecting data for analysis, particular focus was placed on using measurement data from locations where wind turbine noise was the dominant noise source, to minimise the influence of background noise on the findings. This paper does not seek to recommend a particular compliance monitoring methodology but rather to assess the magnitude of differences that result when assessing compliance measurements using the various measurement procedures. This paper complements the findings of our other paper which is also included in this edition of Acoustics Australia [7]. Together they can be used to compare the accuracy of a number of wind turbine noise prediction methods to compliance monitoring results obtained from a variety of compliance measurement and analysis procedures.

STANDARDS USED IN AUSTRALIA

South Australian *Wind Farms Environmental Noise Guidelines* 2009

The 2009 SA Guidelines were developed by the South Australian Environment Protection Authority (EPA) [1]. The 2009 SA Guidelines require that the $L_{A90,10min}$ noise level is measured over the range of wind speeds from cut-in speed to the speed of the rated power of the turbines at a minimum. The data is to cover at least 2000 intervals, with at least 500 intervals corresponding to the worst case wind direction. The worst case wind direction is defined as wind directions within 45° of downwind of the nearest wind turbine to the measurement site. The compliance assessment is based on only the data measured under the worst case wind direction – all data from other directions is excluded from the compliance assessment. A polynomial regression analysis is undertaken to determine the measured wind turbine noise level, with correction for the previously measured background noise data applied if required. Where the above method proves unsuitable for compliance checking the 2009 SA Guidelines allow for alternative techniques to be employed, following discussions with the EPA. Suggested alternatives include attended measurements with periodical shutdown of wind turbines if required.

South Australian *Wind Farms Environmental Noise Guidelines* 2003

The 2003 SA Guidelines [2] were an earlier version of the 2009 SA Guidelines. The 2003 SA Guidelines are still used in some States to assess wind farm noise. Both the 2003 and 2009 SA Guidelines use L_{A90} levels measured under downwind conditions to assess compliance of the wind farm. The most significant difference between the two guidelines is that the 2003 version does not explicitly allow for correction of the measured level for background noise. The increase in measured compliance level that will result from the presence of background noise is not readily quantifiable given the potential for variation of the background noise, so is beyond the scope of this paper. We do not expect any other differences between the compliance measurement methods in these guidelines will result in significant differences in the measured turbine noise level. The two SA guidelines are therefore not separately assessed in this paper.

New Zealand Standard 6808:2010

New Zealand Standard 6808:2010 *Acoustics – Wind farm noise* [4] was recently adopted in Victoria. NZS 6808:2010 expects that at least 10 days (1440 data points) of compliance measurements are undertaken, with data gathered over the range of wind speeds and directions normally expected at the wind farm. The $L_{A90,10min}$ noise level is measured over this 10 day period.

Unlike the 2009 SA Guidelines, there is no specific requirement to exclude data points outside the downwind direction. However, if the initial background noise measurements indicate a significant difference in the pre-construction noise levels under different wind directions or times of day, noise criteria may be set based on particular wind directions or times of day. There is a chance that the pre-construction background noise levels are different under the future downwind direction when compared to the background levels are under other wind directions. If this was the case noise criteria would be set separately for the downwind direction and other wind directions, such that compliance would be assessed under both the downwind direction and all other wind directions. Additionally, there is a chance that the wind that occurs during the compliance measurements is from predominantly downwind directions.

While a downwind assessment might be undertaken under NZS 6808:2010, we have assumed the much more likely assessment using all wind directions is undertaken for the purposes of our investigation. NZS 6808:2010 provides the site operator with the option of taking attended 'on/off' compliance measurements at receivers if appropriate, but a review of the results from on/off testing is not included in this paper.

New Zealand Standard 6808:1998

New Zealand Standard 6808:1998 A*coustics – The assessment and measurement of sound from wind turbine generators* [5] was used to set noise criteria for new wind farm applications in Victoria until March 2011. The key difference in the compliance measurement method outlined in NZS 6808:1998 (as compared to NZS 6808:2010) is that $L_{A95,10min}$ levels are used rather than $L_{A90,10min}$ levels. Like the 2010 standard, NZS 6808:1998 potentially requires compliance measurements under different wind directions and times of day.

While not intended by the standard, Planning Permits issued for wind farms in Victoria have typically included the requirement that compliance is assessed separately for the "all-time" (24 hours) and night time (10pm – 7am) period. The requirements for downwind, and 90° sector analysis have also been previously included in Planning Permits although this is not specifically required under NZS 6808:1998 [8].

Australian Standard 4959:2010

Australian Standard 4959:2010 *Acoustics – Measurement prediction and assessment of noise from wind turbine generators* [3] has been relatively recently introduced. AS 4959:2010 was the first standard to require that the L_{Aeq} noise level from the wind farm is assessed against the pre-determined noise criteria. It outlines two possible methodologies that might be used for compliance testing, but notes that the method used should be agreed with the Relevant Authority prior to the commencement of testing.

Methodology 1 included in the Standard follows the same approach as the background noise measurements, with approximately 2000 representative measurements to be collected. The standard leaves many assessment decisions, such as the speeds and directions to be assessed, to the Relevant Regulatory Authority, but notes that:

Generally, data collected when the wind direction is from the wind farm to the receiver would be the data of primary interest to the Relevant Regulatory Authority.

For the purposes of our assessment it has been assumed that the Authority has requested that a downwind assessment is undertaken (downwind ±45° as per the SA Guidelines).

In acknowledgment of the difficulty of measuring L_{Aeq} compliance levels directly without contribution from extraneous noise sources, Methodology 1 of the Standard requires the measurement of the L_{A90} noise level, with a numerical addition of 1.5 – 2.5 dB added to each measurement to account for the expected difference between the wind farm L_{Aeq} and L_{A90} levels. Methodology 1 considers that all noise measured at the receiver is the result of noise from the wind turbines, with no allowance provided to correct for background noise. The standard notes that this method is likely to be a conservative method.

Methodology 2 provided by the standard requires the use of attended noise measurements to validate prediction model outputs and therefore compliance with criteria. Our interpretation of the wording in the Standard is that it requires measurements at only one location to validate the noise model for the entire site. However, opinions received from others working in the field of wind farm acoustics suggest that it may have been intended that this Methodology require measurements at either a single receiver, two or three representative receivers, or all of the receivers around the wind farm site to calibrate the noise model.

At least ten 10-minute L_{Aeq} measurements are required both above and below the 'critical' wind speed, with the attended measurements to extend to speeds at least 3m/s above and below the 'critical' wind speed. Attended L_{Aeq} measurements with the wind turbines turned off may be used to correct for the influence of background noise if necessary. While this paper presents no results from attended measurements we provide some comment on the suitability of Methodology 2 for determining compliance at all receivers around a wind farm.

Draft National Guidelines July 2010

The Draft *National Wind Farm Development Guidelines* [6] were introduced for a 12 month trial in July 2010. The Draft National Guidelines suggest that initially Methodology 1 of AS 4959:2010 is used for compliance measurements. Where compliance is unclear from those measurements and it is suspected this is as a result of background noise, it is recommended that the same measurement procedure is to be followed, but repeated at a 'secondary location'. The secondary location is a location selected near the receiver that is the same distance from the same wind turbines, where the geographical setting and predicted noise level is the same as the original location, but is further from extraneous noise sources. Where it is not possible or practical to confirm compliance through measurements at a secondary location, attended measurements using Methodology 2 of AS 4959:2010 are recommended. However, it is important to note that the Draft National Guidelines use attended measurements at each problematic receiver, rather than trying to use measurements at one receiver to confirm the accuracy of noise predictions and compliance at other receivers as appears to be required by AS 4959:2010.

In extreme cases where none of the above methods are able to demonstrate that compliance is achieved but the Relevant Authority agrees that compliance is likely to be achieved, the Draft National Guidelines suggest 'derived point measurements'. Derived point measurements use measurement results at a location closer to the wind farm where noise levels are clearly controlled by wind farm noise to calibrate the noise model.

As the Draft National Guidelines initially follow Methodology 1 of AS 4959 they are not separately assessed in this paper. However, comment on the suitability of the secondary methodologies suggested by the Guidelines is provided.

Summary of Assessment Methods

The key requirements of the various assessment methods considered in our analysis are presented in Table 1. The alternative measurement techniques provided by some standards are not listed separately in Table 1. While the alternative measurement techniques use a different measurement duration or location of measurement, the noise descriptor and wind direction used by the alternative method for assessing wind turbine noise match those used by the primary compliance assessment method of each of the standards.

SITE DESCRIPTIONS

Six wind farms and thirteen measurement sites have been selected for comparison in this paper as the measurements collected at these measurement sites appear to be controlled by noise from the wind turbines across a reasonable wind speed range.

The measurement sites are typically representative of the closest receivers to wind farms in South Australia, although one of the measurement sites was approximately 3 km from the nearest turbine. We note that a number of the measurement sites were not actually in the vicinity of a noise sensitive receiver, which has assisted to reduce the influence of ambient noise on those measurements. Turbine noise levels at the measurement sites were typically in the range of 35 to 40 dB(A), so are representative of most noise exposed receivers adjacent to wind farms where noise represents a design constraint.

For commercial reasons, the names and locations of the

Table 1. Summary of key requirements of compliance assessment methods

Method	Descriptor	Wind direction	Comment
2009 SA Guidelines	L_{A90}	Downwind	Selected as the reference method which other methods are compared to.
2003 SA Guidelines	L_{A90}	Downwind	Similar to above 2009 SA Guidelines, so not assessed separately.
NZS 6808:2010	L_{A90}	All	-
NZS 6808:1998	L_{A95}	All	-
AS 4959:2010	L_{Aeq}	Downwind	Assumed that Regulatory Authority has requested downwind assessment.
Draft National Guidelines	L_{Aeq}	Downwind	Similar to above AS 4959, so not assessed separately.

wind farms have not been disclosed and the wind farms will be designated as Wind Farm A through to F. Based on compliance monitoring conducted at each site, all of these wind farms are in compliance with the environmental noise criteria. A description of each wind farm is presented in the following sections.

Wind Farm A

Wind Farm A involves a line of turbines stretching for about 10 kilometres along the top of a range of hills. The turbines are spaced approximately 400 metres apart from each other. Three noise measurement sites have been considered as part of this comparison and have been designated A1, A2 and A3. Each of the measurement sites are located between 800 and 1000 metres from the nearest turbine, and are situated 50 to 70 metres lower than the base height of that turbine.

Wind Farm B

Wind Farm B also involves a line of turbines stretching for about 10 kilometres along the top of a range of hills. The turbines are spaced approximately 300 metres apart from each other. Four noise measurement sites have been considered as part of this comparison and have been designated B1 to B4. Sites B1, B2 and B3 are located approximately 1,000 to 1,500 metres from the nearest turbine, with B4 located approximately 3,000 metres away. All sites are situated 130 to 200 metres lower than the base height of the nearest turbine.

Wind Farm C

Wind Farm C involves a group of turbines distributed over a flat area of about 20 square kilometres. The turbines are spaced approximately 350 metres apart from each other. Three noise measurement sites have been considered as part of this comparison and have been designated C1, C2 and C3. The measurement sites are located between 300 and 900 metres from the nearest turbine.

Wind Farms D, E and F

At Wind Farms D and E, the turbines are arranged in a line, while the turbines at Wind Farm F are arranged into a group. Only one noise measurement site has been selected for this comparison at each of these Wind Farms as noise levels at all other measurement locations had been controlled by background noise. There is relatively flat ground between the turbines and measurement locations, which are located between 350 and 1200 metres from the nearest turbine.

NOISE MEASUREMENT PROCEDURE

A-weighted $L_{eq,10min}$, $L_{90,10min}$ and $L_{95,10min}$ noise levels from the operational wind farms were logged at each of the measurement sites over a period of three to four weeks. Class 2 noise monitoring equipment was used at each of the sites and the calibration checked both before and after the measurement period to check that no significant drift had occurred. The microphone was located at 1.2 to 1.5 metres above ground and fitted with a 90 mm thick windshield, which was adequate to reduce the influence of wind-induced noise on the measurement [9].

Measurements that were obviously affected by extraneous noise sources or that did not coincide with wind speeds between the cut-in and cut-out of the turbines were excluded from the analysis. For certain situations, the measurements were filtered based on wind direction when results for specific wind directions were required, e.g. for the 2009 SA Guidelines. Following the removal of data points, between 2000 and 4000 data points remained at the various measurement sites for the situations where all wind directions were being considered. For those situations where only a single wind direction ±45° was considered, between 200 and 1000 data points remained at the various measurement sites. Where less than 500 data points remained at a particular wind speed, these were confined mainly to the small range of wind speeds where site measured sound power data was available.

The measured noise levels were correlated with wind speeds for the period, measured at the most representative hub height meteorological mast or nearest turbines to the measurement site. A single "measured" noise level value for each integer wind speed was then determined by fitting a polynomial regression line to the data.

A significant issue that can affect measurement results from operational wind farms is the contribution of the background noise environment. While this can be somewhat overcome by subtracting the measured pre-construction noise levels, Delaire and Walsh [10] showed this method is susceptible to error as background noise levels can change across seasons and years. The pre- and post-construction measurement locations may also be different, another possible inaccuracy with this method. To address this, each measurement site was selected such that it was as far away as possible from potential sources of background noise (e.g. trees, occupied dwellings), and such that the noise level at the site was typically controlled by turbine noise. In addition, only wind speeds where the L_{A90} noise level appears to be consistently controlled by turbine noise were considered in our analysis. These wind speeds have been selected based on analysis of the measurement data and supported by observations made on site during the measurements. Wind speeds where there was a significant spread in the measured noise levels were excluded, as observations on site indicated this variation was the result of extraneous noise sources affecting measured levels.

As an example, Figure 1 presents measurement results for Site B3, indicating a wind speed range of 4 to 12 m/s where the measured noise level is controlled by turbine noise. This is evident due to the small spread of the measurement data when compared to wind speeds above 12 m/s where background noise causes significant variation between measured noise levels at the same integer speed. At lower wind speeds, there are also a number of measurements where the turbine clearly cut-out due to low wind speed during the measurement period. These have been excluded from further analysis. For each measurement site, between three and six integer wind speeds were identified as being in the turbine-controlled wind speed range.

The change in measured noise levels with wind speed across this wind speed range correlated almost precisely with the change in sound power levels for the turbines, an indication that the noise levels were controlled by noise from the turbines. This is discussed in more detail in Ref. [7].

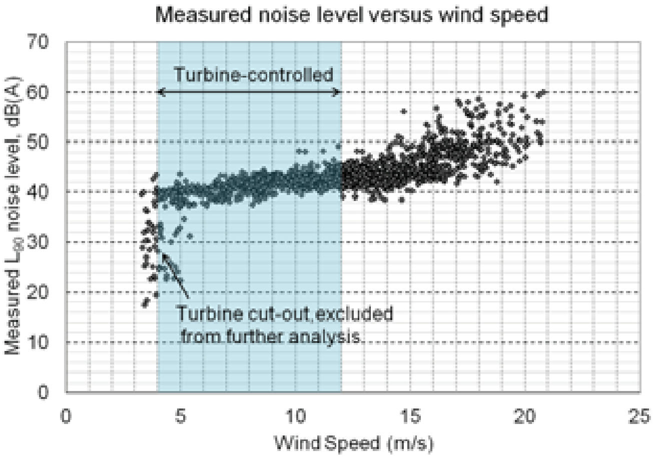


Figure 1. Example of measured noise levels versus wind speed with turbine-controlled wind speed range

RESULTS

The compliance noise level measured using the 2009 SA Guidelines was selected as a reference level, against which the results from all other compliance measurement methods were compared. The 2009 SA Guidelines use the worst case wind direction and the L_{A90} noise level, which is expected to make them less susceptible to variation than some other methods. The use of the downwind directions should, in practice, provide a more repeatable compliance measurement as the result will not be influenced by variations in the distribution of wind directions that occur during the compliance measurement period. Additionally, L_{A90} levels should be less susceptible than L_{Aeq} levels to the influence of short term extraneous noise.

In support of this supposition, compliance measurements were recently repeated at one of the sites in this study, almost two years after they were first assessed using the 2009 SA Guidelines. The variation in the measured compliance level was less than 1 dB(A) over the entire range of wind speeds where the noise level appeared to be turbine-controlled. This demonstrates the repeatability of the 2009 SA Guidelines compliance measurement method when used at locations not influenced by extraneous noise.

Table 2 summarises the average difference in compliance measurement results achieved between the tested methods at each site. To determine the difference between the reference method (chosen to be the 2009 SA Guidelines) and other compliance measurement methods, the wind turbine noise level was determined using each of the compliance assessment methods for all turbine noise controlled wind speeds. At each site, the 2009 SA Guidelines noise level was then subtracted from the noise level determined using the other compliance measurement method at each integer wind speed, to give a difference between the methods at each turbine controlled wind speed. There was typically little difference in the result with wind speed, so these differences were averaged across all turbine controlled wind speeds to give an average difference between the 2009 SA Guideline and the other compliance measurement method.

We note that Method 1 of the AS 4959:2010 requires the measurement of L_{A90} levels, with a numerical adjustment applied to account for the likely difference between the L_{A90} and L_{Aeq} level. As it is assumed that the AS 4959:2010 assessment uses only downwind directions, the required AS 4959:2010 assessment would match the 2009 SA Guidelines assessment, except that the AS 4959:2010 assessment would

Table 2. Compliance level measured using the different compliance methods, relative to the 2009 SA Guidelines (dB(A))

	Difference in level relative to 2009 SA Guidelines (dB(A))		
Site	**NZS 6808:1998**	**NZS 6808:2010**	**AS 4959:2010**
A			
A1	-1.5	-1.1	+2.8
A2	-1.5	-1.0	+2.5
A3	-2.0	-1.5	+1.9
B			
B1	-1.0	-0.7	+1.7
B2	-0.7	-0.4	+1.2
B3	-1.1	-0.7	+1.5
B4	-1.2	-0.7	-
C			
C1	-0.5	-0.2	+1.6
C2	-0.7	-0.4	+1.4
C3	-0.7	-0.4	+1.3
D, E and F			
D1	-	-0.3	+1.1
E1	-0.9	-0.5	+1.9
F1	-1.4	-1	-
Mean Difference	**-1.1**	**-0.7**	**+1.7**
Standard Deviation	**0.4**	**0.4**	**0.5**

require the numerical addition of 1.5 to 2.5 dB(A) to the 2009 SA Guidelines result. Rather than rely on the numerical adjustment provided by the Standard, our AS 4959:2010 assessment is based on measured L_{Aeq} levels instead. The calculated difference between the AS 4959:2010 result and the 2009 SA Guidelines result provides the actual difference between the L_{Aeq} and L_{A90} levels.

No difference is provided between the 2009 SA Guidelines and NZS 6808:1998 for site D1 as L_{A95} levels were not measured at that site. No difference is provided between the 2009 SA Guidelines and AS 4959:2010 for sites B4 and F1 as L_{Aeq} levels at those locations were clearly significantly controlled by short term extraneous noise. Results for the 2003 SA Guidelines and Draft National Guidelines are not reported separately as they share key compliance measurement requirements with the 2009 SA Guidelines and AS 4959:2010 respectively.

Table 2 indicates that the application of other wind farm standards used in Australia results in levels up to 2.0 dB(A) lower, and 2.8 dB(A) higher than respective results obtained through application of the 2009 SA Guidelines. However, as later discussed, the 2.8 dB(A) difference between the 2009 SA Guidelines and AS 4959:2010 at site A1 is believed to be exaggerated by extraneous noise.

Discussion of L_{A90} and L_{A95} Results

It is observed that measurements undertaken using NZS 6808:1998 provide the lowest compliance levels, with a mean level 1.1 dB lower than the 2009 SA Guidelines and a range of results between 0.5 and 2.0 dB lower than the 2009 SA Guidelines. However, we note that this does not necessarily translate to a 0.5 to 2.0 dB less stringent end result at the residences. Existing background noise levels used to determine noise criteria would also be measured using the L_{A95} assuming that the NZS 6808:1998 method had been applied throughout the planning phase as well as during the compliance monitoring phase. Noise criteria determined based on the background L_{A95} + 5 dB approach would be more stringent than those determined using an L_{A90} level.

The variation in differences between noise levels measured under the 2009 SA Guidelines approach and NZS 6808:1998 approach was 1.5 dB (differences of between -2.0 and -0.5 dB). This result appears to be attributable to the combination of the difference in wind directions used for the assessments, turbine layout, and difference between the L_{A95} and L_{A90} levels. The difference in L_{A95} and L_{A90} is 0.3 to 0.5 dB, as provided by comparison of the NZS 6808:1998 and NZS 6808:2010 results in Table 2 (the only difference between these being the use of L_{A90} rather than L_{A95} in NZS 6808:2010). The remaining variation in levels is attributable to different proportions of downwind measurements in the total measurement period, and layout of turbines on site.

Discussion of L_{Aeq} Results

The AS 4959:2010 results provide the highest measured levels across all measurement sites. The comparison of the AS 4959:2010 and SA Guidelines methods provides the average difference between L_{A90} and L_{Aeq} levels across the measurement sites. From site observations at the base of a turbine it might have been expected that locations close to turbines would experience greater differences between L_{A90} and L_{Aeq} levels, due to the blade passing of a single close turbine being more noticeable than the blade noise on a group of distant turbines. However, no discernible relationship between distance and difference in L_{A90} and L_{Aeq} results were observed during our analysis. Rather, the sites where both site observations and plots of noise level versus wind speed suggested greatest influence of ambient noise correspond to the sites with highest difference between the L_{A90} and L_{Aeq} levels.

While it is difficult to quantify the influence of ambient noise on the measurement sets, site observations and the scatter of the L_{Aeq} data points (including at speeds below turbine cut-in) suggest that the L_{Aeq} results at sites A1, A2, A3, E1 and possibly also B1 have been noticeably increased by ambient noise. If these sites which are believed to be affected by significant extraneous noise (A1, A2, A3 and E1) are excluded from the data set the mean difference between L_{A90} and L_{Aeq} across the seven remaining sites is only 1.4 dB(A), with the range of results obtained using the various wind farm standards up to 2.0 dB(A) lower, and 1.7 dB(A) higher than those achieved using the 2009 SA Guideline.

The average difference between L_{A90} and L_{Aeq} results of 1.4 dB(A) is less than the suggested correction of 1.5 to 2.5 dB(A) previously provided by ETSU [11] and adopted by AS 4959:2010. Our results suggests that L_{A90} levels should be increased by no more than the minimum required by AS 4959:2010, which is 1.5 dB(A). It is possible that the difference between our findings and those reported in ETSU is the result of extraneous noise during the ETSU assessment, or measurements undertaken at very close distances to a single turbine where modulation of the noise may have been greater.

Differences of between 1.9 dB(A) and 4.3 dB(A) (at B2 and A1 respectively) are observed between the highest and lowest assessment results obtained at individual receivers, although this range is reduced to 1.9 to 2.7 dB(A) (at B2 and B1 respectively) when L_{Aeq} results at the four measurement sites that appeared to be most significantly influenced by extraneous noise are discarded.

Finally, we note that the AS 4959:2010 Methodology 1 does not allow for the correction of L_{A90} compliance measurements for background noise, which the standard notes is a conservative approach. The lack of the ability to correct for the contribution of background noise when using this method will further increase the difference between the SA Guidelines and AS 4959:2010 results. There is potential for the inability to correct for the significant background noise at a typical compliance measurement site to be sufficient to incorrectly indicate non-compliance with criteria.

Comment on Alternative Measurement Techniques

There are a number of alternative compliance measurement techniques proposed by the various standards including; attended on/off measurements, long term measurements at ‘secondary locations’ adjacent to residences, long term measurements at ‘derived locations’ between the turbine and residence with a correction applied for the predicted difference in noise level between the derived location and residence, and attended measurements at one residence to calibrate a noise model for the site.

Of all the alternative compliance measurement techniques proposed by the standards, the authors most prefer the use of measurements at a 'secondary location' which is a location selected where turbine noise levels are expected to be the same as at the residence but background noise levels are expected to be much lower.

In practice it is not always practical to place a noise logger in a 'secondary location' where the terrain and distance to all turbines match those at the receiver. Where it would be necessary to place a logger slightly closer or further from the turbines we suggest this is preferable (with a small correction applied for the slight predicted difference in noise level), rather than use attended measurements gathered over a limited range of conditions.

The authors demonstrate there is a consistent difference between the measured and ISO 9613-2 (G=0) [12] modelled results at receivers scattered across different wind farm sites, provided that the terrain between the turbines and receivers is consistent [7]. We therefore also support the use of logging at a location slightly removed from a receiver i.e. in a 'derived location'. The correction applied for the difference in location should be determined using the ISO 9613-2 (G=0) prediction method, and the distance between the measurement location and residence should be always be minimised as far as is practical. Our other paper demonstrates that all of the noise models currently in use do not account for the influence of topography on noise propagation. If a 'derived location' is used, it is critical that significant differences in terrain between the derived measurement location and residence are avoided.

Where there is significant background noise, the above two methods will provide a better indication of turbine noise than the primary compliance measurement methods currently used by the various Standards and Guidelines. The primary measurement methods involve taking measurements significantly influenced by background at receivers and then correcting them through subtraction of historical L_{A90} levels or alternatively measuring at the receiver and ignoring the presence of the significant extraneous noise.

The suitability of attended measurements for determining wind farm noise levels at an individual location has not been examined in this paper but we anticipate they would provide acceptable results provided that the sample size is sufficiently large. It may be simpler and less labour-intensive to take long term measurements at a secondary or derived location than it is to take a large number of attended measurements at a location influenced by background noise.

Our interpretation of the alternative compliance technique provided by Methodology 2 of AS 4959:2010 is that it requires attended noise measurements at one noise sensitive receiver to validate prediction model outputs and therefore compliance with criteria at the other receivers. We therefore have concerns regarding the suitability of Methodology 2 for checking compliance across a wind farm site. Using the receivers at Wind farm A as an example; sites A2 and A3 are at a very similar distance but on opposite sides of a small group of turbines. The terrain between the turbines and two measurement sites varied greatly, which resulted in a difference in the measured noise level between the two sites being 5.9 dB(A). However, as the available models to not account for the influence of terrain, the very similar distances to the turbines resulted in predicted noise levels at the two sites being almost identical. If Methodology 2 had been applied using attended measurements at Site A2 to calibrate the noise model the compliance level determined for Site A3 would have been almost 6 dB(A) too low, due to the lack of influence of terrain on the predicted noise levels. We therefore strongly suggest that Methodology 2 should only be used for receivers sharing similar terrain, and this method in the Standard should be revised to reflect this requirement as soon as practical.

CONCLUSIONS

A comparison of the compliance results obtained from the various wind farm standards used in Australia has been undertaken. Noise measurements collected from 13 measurement sites around six different wind farms have been used during our assessment. Each measurement site selected for this analysis exhibited wind speeds where noise measurements were clearly controlled by wind turbine noise, with only data from those speeds assessed.

The compliance noise level measured using the 2009 SA Guidelines was selected as a reference level, against which the results from all other compliance measurement methods were compared. The measurement results obtained using the other wind farm standards are at levels up to 2.0 dB(A) lower, and 1.7 dB(A) higher than respective SA Guideline results, when L_{Aeq} results believed to be increased by ambient noise are discarded.

Application of NZS 6808:1998 results in the lowest measured compliance levels, with mean level 1.1 dB lower than the SA Guideline. This result is attributable to both the use of an L_{A95} descriptor rather than L_{A90}, and assessment over all wind directions rather than just downwind conditions. When compared to the NZS 6808:1998 standard, the new NZS 6808:2010 standard provides compliance results approximately 0.4 dB(A) higher. AS 4959:2010 provides the highest measured compliance results, with mean difference between the L_{A90} and L_{Aeq} found to be 1.4 dB when several outlier sites which were believed to have been influenced by extraneous noise are excluded.

This paper does not seek to recommend noise measurement descriptors or wind directions that should be used to assess wind farm noise, but rather identifies the differences in measured noise levels achieved by the various measurement techniques. Together with the findings in Ref. [7], the accuracy of a number of noise prediction methods to compliance results obtained from a variety of compliance measurement approaches can be compared. Some commentary has been provided on the range of alternative compliance measurement methods used in Australia. The authors strongly suggest that Methodology 2 of AS 4959:2010 is revised as soon as is practical, given the modelling errors that result from variations in topography between the turbines and receivers.

ACKNOWLEDGEMENTS

We thank the South Australian EPA and our other commercial clients for their support by allowing us to use data gathered for them in the preparation of this paper.

REFERENCES

[1] South Australia Environment Protection Authority, *Wind farms environmental noise guidelines*, 2009

[2] South Australia Environment Protection Authority, *Wind farms environmental noise guidelines*, 2003

[3] Australian Standard AS 4959:2010 *Acoustics – Measurement, prediction and assessment of noise from wind turbine generators*

[4] New Zealand Standard NZS 6808:2010 A*coustics – Wind farm noise*

[5] New Zealand Standard NZS 6808:1998 *Acoustics – The assessment and measurement of sound from wind turbine generators*

[6] *Draft National Wind Farm Development Guidelines*, Environment Heritage and Protection Council, July 2010

[7] T. Evans and J. Cooper, "Comparison of predicted and measured wind farm noise levels and implications for assessments of new wind farms", *Acoustics Australia* **40**(1), 28-36 (2012)

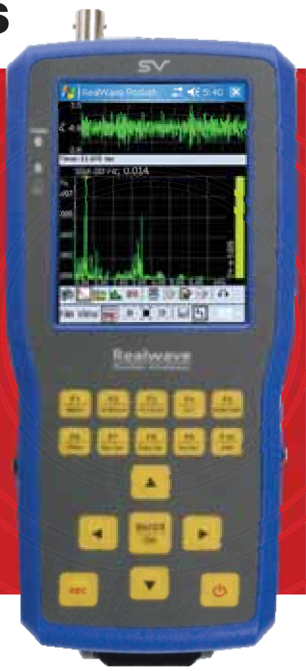
[8] C. Delaire and D. Griffin, "Review of noise conditions from planning permits recently approved in Victoria Australia", *Proceedings of the 4th International Meeting on Wind Turbine Noise*, Rome, Italy, 11-14 April 2011

[9] J. Cooper, D. Leclercq and M. Stead, "Wind induced aerodynamic noise on microphones from atmospheric measurements", *Proceedings of the 20th International Congress on Acoustics (ICA 2010)*, Sydney, Australia, 23-27 August 2010

[10] C. Delaire and D. Walsh, "A comparison of background noise levels collected at the Portland wind energy project in Victoria, Australia", *Proceedings of the 3rd International Meeting on Wind Turbine Noise*, Aalborg, Denmark, 17-19 June 2009

[11] The Working Group on Noise from Wind Turbines, *The assessment and rating of noise from wind farms*, Energy Technology Support Unit, ETSU-R-97, 1996

[12] International Organization for Standardization ISO 9613-2:1996, *Acoustics – Attenuation of sound during propagation outdoors – Part 2: General method of calculation*



MEASUREMENT AND LEVEL OF INFRASOUND FROM WIND FARMS AND OTHER SOURCES

Chris Turnbull[1], Jason Turner[1] and Daniel Walsh[2]
[1]Sonus Pty Ltd, 17 Ruthven Avenue, Adelaide, South Australia 5000
[2]Pacific Hydro Level 11, 474 Flinders Street, Melbourne, Victoria 3000

Infrasound is generated by a range of natural and engineered sources. The measurement of infrasound at low levels requires a specific methodology, as it is readily affected by even light surface breezes on the microphone. Such a methodology, based on measurements below the ground surface in a test chamber, has been developed to measure infrasound at two Australian wind farms and also in the vicinity of a beach, a coastal cliff, the city of Adelaide and a power station. The measured levels have been compared between each source and against the infrasound audibility threshold of 85 dB(G). The measured level of infrasound within the wind farms is well below the audibility threshold and is similar to that of urban and coastal environments and near other engineered noise sources.

INTRODUCTION

Infrasound is generally considered to be sound at frequencies less than 20 Hz and is often described as inaudible. However, sound below 20 Hz remains audible provided that the sound level is sufficiently high [1]. Infrasound is generated by a range of natural sources, including waves on the coastline, waterfalls and wind. It is also generated by a wide range of engineered sources such as industrial processes, vehicles, air conditioning and wind farms. The thresholds of audibility for infrasound have been determined in a range of studies [2]. The G-weighting has been standardised to determine the human perception and annoyance due to noise that lies within the infrasound frequency range [3]. A common audibility threshold from the range of studies is an infrasound level of 85 dB(G) or greater. The audibility threshold limit of 85 dB(G) is consistent with other European standards and studies, including the UK Department for Environment, Food and Rural Affairs threshold developed in 2003 [2], the UK Department of Trade and Industry study [4], the German Standard DIN 45680 [5] and independent research conducted by Watanabe and Møller [6].

There have been concerns raised in the community regarding the generation of infrasound by Australian wind farms. The generation of infrasound was detected on early international turbine designs, which incorporated the blades 'downwind' of the tower structure [7]. The mechanism for the generation was the blade passing through the wake caused by the presence of the tower. Modern wind turbines now locate the blade 'upwind' of the tower.

Australian States presently assess the noise from wind farms under a range of Standards and Guidelines [8-12]. These Standards and Guidelines do not provide prescriptive requirements for infrasound from wind farms due to the absence of evidence that infrasound should be assessed.

A specific methodology was developed to reduce the influence that even light surface breezes can have on the infrasound results. The methodology is based on measurements being conducted below the ground surface in a test chamber that is approximately 500mm square and 500mm deep. Infrasound was measured using this below ground methodology at two Australian wind farms, Pacific Hydro's Clements Gap Wind Farm which has been operating in the mid-North of South Australia since 2010 and comprises 27 Suzlon S88 wind turbines, each with a rated capacity of 2.1 MW, and at the coastal Cape Bridgewater Wind Farm which has been operating since 2008 in south-western Victoria, and comprises 29 REpower MM82 wind turbines, each with a rated capacity of 2.0 MW. Infrasound was also measured in the vicinity of a beach, a coastal cliff, the city of Adelaide and a power station using the below ground methodology. This paper reports on the study that:

- Develops a methodology to measure infrasound that minimises the influence of wind on the microphone;
- Measures the levels of infrasound at a range of distances from a wind turbine, for two wind farms;
- Compares the results against recognised audibility thresholds; and
- Compares the results with infrasound measurements taken near natural sources, such as beaches, and engineered sources, such as a power station and general activity within the city of Adelaide.

MEASUREMENT TECHNIQUE

Equipment

All measurements were conducted with a SVANTEK 957 Type 1 NATA calibrated sound and vibration analyser. The SVANTEK 957 Type 1 meter has a measured frequency response down to 0.5 Hz. A GRAS 40AZ ½" free field microphone with a frequency response of ±1dB to 1 Hz and ±2dB to 0.5 Hz was used with the SVANTEK meter. The meter and microphone arrangement is therefore suitable for measurement of noise levels in the infrasound range to the level of accuracy required for the assessment.

Microphone Mounting Method

A microphone mounting method is provided in IEC 61400-11 [13]. The method was developed to minimise the influence of wind on the microphone for the measurement of noise in frequencies higher than those associated with infrasound. This is achieved by mounting the microphone at ground level on a reflecting surface and by protecting the microphone with two windshields constructed from open cell foam. The method was not developed specifically for the measurement of infrasound, and wind gusts can be clearly detected when measuring in the infrasound frequency range using the above method. Therefore, this study has developed an alternative method to reduce the influence of wind on the microphone that would otherwise mask the infrasound from a particular source. A below ground surface method was developed based on a similar methodology [14]. This method has been adapted for this study, and includes a dual windshield arrangement, with an open cell foam layer mounted over a test chamber and a 90mm diameter primary windshield used around the microphone. The microphone mounting arrangement is depicted in Figure 1.

Verification of Technique

The below ground technique was analysed at a remote site away from wind farms, transport corridors and other appreciable noise sources and in very still conditions. The aim of the analysis was to determine the level of transfer of infrasound from outside to inside the chamber. The following procedure was used:

- A constant level of infrasound was generated using a tone signal generator and sub-woofer speaker (B&W Type ASW CDM), mounted 1m above the ground at a distance of 10m horizontally from the chamber. The lowest frequency that could be generated by the signal generator was 8 Hz and therefore the infrasound was generated at a number of discrete frequencies between 8 and 20 Hz.
- The infrasound was measured using the IEC 61400-11 above ground technique;
- The infrasound was measured using the below ground technique;
- The infrasound was measured without the tone signal generator operating to determine the ambient level of infrasound.

The measurement results are summarised in Table 1. The measured levels inside and outside of the chamber were consistent at all of the frequencies produced by the signal generator. The measurement of a constant source of infrasound in still conditions is the same above the ground as in the chamber using the technique described above.

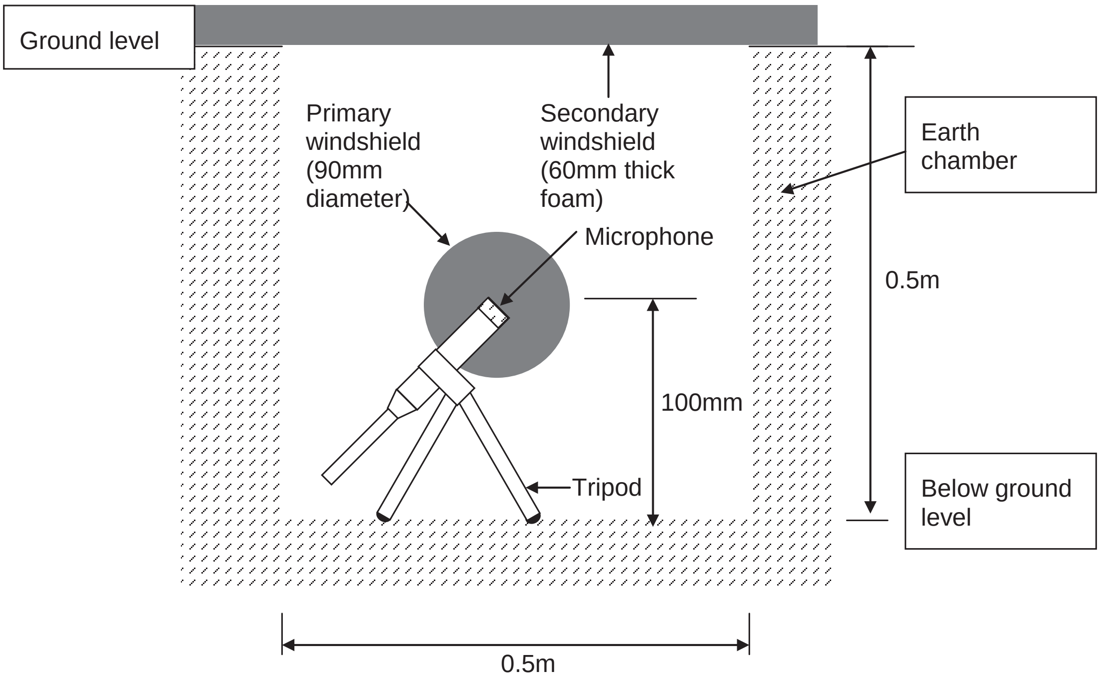


Figure 1. Schematic diagram of the microphone position (not to scale)

Table 1. Measurement at approximately 10m from the controlled source with no wind

Frequency (Hz)		8.00	10.0	12.5	16.0	20.0
Noise Level (dB)	Inside chamber	47	50	54	60	63
	Outside chamber	47	50	54	60	63
	Ambient level	39	38	39	39	37

RESULTS

Infrasound was measured at the Clements Gap Wind Farm and the Cape Bridgewater Wind Farm, using the below ground methodology. In addition, the level of infrasound was measured in the vicinity of a beach, a coastal cliff, a city and a power station using the same methodology. At Clements Gap Wind Farm, the infrasound was measured at distances of 85m, 185m and 360m from the base of a turbine in a downwind direction. The testing was conducted between approximately 7pm and 11pm on Tuesday 11 May 2010, under a clear night sky with a light breeze. Operational data indicates that the turbines were subject to hub height wind speeds of the order of 6 to 8m/s during the period of the testing. The wind speed at ground level was not measured.

At Cape Bridgewater Wind Farm, the infrasound was measured at distances of 100m and 200m from the base of a turbine in a downwind direction. The testing at the wind farm site was conducted between approximately 4am and 6am on Wednesday 2 June 2010, under a clear night sky with a light breeze. During the testing, the operational status of the turbines was constantly observed and confirmed. Measurements were conducted with both the turbines operational and with the turbine blades stationary.

To determine the level of infrasound from natural sources, measurements using the below ground method were made at Cape Bridgewater 25m from the high waterline of a beach, at approximately 250m inland from a coastal cliff face and at 8km inland from the coast. To determine the level of infrasound from other engineered noise sources, measurements using the below ground method were conducted at a distance of approximately 350m from a gas fired power station as well as within the city of Adelaide at least 70m from any major road. The measured levels of infrasound are summarised in Table 2 and are shown graphically in one third octave bands in Figures 2, 3, 4 and 5.

Table 2. Measured levels of infrasound

Noise Source	Measured Level (dB(G))
Clements Gap Wind Farm at 85m	72
Clements Gap Wind Farm at 185m	67
Clements Gap Wind Farm at 360m	61
Cape Bridgewater Wind Farm at 100m	66
Cape Bridgewater Wind Farm at 200m	63
Cape Bridgewater Wind Farm ambient	62
Beach at 25m from high water line	75
250m from coastal cliff face	69
8km inland from coast	57
Gas fired power station at 350m	74
Adelaide CBD at least 70m from any major road	76

DISCUSSION

At the Clements Gap Wind Farm, the level of attenuation with increasing distance from the turbine is consistent with the theoretical reduction of 6dB for each doubling of the distance due to “hemispherical spreading” of the sound wave. This observation confirms that the measured levels were predominantly produced by the turbine. At the Cape Bridgewater Wind Farm, higher ambient noise levels (without the turbines operating) were encountered than at the Clements Gap Wind Farm and therefore the same attenuation with increasing distance was not observed. This indicates that the measured levels included a significant contribution of infrasound from the turbine at 100m but at a distance of 200m, the infrasound from other sources was at least as significant. The levels of infrasound from waves at a beach (in light swell conditions) and in the vicinity of a coastal cliff were in the same order of magnitude as the infrasound measured close to the wind turbines.

At 8km from the coast, the level of infrasound was significantly lower than levels observed in close proximity to the beach and the coastal cliff. The levels of infrasound in the city of Adelaide and in the vicinity of a gas fired power station were greater than the levels observed close to the wind turbines. The measured levels of infrasound from the wind turbines and all other natural and engineered sources were well below the 85dB(G) threshold of audibility.

CONCLUSIONS

A method for measuring infrasound from wind turbines has been successfully demonstrated. The method shows that wind turbines generate infrasound and that close to wind turbines, the level of infrasound is well below the audibility threshold of 85 dB(G). An attenuation rate of 6dB per doubling of distance from a single turbine was also demonstrated. Infrasound is prevalent in urban and coastal environments at similar levels to the level of infrasound measured close to a wind turbine.

ACKNOWLEDGEMENTS

Pacific Hydro commissioned Sonus to conduct a study with the aim of gaining a better understanding of the levels of infrasound from wind farms and more generally in the environment.

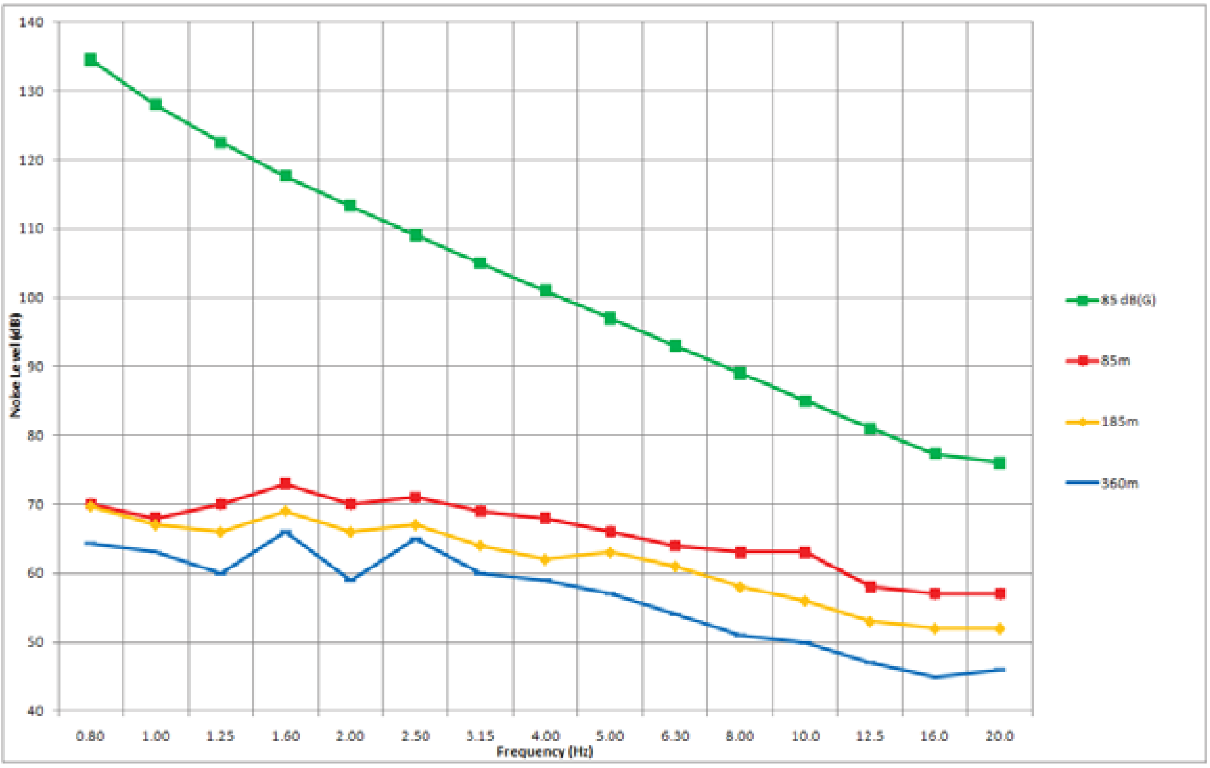


Figure 2. Measured levels of infrasound at Clements Gap Wind Farm

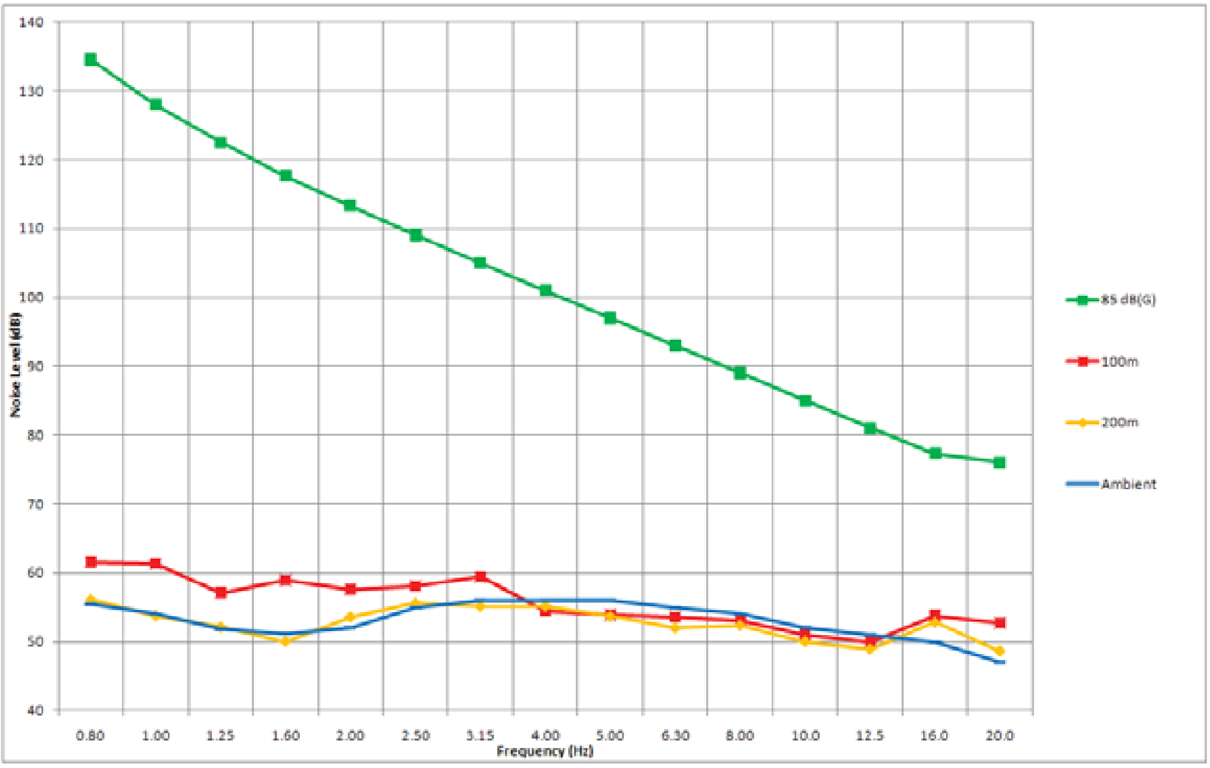


Figure 3. Measured levels of infrasound at Cape Bridgewater Wind Farm

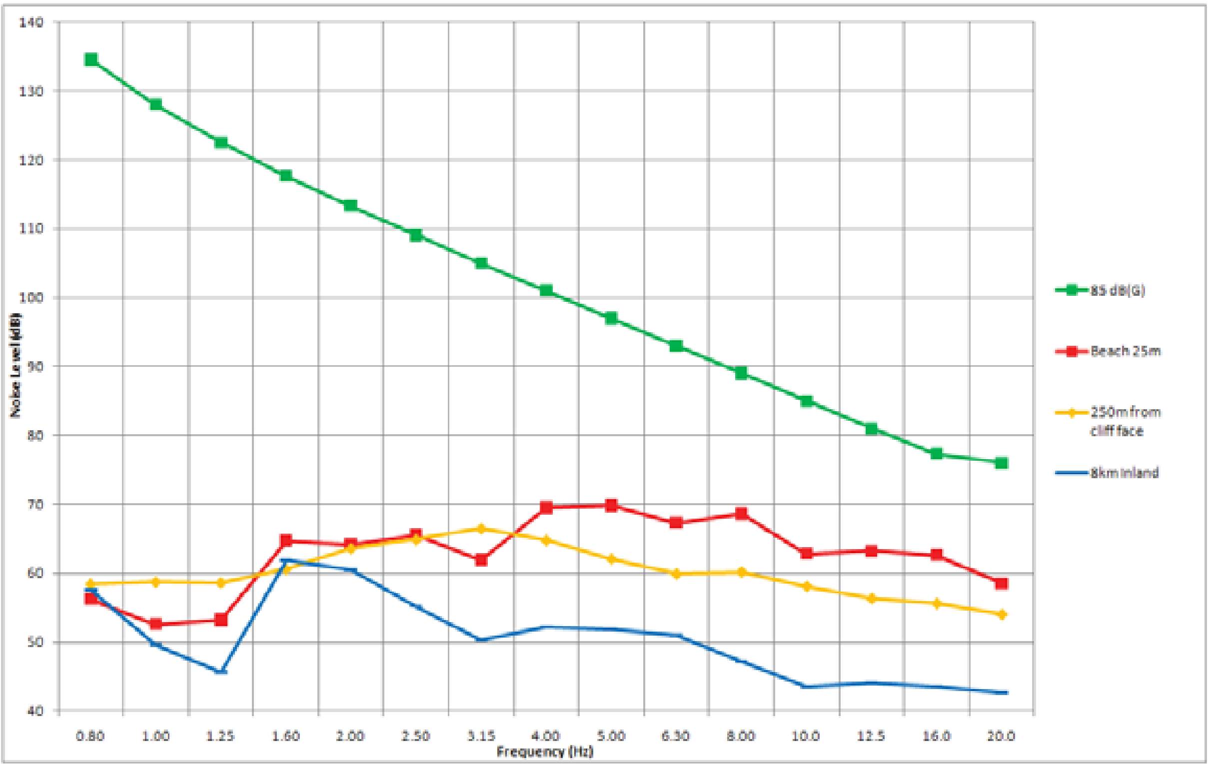


Figure 4. Measured levels of infrasound from natural sources

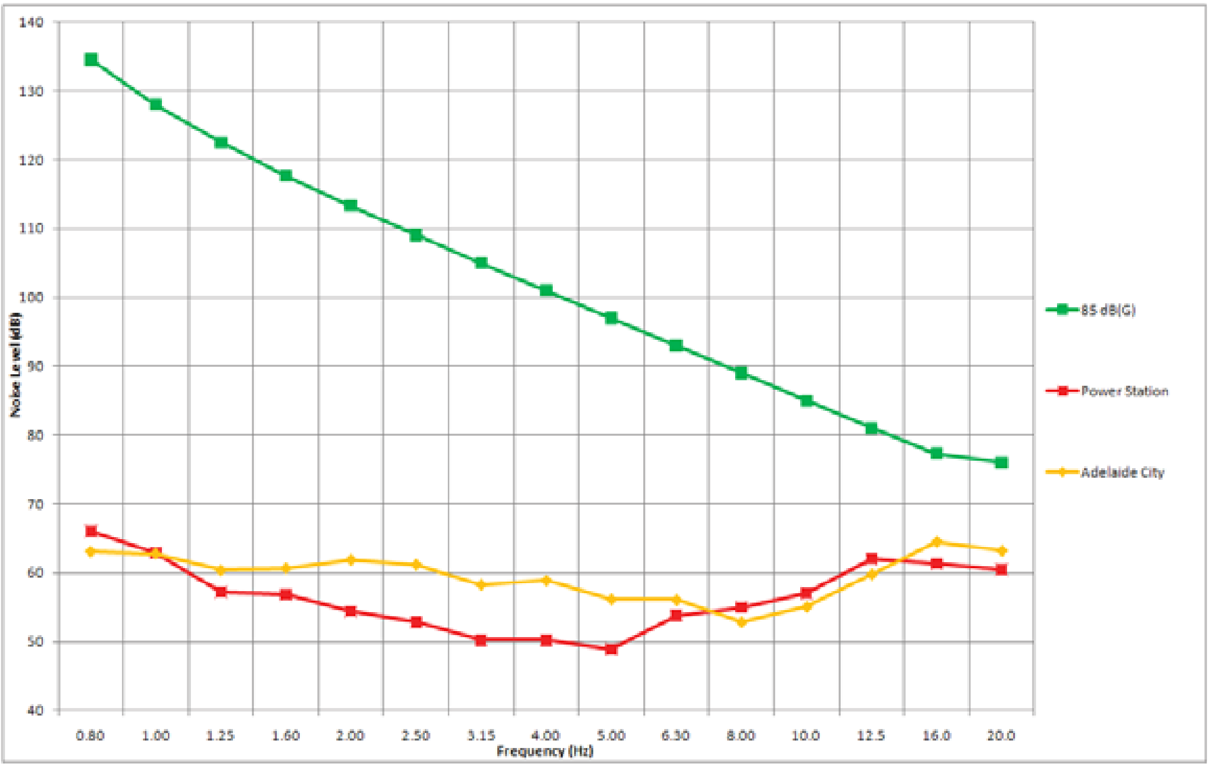


Figure 5. Measured levels of infrasound from engineered sources

REFERENCES

[1] R.D. O'Neal, R.D. Hellweg Jr. and R.M. Lampeter, *A study of low frequency noise and infrasound from wind turbines*, prepared by Epsilon Associates, Inc. for NextEra Energy Resources, Report No. 2433-01, 2009, http://www.cpuc.ca.gov/environment/info/dudek/ecosub/E1/D.8.2_AStudyofLowFreqNoiseandInfrasound.pdf (Last accessed 28 March 2012)

[2] G. Leventhall, *A review of published research on low frequency noise and its effects*, Report for the Department for Environment, Food and Rural Affairs, DEFRA, UK, 2003 http://archive.defra.gov.uk/environment/quality/noise/research/lowfrequency/documents/lowfreqnoise.pdf (last accessed 28 March 2012)

[3] International Organization for Standardization ISO 7196:1995, *Acoustics – Frequency-weighting characteristic for infrasound measurements*

[4] Hayes McKenzie Partnership, Ltd., *The measurement of low frequency noise at three UK wind farms*, Report prepared for the UK Department of Trade and Industry (DTI), Contract No. W/45/00656/00/00, UK, 2006

[5] DIN 45680 (German National Standard), *Measurement and assessment of low-frequency noise immissions in the neighbourhood*, 1997

[6] T. Watanabe and H. Møller, "Low frequency hearing thresholds in pressure field and in free-field", *Journal of Low Frequency Noise and Vibration* **9**(3), 106-115 (1990)

[7] H.H. Hubbard and K.P. Shepherd, *Wind turbine acoustics,* NASA Technical Paper 3057, DOE/NASA/20320-77, 1990

[8] Australian Standard AS 4959:2010 *Acoustics – Measurement, prediction and assessment of noise from wind turbine generators*

[9] South Australia Environment Protection Authority, *Environmental noise guidelines: Wind farms*, 2003

[10] South Australia Environment Protection Authority, *Wind farms environmental noise guidelines*, 2009

[11] New Zealand Standard NZS 6808:1998 *Acoustics – The assessment and measurement of sound from wind turbine generators*

[12] New Zealand Standard NZS 6808:2010 *Acoustics – Wind farm noise*

[13] International Electrotechnical Commission IEC 61400-11 *Wind turbine generator systems – Part 11: Acoustic noise measurement techniques*, edition 2.1 2006-11

[14] K. Betke, M. Schultz-von Glahn, O. Goos and H. Remmers, "Messung der infraschallabstrahlung von windkraftanlagen", *Proceedings of DEWEK '96, 3rd German Wind Power Conference*, Wilhelmshaven, Germany, 23-24 October 1996, pp. 207-210 (in German)

ANALYSIS TECHNIQUES FOR WIND FARM SOUND LEVEL MEASUREMENTS

Michael Smith and Stephen Chiles
URS, Christchurch, New Zealand. michael.j.smith@urs.com

NZS 6808 and other similar wind farm assessment standards require sound level measurements at neighbouring houses with and without the wind farm operating. While outlining a procedure for assessment using regression curves, the standards allow significant discretion in how the data are analysed. Issues with this analysis are reviewed and suggestions are made as to how specific parts of the process could be standardised. These issues are illustrated with background sound datasets from actual wind farm proposals. In particular, this paper examines: the process for separation of data by time-of-day and wind direction; the effects of altering the wind speed range for analysis; use of bin analysis; and removal of outliers.

INTRODUCTION

Assessment of wind farm sound usually requires pre- and post-construction sound surveys, to establish a baseline and to demonstrate compliance with noise limits. In a survey, between 2,000 and 4,000 10 minute measurements are typically made and a relationship between sound levels and wind speeds is determined. Statistical techniques are used to address the significant and unavoidable scatter in the sound data caused by relationships with other factors in addition to variances associated with wind speed. Achieving a robust analysis is dependent on careful inspection and separation of data.

General noise assessment standards such as NZS 6802 [1] and AS 1055 [2] do not provide an assessment framework for this analysis of wind farm sound. Wind farm specific standards discussed below do provide guidance, but still allow significant discretion in the analysis. This can leave the assumptions and choices in the analysis open to debate during statutory approval processes for wind farm proposals.

This paper reviews the analysis of background sound level data under the wind farm noise standard NZS 6808 [3], and explores methods for reducing variability. This paper does not critique the noise limits recommended by the standard. The issues discussed are common to other standards such as the 'ETSU' method [4], on which NZS 6808 was originally based, and AS 4959 [5], which in turn is partly based on the old 1998 version of NZS 6808 [6]. Similar topics have been raised as part of a broader review of wind farm acoustics [7], and a working group is currently formulating guidance [8].

In contrast to NZS 6808, the standard for measuring wind turbine sound power levels IEC 61400-11 [9] has a precise methodology, but in that application measurements are adjacent to a wind turbine rather than hundreds of metres away at the nearest houses as required by NZS 6808. However, some aspects of that method can still be applied to analysis under NZS 6808 and these are discussed in this paper.

Regression analysis

The mainstay of analysis under NZS 6808 and similar standards is determination of the regression between sound levels at receivers and wind speeds at the wind farm site. This analysis is performed using a large number of background sound level measurements (L_{A90}) under varying wind conditions. In NZS 6808, wind farm noise limits are then set at the higher of 40 dB or 5 dB above the regression curve.

Figure 1 is an example graph of background sound levels plotted against wind speeds, as would typically be produced when analysing background sound measured outside a neighbouring house.

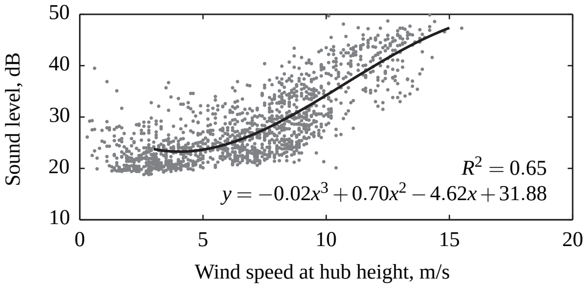


Figure 1. Example of regression analysis

In this example a third order polynomial curve is shown fitted to the data, although the different standards provide varying guidance to the choice of regression function. In NZS 6808 the parameters are not fixed, whereas AS 4959 limits curves to no more than third order polynomials, and the ETSU method recommends the use of logarithmic curves, although it also shows examples with polynomial curves.

The accuracy of a fitted curve between sound level and wind speed is sometimes expressed as a correlation coefficient (R^2), as defined in Equation 1. While this is referenced in this paper, it is not considered a key parameter for analysis.

$$R^2 = \frac{(\sum(x_i - \bar{x})(y_i - \bar{y}))^2}{\sum(x_i - \bar{x})^2 \sum(y_i - \bar{y})^2} \qquad (1)$$

The focus of this paper is on how fitting a regression curve or an alternative could be standardised. As the curve defines the noise limits and compliance for a wind farm, the effect of any variation in the analysis could be significant. This paper looks at examples for the analysis of background sound data as the first step in wind farm noise assessment, but the issues apply equally to analysis of measurements including wind farm sound. Different example datasets have been used to illustrate the various issues discussed in this paper.

TIME-OF-DAY

In situations where the background sound is dominated by sources such as vegetation moving in the wind, there is usually a clear relationship between background sound and wind speed. However, in many situations there is a poor correlation, for example due to other sound sources in the area such as insects, birds, and road-traffic, or due to houses being more sheltered by terrain in certain wind directions. As a first step, separating the sound level data into day and night periods will generally improve the correlation with wind speed.

NZS 6808 requires viewing of the sound level versus wind speed graph, and separation of data if there are ‘markedly different groups’. Procedures for defining different groups are not provided, although time-of-day is given as a possible factor. In New Zealand, time periods for day and night are usually defined in local council planning documents, together with an evening period in some instances, with different noise limits for each time period. For wind farm sound there is a single fixed noise limit, and separation of time periods is only used to identify wind farm sound over the background. Therefore while potentially an attractive option for background sound analysis, the council time periods are usually inappropriate as they do not define the actual daily variation in sound levels. The following example illustrates an alternative whereby a visual inspection is made of sound levels plotted against time-of-day, to establish time periods based on the actual environment.

For this example, Figure 2 shows the variation in sound levels throughout the day, measured over two weeks at a house near a proposed wind farm. Patterns can be seen on the graph and based on visual inspection of the sound levels in this example a daytime period has been identified as 0630 h to 1800 h, with night-time from 1800 h to 0630 h. Care is required in this visual inspection as there are lots of overlapping data points and outliers can appear to have undue prominence. Sunrise and sunset times will vary during the sound survey, potentially by 30 minutes over a month, leading to a blurred transition between time periods. Plots of sound level versus wind speed are shown in Figure 3 for these day and night periods, in addition to the complete dataset.

There is no minimum duration specified for day, night or other time periods in NZS 6808. It could be interpreted as allowing a noise limit to be based on the quietest one hour period in the middle of the night. To standardise this matter and to provide an assessment of a representative scenario, it is suggested that a minimum of eight hours should be used for any time period. If background and compliance sound surveys for the same site are performed at different times of the year, the day and night periods may have different definitions.

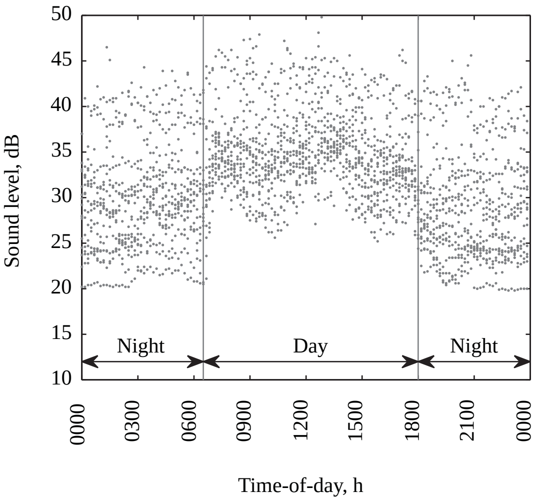


Figure 2. Daily variation in background sound

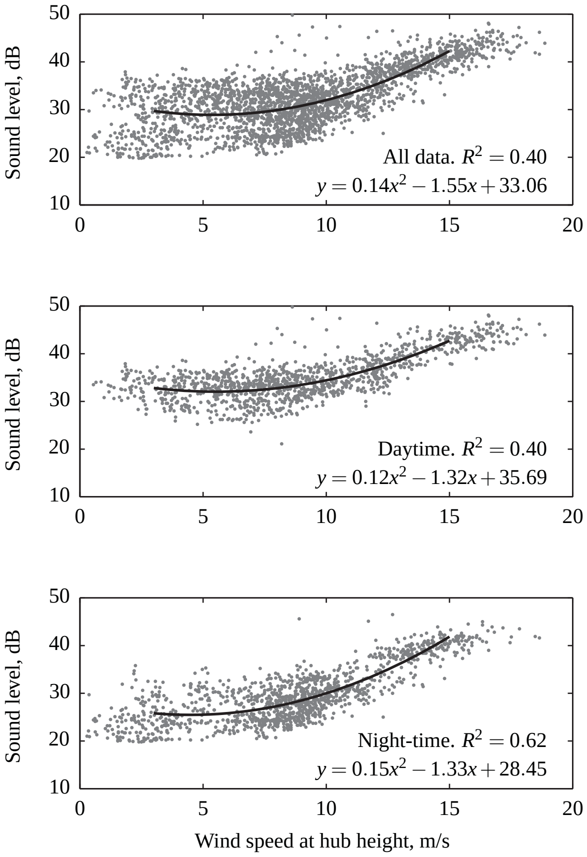


Figure 3. Regression curves for day and night periods

The example in Figure 3 is similar to most locations in New Zealand in that there is better correlation between wind speed and background sound levels at night. This is due to a lesser contribution from man-made sound sources and birds at night, so the background sound is controlled to a greater extent by sources such as rustling leaves and vegetation, which depend on the wind speed. Similarly, the correlation generally improves at higher wind speeds during both day and night, when wind-induced sources become more prominent.

NZS 6808 requires further investigation if correlations are ‘poor’ but does not specify a correlation coefficient. In this example there are relatively low correlation coefficients due to the unavoidable scatter of environmental sound levels, although the regression curves do still provide a reasonable representation of the data. Also, the greatest spread of sound levels giving rise to the low correlation coefficients is at lower wind speeds where the 40 dB fixed part of the NZS 6808 noise limit would apply rather than the ‘background +5 dB’ part of the noise limit. At these low wind speeds the position of the regression curve is not critical.

WIND DIRECTION

Wind direction effects can be another cause of markedly different groups in sound level versus wind speed plots. In New Zealand, neighbouring houses are often in valleys below a wind farm, and there can be variation in wind at a house relative to wind at the wind farm depending on whether the wind is blowing across or along the valley. In such cases separation of data by wind direction can improve the correlation of sound levels and wind speeds. Again, no method is provided by NZS 6808, and no guidance is given as to how many wind directions should be used when separating the data.

It is common to see measurement data separated into 4 or even 8 wind directions, based on the cardinal points. However as for time-of-day, better results can be obtained by basing the separation on the actual environmental conditions. Unnecessary separation of data should be avoided as it complicates compliance assessment and can result in sparse datasets.

To determine appropriate wind direction sectors, the wind distrubution during the sound survey should be reviewed, along with the annual distribution. This is typically presented as a wind rose, such as Figure 4. In this example it can be seen that there would be little value in separately analysing the south quadrant independently. From visual inspection of this graph and after experimenting with different splits, in this instance the data was separated into two sectors: the west quadrant and the other three quadrants combined.

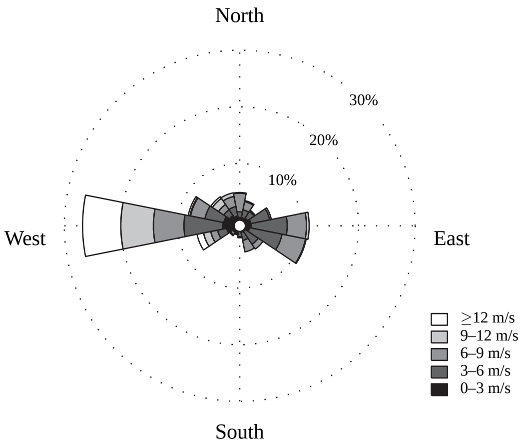


Figure 4. Wind speed distribution

The wind distribution during the sound survey should be representative of the annual wind distribution, however this is difficult where there are large seasonal variations. It is desirable for the background and compliance surveys to be performed at the same time of year, however it is common for consent conditions to require compliance surveys within 3 months of completion. If surveys are performed at different times of the year, the chosen direction splits in the background survey may result in sparse data sets in the compliance survey. It may be necessary to re-analyse the background sound data to best establish the wind farm sound levels.

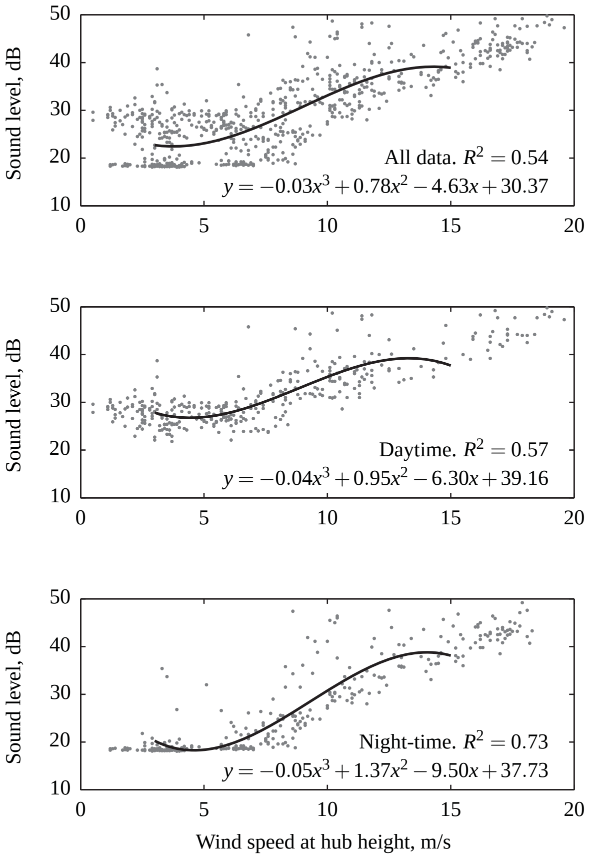


Figure 5. Regression curves for west quadrant

Table 1. Separation by wind direction

Item	All	West	North–East–South
Total data points	1703	693	1010
Night-time data points	840	330	510
Night-time R^2	0.42	0.73	0.12

Figure 5 shows the sound level versus wind speed for the west quadrant, also including graphs for time-of-day separation of that reduced dataset. Starting with 1703 data points, only 330 of these are in the west quadrant at night, and if a south quadrant had been used there would only have been 40 points for that regression analysis at night. For the night period, the correlation coefficients in Table 1 show the benefit of separating the west quadrant, and also show that for the other wind directions there is not a significant range of wind speeds controlling the sound levels.

WIND SPEED RANGE

A related issue to the separation of data discussed above is the selection of the wind speed range over which data are included in the analysis. NZS 6808 does not provide guidance on the wind speed range for fitting a curve. The ETSU method bases analysis on a 0–12 m/s wind speed range (10 m height), assuming an average wind resource of 8 m/s.

The suitability of fitting a curve to a wide wind speed range is dependant on the data set. In many instances three distinct regions can be observed: at low wind speeds, the background sound level is independent of wind speed; at medium wind speeds (often the critical range) there will be increasing sound level with wind speeds; and at higher wind speeds there can often be a flattening off. The inclusion of data outside of the critical range may disturb the fit of a polynomial curve. In other instances, the wider wind speed range may result in a better fit, as demonstrated in Figure 6. In general, a wider wind speed range is more likely to include different trends in sound level versus wind speed, requiring a higher order polynomial.

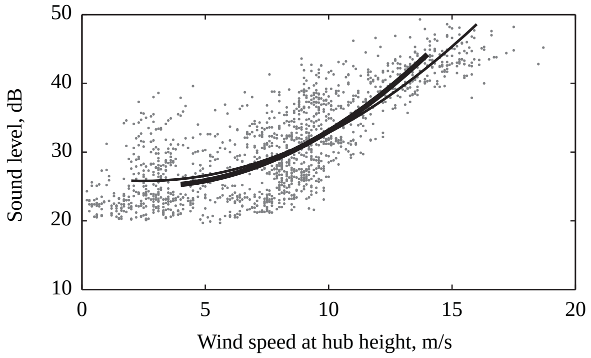


Figure 6. Effect of wind speed range on regressions analysis

As demonstrated in Table 2, the correlation coefficient is highly sensitive to the wind speed range. While it is a useful parameter for comparing curves for a given dataset, it does not provide a direct and consistent measure of the scatter in the data in the critical range. NZS 6808 does not require correlation coefficients to be reported.

Table 2. Correlation coefficients (R^2) for different wind speed ranges

Wind speed range	Polynomial order 2	3	4
4–12 m/s	0.23	0.23	0.24
4–13 m/s	0.37	0.37	0.37
4–14 m/s	0.52	0.52	0.53
4–15 m/s	0.62	0.62	0.63
4–16 m/s	0.66	0.67	0.67
4–17 m/s	0.67	0.69	0.69
4–18 m/s	0.67	0.69	0.69

NZS 6808 specifies that the wind farm noise limit should be met at any wind speed, although the controlling wind speed range is between cut-in and 95% of rated power. For example this might be from 4 m/s to 12 m/s at hub-height. At higher wind speeds background sound levels increase, but the wind turbines will have already reached their maximum sound output. Therefore analysis of background sound levels at higher wind speeds should not be required. Likewise for low wind speeds below cut-in. As an aside, sound power levels measured in accordance with IEC 61400-11 are only provided for wind speeds corresponding to approximately 7 m/s to 14 m/s at hub-height. Wind farm sound level predictions are based on that data, and therefore do not extend to higher wind speeds.

To standardise the wind speeds used for analysis it is suggested that curves should only be fitted to data in the range between cut-in and 95% of rated power. Compliance with noise limits at all other wind speeds can be inferred from compliance in this range.

Another issue encountered at low wind speeds is the noise floor of measurement equipment. Type 1 equipment typically has a noise floor of 18 dB to 25 dB, which can be readily observed by the ‘flat lining’ in sound level graphs for most rural areas. While there is sometimes concern this will affect a regression curve, in practice, given the fixed part of the noise limit is 40 dB, any errors in measurements below 25 dB should be inconsequential.

DATA BINNING

NZS 6808 includes a comment that in some cases ‘bin analysis’ may be more appropriate than a regression curve. In bin analysis sound level data is separated into wind speed ‘bins’ centred on integer or half-integer wind speeds. A representative sound level is then determined for each bin in isolation. Potentially, this could resolve some of the issues discussed above with regression analysis, and in a future version of NZS 6808 it seems likely that bin analysis will replace regression analysis, as is occurring with IEC 61400-11 version 3[10].

For measurements adjacent to wind turbines IEC 61400-11 version 2 details both regression analysis and data binning techniques. Regression analysis is used where a correlation coefficient of 0.8 is achieved when fitting a fourth order polynomial to the data. A high degree of correlation is common when measuring in close proximity to wind turbines. The standard requires turbine sound level to be 6 dB above the background sound level, and far less scatter is observed. In contrast, correlation coefficients above 0.8 are uncommon when measuring at neighbouring houses as required by NZS 6808, where contributions from other sources are significant.

Under IEC 61400-11 version 2 the data binning option is relatively complex and still involves a linear regression analysis within each bin and curve fitting to the results. A regression curve is then fitted through the bin values over a fixed range of 6 to 10 m/s wind speeds at 10 m height. An example of the linear regression used within each bin, under the current version of IEC 61400-11 to determine the bin centre value, and the regression curve through those values, is shown in Figure 7.

The proposed IEC 61400-11 version 3 will require the sole use of data binning but will refine the process by changing the time interval, bin width, and averaging method. Table 3 summarises the key parameters from each version of the standard.

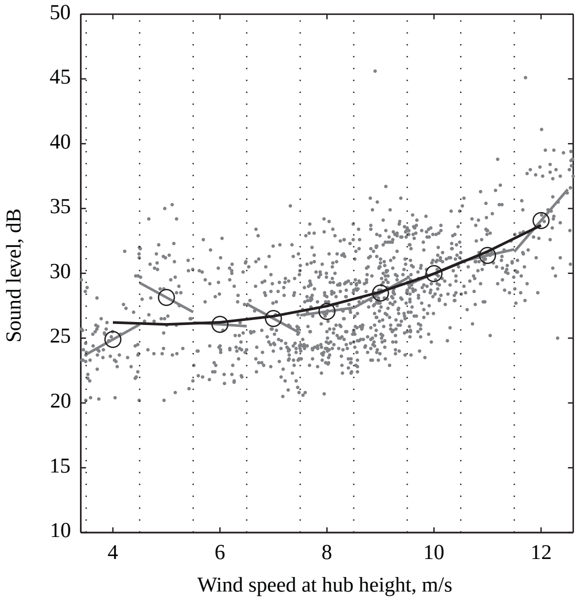


Figure 7. Linear regression in 1 m/s bins used to determine bin centre values

Table 3. IEC 61400-11 bin analysis parameters

Version	Parameter	Bin width	Average type
v2 (current)	$L_{\mathrm{Aeq(1\,min)}}$	1 m/s	Linear regression
v3 (proposed)	$L_{\mathrm{Aeq(10\,s)}}$	0.5 m/s	Energy average

In addition to using an energy average for sound levels, IEC 61400-11 version 3 uses an arthimetic average of the wind speeds in each bin to determine the bin average. To determine the sound level at the bin centre, linear interpolation between adjacent bin averages is used. The benefit of this procedure for narrow, 0.5 m/s, bins is unclear.

Some of these parameters are not appropriate for use under NZS 6808. IEC 61400-11 also uses the time average level, L_{Aeq}, rather than the centile level L_{A90} used under NZS 6808. Energy averaging a centile level does not make mathematical sense. For bin analysis under NZS 6808 it is suggested here that to obtain the bin sound level a simple arithmetic average of all sound levels in the bin should be made, rather than regression or energy averaging.

A possible weakness of data binning is that certain bins may have sparse data, whereas when fitting regression curves that issue is avoided by reliance on neighbouring data. However, IEC 61400-11 can provide ample data in each bin with a measurement time interval of only 10 seconds or 1 minute, compared to 10 minutes measurements used for NZS 6808.

In practice, most surveys under NZS 6808 are for two or more weeks and sufficient data would be generated for 1 m/s bin widths across the critical range from cut-in to 95% rated power. Figure 8 shows the bin values using a simple arithmetic average with one standard deviation for an example dataset. The standard deviation is a useful parameter for describing the amount of scatter in the data, and where wind farm sound is clearly measured over the background can be used to describe the measurement uncertainty. The solid line is a conventional regression curve fitted to the complete dataset. It can be seen that the average bin values show good agreement with the regression. It is suggested that for bin analysis under NZS 6808, 1 m/s wind speed bins should be used, and the bin arithmetic average sound level values should be taken as the final results without further regression analysis.

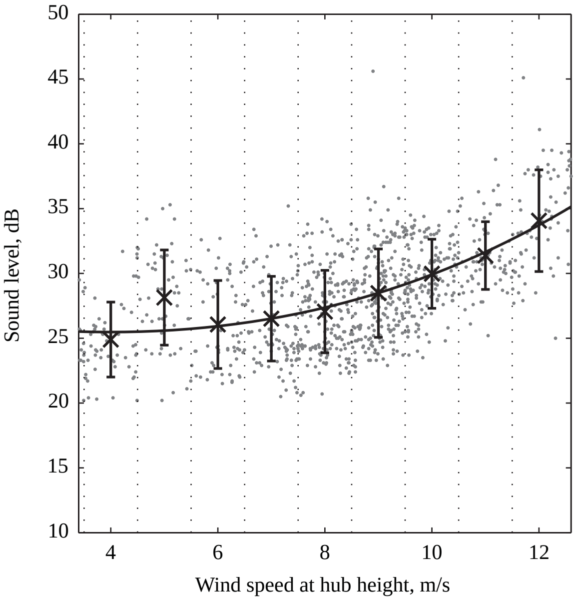


Figure 8. Bin analysis using 1 m/s bins and averaging, showing 1 standard deviation and a conventional regression curve.

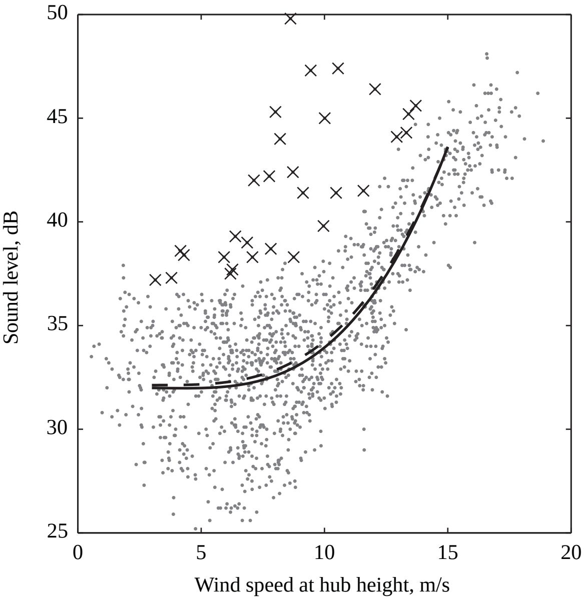


Figure 9. Removal of outliers

OUTLIERS

Extraneous events should not unduly influence the regression curve or bin analysis. A typical source of extraneous sound is extended periods of precipitation, but these should be simply excluded from the dataset on the basis of rainfall monitoring at the site. Another common issue is seasonal insect noise or watercourses, which is best avoided by monitoring at an appropriate time of year. For other sources of momentary sound such as a dog bark or car door slam, as noted in NZS 6808, the L_{A90} metric is effective at removing most short-term events from the measurement.

Despite the controls described above, there will always be significant scatter in environmental sound measurements, and some events such as mowing grass near the measurement location could cause spikes in the dataset. NZS 6808 states that obvious outliers should not be allowed to unreasonably influence the regression curve. However, the following example demonstrates how 'obvious' outliers generally have a minimal effect on results.

Figure 9 shows an example sound level versus wind speed graph. The dashed line represents the regression with the entire data set included, and the solid line is the regression with the × data points manually identified and removed. The fitted values at integer wind speeds vary by less than 0.5 dB.

CONCLUSIONS

Sound level measurements are required by NZS 6808 and similar standards at neighbouring houses, with and without the wind farm operating. The analysis has to take into account the presence of wind, which is not a factor when measuring general environmental noise as wind generally can be avoided. Due to the high variability of sources and locations encountered, assessment standards such as NZS 6808 are not prescriptive as to how measured sound levels are analysed. However, this can affect noise limits and compliance assessment. There are some aspects of the analysis process which could be standardised to provide better consistency.

When separating data it is suggested that:

- daily patterns should be visually examined on a plot of sound level data against time-of-day, and 'day' and 'night' periods identified,
- day and night periods should not be less than 8 hours each,
- clusters/trends should be visually examined on a plot of sound level data against wind direction to identify wind sectors for analysis, and
- sectors for wind direction should be limited and not based simply on cardinal points.

Analysis should only be conducted for the wind speed range from cut-in to 95% rated power.

Bin analysis is already used in IEC 61400-11, and is allowed for in certain circumstances in NZS 6808. Data binning offers some advantages over regression curves and removes some variability from the analysis options. IEC 61400-11 differs substantially from NZS 6808 in that it uses L_{Aeq} rather than L_{A90}, the measurements are adjacent to a turbine, and the measurements are 1 minute rather than 10 minutes. For bin analysis in the context of NZS 6808 it is suggested that a simple arithmetic average should be used to determine the bin value for 1 m/s bins, with no further interpolation or curve fitting.

Providing steps are taken to control known effects from sources such as precipitation, seasonal insects and watercourses, other data outliers generally have a minimal effect on sound level results.

The issues raised in this paper are only significant in environments with high background sound levels or where wind farm sound levels are predicted to exceed 40 dB L_{A90}. In other instances background sound level measurements might not be required.

ACKNOWLEDGEMENTS

The authors would like to thank Meridian Energy Limited and Pioneer Generation Limited for allowing us to use data from their projects in this paper.

REFERENCES

[1] New Zealand Standard NZS 6802:2008 *Acoustics – Environmental noise*

[2] Australian Standard AS 1055:1997 *Acoustics – Description and measurement of environmental noise*

[3] New Zealand Standard NZS 6808:2010 *Acoustics – Wind farm noise*

[4] The Working Group on Noise from Wind Turbines, *The assessment and rating of noise from wind farms*, Energy Technology Support Unit, ETSU-R-97, 1996

[5] Australian Standard AS 4959:2010 *Acoustics – Measurement, prediction and assessment of noise from wind turbine generators*

[6] New Zealand Standard NZS 6808:1998 *Acoustics – The assessment and measurement of sound from wind turbine generators*

[7] Hayes McKenzie Partnership Ltd, *Analysis of how noise impacts are considered in the determination of wind farm planning applications*, HM:2293/R1, prepared for the Department of Energy and Climate Change, UK, 2011

[8] Institute of Acoustics, UK, *Good practice guide to wind turbine noise assessment – Working group terms of reference*, 2011, available at http://www.ioa.org.uk/pdf/ioa-good-practice-guide-terms-of-reference-v-09-12-11-version-5.pdf (last accessed on 25 March 2012)

[9] International Electrotechnical Commission IEC 61400-11 *Wind turbine generator systems – Part 11: Acoustic noise measurement techniques*, edition 2.1 2006-11

[10] B. Søndergaard, "The next version of the IEC 61400-11 measurement method", *Proceedings of the 3rd International Meeting on Wind Turbine Noise*, Aalborg, Denmark, 17-19 June 2009

Technical Note

THE STEEP AND THE TEARFUL - A NEW ZEALAND PERSPECTIVE OF WIND TURBINE NOISE

Stuart Camp
Marshall Day Acoustics Ltd, Christchurch, New Zealand

WIND

Oh, for the gentle breeze. On one wind farm in the North Island, when I was struggling to stand up and commented on how windy it was, the farmer nonchalantly replied that it wasn't as windy as the day before, when he had trouble shutting his front gate. His response wouldn't have surprised me as much as it did, if I hadn't noticed that his front gate was galvanized netting on a pipe frame—not something I consider to have any significant wind resistance at all. On that occasion, wind records showed that the wind speed didn't drop below 23 m/s for 3 days.

Both Australia and New Zealand bat well above average when it comes to wind resources. According to Wikipedia, the world average 'capacity factor'[1] is 25%, while Australia is 30-35%. Contrast this with New Zealand, where the average is 41%, with some farms reporting 46% or more. To achieve this, wind farms are typically generating power 85-95% of the time.

New Zealand is known for strong gusty winds, and in the early days of wind turbines, European manufacturers had to do a bit of soul searching to develop systems for coping with this situation—something that isn't normally experienced in the northern hemisphere. Imagine acoustic modelling of wind farms in The Netherlands, where the terrain is completely flat, and the wind seems to blow about 5 m/s all day every day.

TERRAIN

New Zealand, built on a significant geological faultline, has an abundance of rather large hills, and it is hardly surprising to find that the windiest places in the country are on top of some of these landforms. Contrast this with Australia, where the gentle rolling grasslands of some wind farm sites resemble cricket pitches.

A paper presented at the 2011 Australian Acoustical Society conference discussed the need/merits of terrain modelling for wind farms. The study concluded that it was necessary to model terrain effects, otherwise noise measurement data from one location near an existing wind farm could not reliably be used to validate the model for other locations.

This may well flow from the now obsolete New Zealand wind farm noise standard (NZS6808:1998) still used in parts of Australia. That standard adopted a simple prediction model which ignored all terrain effects—and ground/wind effects for that matter. The standard was revised in 2010, and terrain modelling is now very much the norm. When one visits some of the New Zealand wind farms, it is easy to see why (see Figure 1).

Figure 1. West Wind, Wellington (Source: Wind Energy Association of New Zealand)

HOUSES

Contrary to the long-held belief of some Australians, we do have houses in New Zealand. Just not very many. And, because wind turbines are perched on the top of steep hills in unbelievably windy places, the few which do exist tend to be snuggled into secluded valleys, sheltered within copious plantings of trees, or generally somewhere well away from the ridgeline.

---

[1] Capacity Factor is the ratio of the actual output over a period of time to the potential output if the wind farm had operated at full capacity the entire time.

The upside of this is that the number of houses affected by turbine noise is often very small. On one proposed wind farm, for example, the application for 33 turbines (2.3 MW each) assesses noise levels at 73 existing dwellings. Of these, only 3 will receive noise levels above 35 dBA. Most houses are at least 2 km from the nearest turbine. One might therefore expect the number of complaints about noise, and/or the opposition to proposed wind farms to be small. More on that later.

The downside is that long-time residents in these areas have often planted extensive landscaping, using large trees. Whilst the trees can generate wind noise, there are examples where the tree planting is so dense that the garden surrounding the house can be remarkably sheltered from wind. Ambient noise data for one proposed wind farm showed that at one existing dwelling, the background noise level didn't exceed 20 dBA when the wind was blowing from the north-west—despite hub height wind speeds of up to 13 m/s.

Despite most of New Zealand having been modified by man for a century or so, rural residents are still known to refer to their living arrangements as "going back to nature". Even farmland is now considered to be natural, and those who choose to live in rural areas don't take kindly to the idea of a man-made intrusion such as a wind farm. Not only is the "industrial" noise from wind turbines a totally abhorrent idea, the rugged terrain means that turbines can be visible from many kilometres away.

TURBINE LOCATIONS

Optimising turbine locations in New Zealand is a simple task—at least when viewed from the eyes of a mere acoustic consultant. To a large extent, the terrain dictates the locations. Move a turbine more than a few dozen metres, and it falls off a cliff, or ends up in the lee of a hill and prone to significant turbulence. Couple this with some windy spots being inaccessible by anything other than a mountain goat, and our wind farm is more or less laid out by nature.

The whole idea of optimizing the number of turbines based on predicted noise levels and surrounding dwellings doesn't enter the fray in New Zealand. The acoustic consultant is presented with a plan showing proposed turbine locations, a computer model is undertaken, and the resource consent process begins. It is rare for there to be houses exposed to greater than 40 dBA, other than the landowners, and the energy company doesn't often have to forego turbines to reduce noise levels at affected dwellings.

COMMUNITY REACTION

There is a saying in New Zealand, "no sooner is an idea proposed, than a community group is set up to oppose it". This has never been more true than with proposed wind farms. Communities are united, and strengthened by their opposition to turbines blotting their back yard. Experts are engaged to counter other experts, lawyers get rich, and the courts are filled with warring factions.

Many wind farms are eventually approved, and built, and what then? Are the actual effects as horrific as the community said they would be?

A difficult question to answer, because tempers are too raw from the fight for researchers to be able to judge quite what is real and what is a defence against a pre-disposition. What is seen in some instances, is complaints about noise which don't seem to bear any relationship to noise level. Residents at the 40 dBA contour can be quite happy, sleeping peacefully, with no concerns, whilst others exposed to 30 dBA or less complain vigorously, and sleep hardly at all.

But perhaps this is to be expected. After all, when one examines the well defined "Schultz" curve of dose-response to other forms of environmental noise, one sees an exponential curve, until a closer examination of the data reveals a scatter plot reminiscent of a large ink blot. When a new road is built through the middle of a quiet area, the annoyance is almost 100%, irrespective of noise level. Over time, with the expected change in house ownership, we gradually see some sort of acceptance of noise, and the dose-response moves towards what Schultz foretells. Those of us who don't like traffic noise choose not to live in those areas, and those of us who happened to live there when the road got foisted upon us, sooner or later buy a bigger house to accommodate the growing family, and we leave the area. The raw tempers are soothed over time, and the actual effects become the driver for response rather than the pre-disposition.

So, maybe we will see a growing acceptance of wind turbines. Small rural farms, traditionally called lifestyle blocks, are more cynically known as life sentence blocks because of the hard work involved on them, and as a result, the average ownership period in some parts of New Zealand is only about 2 years. We can therefore expect to see a number of dwellings around wind farms to change hands over the next decade—irrespective of effects from the wind farm, and the new owners will only choose to move in if they are happy with the generation capacity at their back door.

An interesting anecdote from one recently completed wind farm. There is another proposal in the wind several kilometres away, if you'll pardon the pun, and complaints about noise have been received from residents who could be affected by the next wind farm—even though they are in the order of 6 km from the existing turbines.

Technical Note

Note: Technical notes are aimed at promoting discussion. The views expressed are not necessarily those of the editors or the Australian Acoustical Society. Contributions are not formally peer-reviewed.

NOISE DOSE ASSESSMENT OF WIND FARM NOISE

Andy McKenzie
Hayes McKenzie Partnership, Salisbury, UK

INTRODUCTION

Environmental Impact Assessment is the process by which decision makers evaluate whether larger projects should be allowed to proceed, either in the form which they are submitted, or incorporating mitigation identified as part of the EIA process. The method by which such assessments are carried out can be a contentious issue, whatever the impact which is being assessed (ie. landscape and visual, ecological, archaeological etc.) and whatever the source of such impact (new road scheme, power generation project, minerals extraction etc.). Wind turbine projects and noise are, of course, no exception to this.

Noise impact assessment tends to be carried out with reference to the particular assessment methodology which has been laid down in planning guidance for the particular country in question. It has been argued that noise assessment required for planning purposes may not always be indicative of the 'true' noise impact which may occur in practice. Noise impact is, of course, a purely subjective issue and it can be argued, on the other hand, that the noise impact can only be assessed by reference to the criteria laid down by the planning process and that the planning process should not, by its very nature, allow development to go ahead if significant impacts are predicted.

Notwithstanding the above, the prediction of noise impact has always been something of a holy grail for noise professionals, with a great deal of effort going into subjective studies of various environmental noise sources and the production of resulting dose response curves. One of the outcomes of these types of studies is the use of the L_{den} measurement index as a strategic assessment tool, and this has been adopted as such in Europe through the Environmental Noise Directive [1]. This index is, effectively, a long term L_{Aeq} corrected by the addition of 5 dB for noise occurring during the evening hours (1900-2300) and 10 dB for noise occurring at night (2300-0700) although the definitions of the time periods are flexible and may be adjusted to allow for local circumstances.

This study shows how the use of L_{den} could be applied to the assessment of wind farm proposals to provide an objective approach to wind turbine noise assessment, taking into account the range of wind speeds and wind directions, and hence noise levels at specific residential or other properties, occurring 'long term' for measured wind conditions at a specific site. It is not argued that this methodology would necessarily predict subjective impact any better than that which is being currently used in any particular country for either impact assessment or planning purposes. It is, however, a means for quantifying impact which takes account of the existing noise environment and the predicted noise environment due to the development which is being proposed, taking into account the variation in both existing and predicted noise due to wind conditions. It should be noted that this metric is unlikely to be suitable for practical noise control purposes which normally form part of the conditions or limits on wind farm planning consents. It may be that, nevertheless, it may constitute a useful control measure to be applied at the design stage, given the practical difficulties encountered in the measurement of noise from operational wind farms.

NOISE IMPACT ASSESSMENT

Noise limits for planning or assessment purposes can be expressed as absolute limits, relative limits, or as a hybrid of the two approaches. Absolute limits refer to a fixed decibel value which may, or may not, be dependent on time of day (ie. day, evening or night) or type of area (ie. mixed industrial, urban residential, sub-urban residential, rural etc.). Relative limits are limits which relate to a permitted level of noise change or a permitted level of noise increase above the existing background noise. Hybrid noise limits involve an element of both of these such as the UK limits commonly applied to wind turbine noise which relate to the existing background noise except for situations where background noise levels are very low, at which point absolute limits apply.

One of the unique factors of wind turbine noise assessment is that not only does the source noise level change with wind speed but the level of existing noise, in most cases, also changes with wind speed. As with most noise sources, the propagation of noise from source to receiver also changes with wind direction. The level of existing noise may also change with wind direction and the effect of wind direction may also depend on wind speed!

The most common approach for wind turbine noise assessment is either to compare the turbine noise with fixed noise limits under specific operational conditions (that is, at a fixed 'reference' wind speed or at the rated power[1] of the turbine as is commonly used in continental Europe), or with hybrid noise limits related to a derived background noise level, or a fixed limit if background level is low, as is commonly used in the UK, Australia and New Zealand.

In the Netherlands, the assessment methodology has recently been changed to the use of a 47 dB yearly L_{den} criterion [2]. This does not, however, make any reference to the existing L_{den} prior to the site becoming operational. Although

---

[1] The point at which the turbine is generating its specified power (eg. 2MW). Source noise level does not generally increase above the point at which it reaches rated power for pitch regulated turbines.

it is helpful, therefore, in terms of providing for an aggregate noise level once the variation in noise level with wind speed and direction is taken into account, it does not continue this approach to looking at the change in yearly L_{den} caused by the operation of the site. What is proposed here is a comparison of the L_{den} prior to, and subsequent to, the operation of the wind farm.

CALCULATION OF NOISE DOSE FROM A WIND FARM

In order to calculate noise dose with any degree of accuracy, access is required to a full year of wind speed and direction records, for consecutive intervals of maximum 1 hour duration, at the hub height of the proposed turbines. Where only sub-hub-height wind speeds are available, a reasonable approximation to hub height wind speed for each measurement interval may be calculated from two or more wind speeds at lower height. This can then be converted to 'standardised' 10 metre height wind speed[2] as used by wind turbine manufacturers for the specification of sound power level data[3]. In this way the noise output from the turbine can be defined for each hour of the whole year of records or for shorter intervals if the data is available.

The noise output can then be combined with wind direction information, together with other propagation factors including geometric, atmospheric, ground and barrier attenuation as specified in an appropriate prediction algorithm such as ISO9613, Part 2 [3]. In this way, the noise levels for every hour (or less) of the whole year of records can be predicted and used to calculate the L_{den} over the whole year by adding 5 dB to predicted levels for wind speed measurement intervals falling during the evening periods and 10 dB for those falling during the night-time periods.

In the absence of the incorporation of wind direction information in the prediction algorithm used[4], it may be helpful to refer to the work of Wyle Laboratories [4] which suggests an upwind attenuation increasing from 0 dB at the edge of the shadow zone, taken as 5.25 x hub height, increasing linearly to 20log(f) – 30 dB at the point at which the shadow zone is fully formed, taken as 15.75 x hub height. A reasonable approximation to cross-wind propagation may be to apply an attenuation of 2 dB which relates more to the change in source noise level for cross-wind propagation. For any given wind direction, each wind turbine may be categorised as falling into downwind, upwind or crosswind propagation directions relative to the receiver location which is being evaluated. Any number of different receiver locations can then be evaluated with the result that a receptor located in the same direction as the prevailing wind from the site[5] will receive a significantly higher L_{den} than one located in the opposite direction, not only due to the greater statistical prevalence of those wind directions but also due to the higher wind speeds, and hence higher noise levels, for such wind directions.

CALCULATION OF PRE-WIND FARM NOISE DOSE

Measurements of 'background noise level' are routinely carried out for wind farm noise assessment in the UK, Australia and New Zealand where appropriate noise limits are usually derived from such measurements by assessing the typical background noise for different wind speed conditions and adding an allowed exceedance at each wind speed[6]. This is, in effect, a legacy from industrial noise assessment standards which commonly allow a similar 5 dB exceedance. It is relatively unusual, certainly in wind farm noise assessment, for the existing noise to be quantified in terms of the L_{Aeq} or L_{den} measurement index where a measure of background noise such as L_{A90} or L_{A95} is normally used. It is, however, possible for existing noise level to be specified in terms of the L_{Aeq} index as it varies with wind speed based on best fit curves to plots of measured L_{Aeq} values against hub height wind speed. The best fit curves effectively represent an average L_{Aeq} value, as it varies with wind speed for the corresponding times of day. These can be used to define a reasonable approximation to the corresponding hourly L_{Aeq}, in the absence of noise from the proposed wind farm, for each wind speed value as used for the calculation of the wind farm noise dose. If sufficient data is available it may also be possible to subdivide this data into various wind direction sectors. This can then be used to predict a reasonable approximation to the whole year L_{den} in the absence of the proposed wind farm, with the appropriate corrections to noise levels occurring during the evening and night-time periods. It should be noted that this methodology does not allow the L_{Aeq}, as it varies through the day, evening and night periods to be taken into account. For situations where there is no variation in L_{Aeq} with wind speed, such as is likely to occur in more populated area where it would be expected to be more affected by non wind related sources, this could provide a variation to the approach proposed.

CALCULATED CHANGE IN NOISE DOSE

The above data can be used to provide the change in yearly L_{den} noise dose by comparing the dB addition of the post wind farm noise dose (ie. wind farm noise dose plus pre-windfarm noise dose) to the pre-wind farm noise dose. It could reasonably be expected that this would show a higher noise dose for properties subject to downwind propagation for more commonly occurring wind directions and higher wind speeds than those in other sectors, and a higher degree of noise dose change where a property is exposed to lower levels of existing noise, especially at night where higher levels of wind farm noise relative to background noise would be accentuated by the application of the 10 dB correction applicable to noise levels generated at night.

---

[2] 10 metre height wind speed converted from hub height assuming reference ground roughness conditions of z=0.05m.

[3] Where noise data is specified in terms of hub height wind speed this conversion is not required.

[4] ISO9613-2, for instance, only predicts short term noise levels for 'moderate downwind' conditions.

[5] ie. located to the north-east for a prevailing south-westerly wind direction.

[6] In the UK, for instance, noise limits are commonly set at 5 dB above this 'prevailing' background noise at each wind speed except at very low background noise levels where a fixed limit applies.

CONCLUSIONS

A method is proposed for strategic assessment of wind farm noise which takes into account the variation in wind speed and wind direction over a typical year of operation and the increased annoyance which may result from noise during the evening period and during the night. This is compared with noise from existing sources, quantified in a similar way. In this way an assessment of the existing noise dose, the proposed additional noise dose, and a comparison between the post and pre-development noise dose can be assessed for representative properties around a proposed wind farm scheme to provide a more comprehensive assessment than is provided by more traditional comparisons of worst case propagation conditions with absolute or relative noise limits.

REFERENCES

[1] *The Environmental Noise Directive* (2002/49/EC), European Commission, 2002

[2] M. Dijkstra and T. Kerkers, "Continuous noise monitoring of wind turbines", *Proceedings of the 4th International Conference on Wind Turbine Noise*, Rome, Italy, 11-14 April 2011

[3] International Organization for Standardization ISO 9613-2: 1996, *Acoustics – Attenuation of sound during propagation outdoors – Part 2: General method of calculation*

[4] *Measurement and evaluation of environmental noise from wind energy conversion systems in Alameda and Riverside counties*, Research Report WR 88-19, Wyle Laboratories, October 1988

The 2012 conference of the Australian Acoustical Society will be held in Fremantle, Western Australia, from 21 to 23 November 2012. Acoustics 2012 Fremantle will be another great opportunity for Australian and International guests to get together to discuss all aspects of acoustics. Below are some updates on key presentations, workshops and dates.

Plenary and keynote presentations

The conference will include many interesting plenary and keynote presentations. Guest speakers include:

- Dr Irene van Kamp of the National Institute of Public Health and the Environment (Netherlands).
- Dr Ross Chapman of the School of Earth and Ocean Sciences, University of Victoria, Canada.

Pre-conference workshops

A variety of specialist workshops/short courses will take place prior to the event, including:

- *Active Noise Control*, University of Western Australia
- *Underwater Passive Acoustic Monitoring*
- *Advanced Machine Diagnostics and Condition Monitoring*, (2 day course), the course will be given by Em. Prof. Bob Randall from UNSW and will be held at Curtin University.

The key dates for the Acoustics 2012 Fremantle conference are:

Papers		**Registrations**	
Abstract acceptances	28 April	Registration begins	1 July
Full papers due	11 June	Late registration fees apply	1 September
Reviews released	27 August	Conference begins	21 November
Final papers due	19 September		

Please refer to the conference website for all the up-to-date information regarding the conference:
http://www.acoustics.asn.au/joomla/acoustics-2012.html

If the conference website does not answer any of your queries,
please contact the WA Division AAS secretary via e-mail (wa-secretary@acoustics.asn.au)

Technical Note

Note: Technical notes are aimed at promoting discussion. The views expressed are not necessarily those of the editors or the Australian Acoustical Society. Contributions are not formally peer-reviewed.

FINDING THE CHARACTER OF WIND TURBINE SOUND

Bob Thorne
Principal, Noise Measurement Services Pty Ltd, Brisbane QLD 4051

INTRODUCTION

Wind turbine sound has a unique nature that is variable over time and is highly dependent on wind speed and directions, as well as locale. Objective measurement of such sound is not easy yet can be achieved using suitable measurement methods. A tried and consistent methodology using sonograms is presented.

Considerable discussion has been raised over the last few years concerning the character of wind farm noise. Some standards refer to “special audible characteristics”. Others standards and guidelines refer to amplitude modulation, tonality, impulsiveness and so on. Much of the debate has centered around the meaning of the various terms. A simple assessment can be made by spending a few hours actually listening to single and multiple turbines. The objective characterisation of turbines, individually and collectively, is complex. This article presents a tried and consistent methodology using sonograms.

AUDIBLE SOUND CHARACTER

The author has studied the sound fields and investigated the sound character and perception of turbines at different wind farms in different countries over different weather conditions. At each location the wind farm could be clearly heard at dwellings approximately 2000 metres from the nearest turbines. The sound of turbines can be heard upwind and downwind, as well at an angle to the turbines. The author has somewhat aged hearing and assumes that younger people with better hearing will be able to hear the turbines as well. The sound, with turbines operating, can be described as a steady rumble with a mixture of rumble – thumps. Some turbines had distinctive tonal character. Wind in the trees or vegetation did not mask the sound of the turbines.

Turbine sound character varies regularly both in “loudness” and “tonality”. The general character of a long time period of an hour or so is of a steady rumble. This, however, depends considerably on wind speed and direction. The sound of turbines is also evident and sometimes more pronounced inside a dwelling, windows open. It is concluded that wind turbine sound at residences around 2000 metres or so is perceptible outside or inside a dwelling.

The question then becomes “Can the sound be analysed and assessed in a meaningful way?” This is an important question as sound character of the wind farm is clearly different within locales.

Figure 1 represents a time-slice for a survey (2009 and 2012) when the sound of the turbines was audible inside a bedroom. The observation from figure 1 is that the overall sound character shows substantial variation between the un-weighted minimum level, LZmin and the maximum levels LZmax in each third octave band. The variation is significant above 20 Hz because this is when the difference in sound levels becomes audible and potentially disturbing to sleep. The levels show the failure of A-weighted statistical levels in presenting the true sound character. Studies from Thorne (2007) and recently in 2012 indicate similar patterns for audible and inaudible sound.

These broad values tell little about the detailed character of the sound. To do this a more refined analysis method is required. The method often used to display sound character, modulation, tonality or tonal complexes is through sonograms[1]. These show the ‘special audible characteristics’ of sound at various frequencies over time. Amplitude and frequency modulation can be identified in the sonograms by distinctive regular patterning at 1 second (or longer or shorter) intervals. Tonality and tonal complexes can also be identified using sonograms. Generally the sonograms are not calibrated against measured sound level but present a comparison between peak and trough (maximum and minimum) levels in a short period of time. These show sound at various frequencies over time as shown in figure 2.

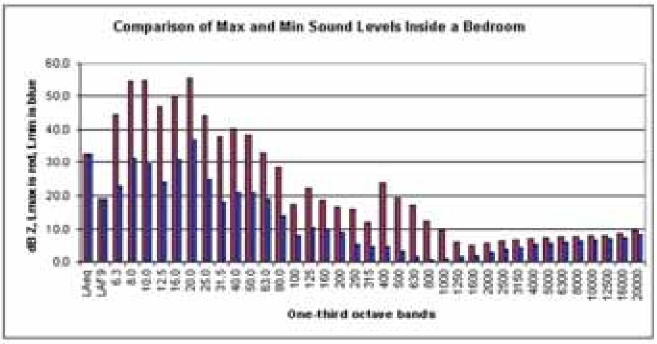


Figure 1. Indoor sound character for the initial survey (LZmax vs LZmin)

A sonogram can be thought of like a sheet of music or an old pianola roll; the left axis is frequency - musical pitch - while the bottom axis is time. The colour indicates the loudness in unweighted dB (SPL) with the colour bar at the right providing a key to the ‘loudness’ in decibels associated with each colour.

---

[1] Various methodologies are available to display sonograms or modulation. The methodology by Dr H. Bakker, Astute Engineering, is described.

The values (-30 to 20, for example) on the right-hand side of the sonogram are decibel levels. Loud notes appear yellow or while; soft notes would appear purple or black. In the following sonograms much of the colour scale has been made black so that peaks stand out better.

Generally the sonograms are not calibrated against measured sound level but present a comparison between peak and trough (maximum and minimum) levels in a short period of time. At the time of recording it is possible to include reference sound levels in order to assess the sonogram values against measured values.

To produce sonograms it is necessary to record the sounds. In figure 2 the audio file which extends to 1 Hz identifies wind and wind farm sounds. The regular bands or modulations at around 1 Hz indicate wind turbine blade pass frequency. Higher frequency content (800-5000 Hz) evident in the third octave band chart is not evident in the sonogram. Low frequency content is evident in both the sonogram and the third octave band chart.

Two sonograms shown; one is for audible frequencies (20 Hz to 1000 Hz), while the other is for low frequencies (0.8 Hz to 20 Hz), referred to as *infrasound*. The use of sonograms can show the presence of modulation. The rumble/thump of wind turbine modulation has been demonstrated to exist in three, geographically separate wind farms.

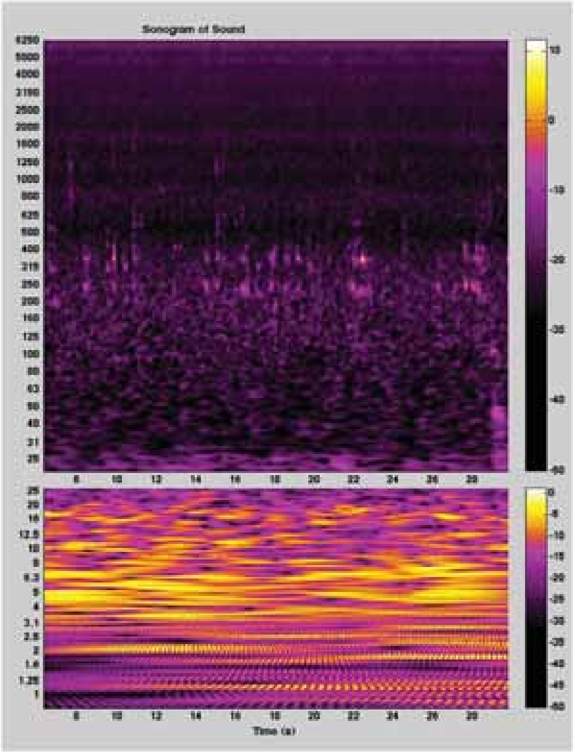


Figure 2. Wind farm sonogram inside a dwelling

SOUND PERCEPTION

If the character of the sound is foreign to the existing environment then it has less chance of being accepted. To an individual, the time of the day the sound is heard is important with unusual sounds in the early morning being less acceptable than if they are heard during the day. If a sound affects the personal space of a person while at home, inside or outside, that sound has a high degree of probability as being a disturbance. Additionally, if the sound has information content that the person does not want to hear that sound is perceived negatively. Personal perception therefore combines a variety of attributes that cannot be measured by instrumentation.

Clearly audible sound emissions from turbines will not occur all the time, of course, as turbines are often stopped and operate at different times and under different prevailing wind directions and wind speeds. The evidence, however, is that once a person has become sensitised to the activity of the turbines this sensitivity is not habituated.

The perception of audible character by individuals is 'active all the time'. This means that monitoring, measurement and assessment needs to be in real-time on a continuous '24/7' basis if identification and compliance with 'special audible characteristics' is required.

DEFINITIONS

Modulation (1)	'Amplitude modulation' is a spectral modification process that produces discrete upper and lower sidebands determined by the modulation frequency and the modulation depth m.
Modulation (2)	'Amplitude modulation depth' is a measure of the spectral energy spread of an amplitude modulated signal.
Modulation (3)	Modulation, by amplitude, is defined as a peak to trough variation that exceeds 3dB on a regular basis (3dB is taken as negligible, 6dB as unreasonable and 9dB taken as excessive); by frequency, modulation is defined as a variation that exceeds one semi-tone on a regular basis.
Special audible characteristics	Sound that has distinct features such as impulsiveness, modulation or tonality that makes the sound stand out from other sounds in the same soundscape
Tonal	Evoking pitch or tone sensation(s)
Tonality	A sound sensation having unambiguous pitch; other attributes include loudness or salience, timbre, and apparent duration *Cf. tone sensation*
Tonalness	The extent to which a sound evokes (pure or complex) pitch or audible tone sensations
Tone (1)	Sound which evokes a tone sensation; approximately or exactly periodic sound in the audible range of frequencies; sound whose various possible pitches belong mostly to a single chrom
Tone (2)	A sound sensation having pitch
Tone sensation	Auditory sensation having one, unambiguous pitch; other attributes include loudness or salience, timbre, and apparent duration

REFERENCES

[1] R. Thorne, *Assessing intrusive noise and low amplitude sound*, PhD Thesis, Massey University, New Zealand, 2007

Technical Note

Note: Technical notes are aimed at promoting discussion. The views expressed are not necessarily those of the editors or the Australian Acoustical Society. Contributions are not formally peer-reviewed.

LOW FREQUENCY, INFRASOUND AND AMPLITUDE MODULATION NOISE FROM WIND FARMS – SOME RECENT FINDINGS

Colin Tickell
Senior Consultant – Environment and Acoustics, Hatch Associates, Neutral Bay, Australia

This article reviews some recent papers describing low-frequency, infrasound and amplitude-modulation noise from wind turbines, and whether low-frequency and infrasound from wind farms is a real, measurable issue. Some of the information was included in a literature review for the MOE Ontario. Some new information on low-frequency sound and amplitude-modulation at different angular locations from wind turbines presented at Inter-Noise 2011 in Osaka are also included in this review. One proposal for low frequency noise objectives is also discussed.

INTRODUCTION

Recently, amplitude modulation, low frequency and infrasound noise from wind farms has been the subject of complaints, many different media reports and a Senate Inquiry in Australia. The Ministry of Environment of Ontario province in Canada, amongst many other regulators, has been considering a new policy on low-frequency infrasound noise from wind farms and commissioned a literature review into it in 2011. That report collated and considered many papers dealing with the audibility of low-frequency sound and noise from wind farms. Some of the papers presented at Inter-Noise 2011 in Osaka included measurements or predictions of sound levels and frequency spectra from wind turbines, including the low-frequency range and amplitude-modulation. These papers help provide some further information to acousticians dealing with wind farm noise.

Broner [1] suggested an environmental noise quality criterion for low-frequency sound, based on the C-weighted sound level. Comment is provided using comparisons of low-frequency and infrasound hearing thresholds with measured wind turbine sound frequency spectra, and amplitude-modulation sound levels from wind turbines.

LOW FREQUENCY NOISE FROM WIND TURBINES

There have been regular discussions about the existence and potential effects of low frequency and infrasound noise from wind turbines for at least the past 5 years. Studies have been undertaken by or for governments and their agencies, including the NHMRC in Australia [2] and the Ministry of Environment of Ontario in Canada [3], as well as other wind industry groups. These studies have all noted that there is no evidence to support the contentions that low frequency and infrasound noise from wind farms are injurious to health.

It is considered relevant (and hopefully helpful) to acousticians and others working in this area to be aware of studies that have compared the frequency spectrum sound levels of modern wind turbines with the hearing thresholds of otologically normal people. References in the Ontario report have been used to provide eight different low-frequency and infrasound hearing threshold levels reported between 1974 and 2008 [4-8].

One of the papers presented at Inter-Noise 2011 provided sound levels at the reference distance (hub-height + rotor radius) for five different modern wind turbines in Japan, ranging in electrical power capability from 285kW to 2MW [9]. Figure 1 compares the eight different low-frequency and infrasound hearing thresholds from the four references studies, with the measured sound levels of 5 different single wind turbine generators in Japan, over the range 1 to 50 Hz at the distance given.

The figure shows that for the frequency range below 25 Hz, which includes the infrasonic range, the sound levels from the 5 wind turbines is less than the threshold of hearing – for frequencies less than 20 Hz, this difference is at least 10 dB and increases with reducing frequency. The measurement distances range from 44 to 77 m.

Several references listed in the Ontario report describe other natural and man-made sources of low-frequency and infrasound noise and their comparison to wind turbine noise. Man-made sources include pumps, fans, boilers, ventilation plant, road, rail, sea and air transport (and travelling in them) and cooling towers. Natural sources include wind in vegetation, surf breaking and waterfalls. One study reported had sound levels inside passenger road vehicles of 90 to 110 dB at 10 Hz, (compared to the maximum 75 dB for the wind turbines shown in Figure 1).

A report by DELTA [10] compared graphically the sound levels of sources of low-frequency sounds. This showed that many of these sources had much higher levels of low frequency sound than a 3.6MW wind turbine at measured at a distance of 250m.

These reports also noted that there is no evidence that exposure to sound below the threshold of hearing can cause any damage to hearing or other physiological effects. Other naturally occurring and transport noise sources produce much higher levels of low-frequency and infrasonic sound, also without evidence of such effects.

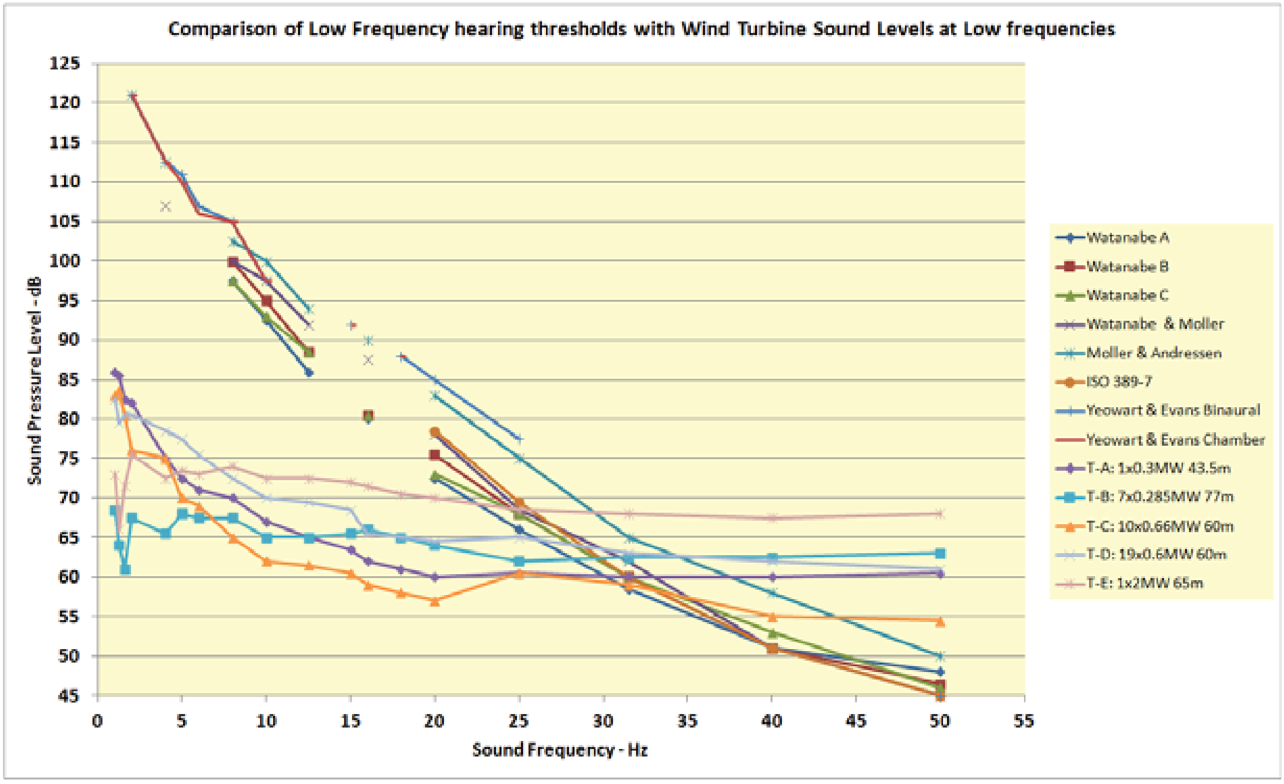


Figure 1. Hearing thresholds and spectrum sound levels from 5 wind farms in the low and infrasonic region

MODULATION SOUND LEVELS FROM WIND TURBINES

Other recent work presented at Inter-Noise 2011 has identified that the amplitude-modulation of sound from the blade pass – the modulation depth (the difference in sound level between the minimum sound level) is highest at the +210° to 240° downstream measurement locations, and can be discernible at relatively long distances from the turbine [9, 11]. This indicates that predictions of sound levels from wind farms could include modulation depth and consider these in the assessment of potential impacts at residential receiver locations. NZS 6808:2010 [12] requires this to be done as part of the assessment of Special Audible Characteristics (SACs), and this method is required for assessment of wind farms in Victoria. Assessment of SACs is also included in the Draft NSW Planning Guidelines: Wind farms [13] (along with tonality and low frequency noise), and a limit of 4 dB modulation depth is proposed.

Miyazaki et al. [9] measured sound levels at 12 equal angled reference distance locations around five different wind turbines to provide measurements for all wind directions. The directionality graph is shown in Figure 2 and shows the higher level locations are away from the centreline and are explained by the directivity of the moving source – this and other papers have shown that the rotor trailing edge is a source of high noise emission, directed forwards from the rotor in the direction of travel in the rotor plane. The reasons for different directivity curves between different types of turbines is not discussed, but could be related to blade profile or wind conditions.

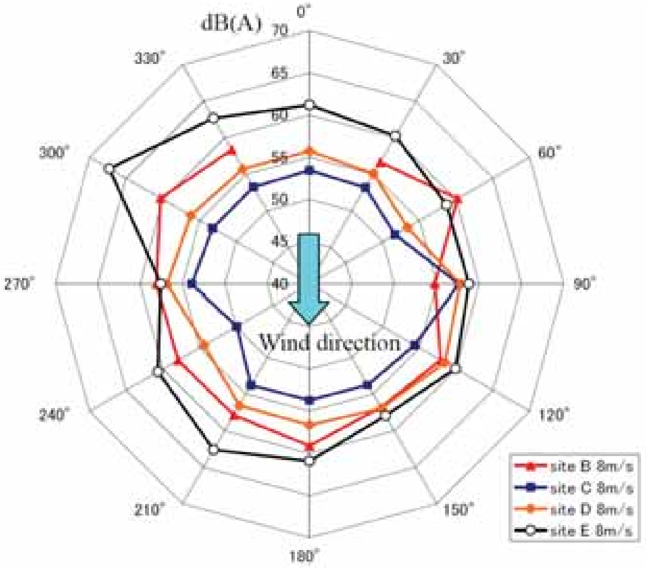


Figure 2. Sound levels at reference distances from 5 wind turbines [9]. Note some locations were affected by background noise

Lee et al. [11] predicted the acoustic pressure for a 2.5 MW wind turbine with 82m hub height and 93m rotor diameter and 15.4 rpm. Sound levels were predicted at the reference positions used in IEC 61400-11:1998 [14], and then at distances out to 1000m. While the sound levels at 1000m were higher along the direct 0^{o} axis than off the axis (37 dBA compared to 30 dBA), and amplitude modulation was not identified at the 0^{o} position, for the 60^{o} off axis position, amplitude modulation was identified. Their study also identified that while the overall sound pressure level decreased with distance, the modulation depth was consistent with distance. This is shown in Figure 3.

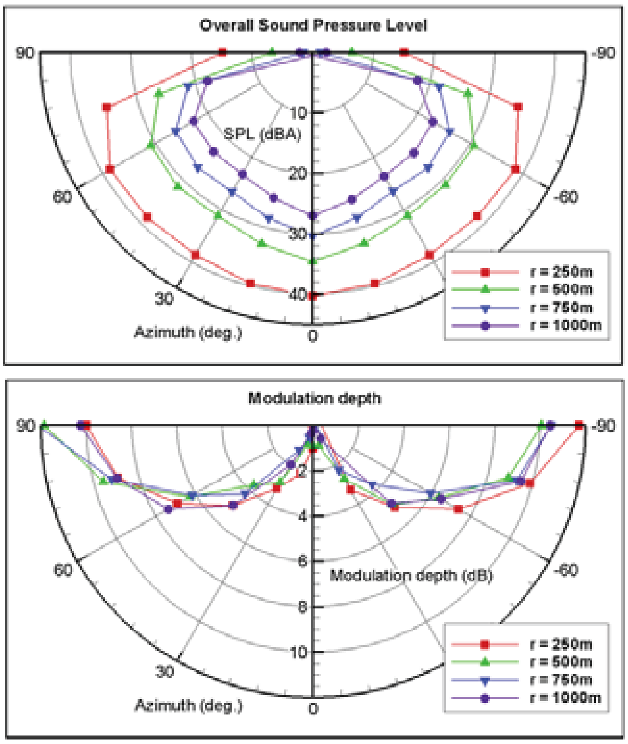


Figure 3. Results of predicted sound levels at increasing distances from a 2.5MW wind turbine, for overall sound levels and modulation depth [11]

Taking these two items together, it may be relevant to consider amplitude modulation as an addition to the predicted overall sound level at receiver locations for comparison with environmental noise quality objectives. This approach would assist in reducing the potential for annoyance that could occur from wind turbines.

LOW-FREQUENCY AND INFRASOUND ENVIRONMENTAL NOISE CRITERIA

Broner [1] discussed different approaches to regulating low-frequency and infrasound noise from industrial sources, including wind turbines. After a detailed review, he recommended a desirable objective external sound level for residential receivers of 60 dBC for night-time. The author's experience with other industrial sources of low-frequency noise indicates that this is a reasonable objective to minimise the potential for noise annoyance.

A benefit of this objective is that it would allow use of most currently used and available Class 1 or Type 1 sound level meters. Other reports have suggested use of the ISO G-weighting for measurement of infrasound. This has the difficulty of having to either find a meter with such a weighting built in, or making one-third octave band measurements in the frequency range 10 to 25 Hz and then converting it. In any case, some development of appropriate methods to measure sound accurately in the low-frequency and infrasound range will be necessary. Such things could be included in revisions to either Australian Standards AS 1055 Acoustics - Description and Measurement of environmental noise, or AS 4959 Acoustics – measurement, prediction and assessment of noise from wind turbine generators.

REFERENCES

[1] N. Broner, "A simple outdoor criterion for assessment of low frequency noise emission" *Acoustics Australia* **39**(1), 7-14 (2011)

[2] NHMRC, *Wind Turbines and Health: A Rapid Review of the Evidence*, National Health and Medical Research Council, Australian Government, July 2010, available online at http://www.nhmrc.gov.au/_files_nhmrc/publications/attachments/new0048_evidence_review_wind_turbines_and_health.pdf

[3] Howe Gastmeier Chapnik Limited "Low frequency noise and infrasound associated with wind turbine generator systems – A literature review", *Ontario Ministry of the Environment* RFP No. OSS-078696, Canada, December 2010, available online at http://www.ene.gov.on.ca/stdprodconsume/groups/lr/@ene/@resources/documents/resource/stdprod_092086.pdf

[4] T. Watanabe, "Simultaneous masking and temporal masking of low frequency sound", *Proceedings of the 13th International Conference on Low frequency Noise and Vibration and its Control*, Tokyo, Japan, 21-23 October 2008

[5] T. Watanabe and H. Møller, "Low frequency hearing thresholds in pressure field and in free-field", *Journal of Low Frequency Noise and Vibration* **9**(3), 106-115 (1990)

[6] H. Møller and J. Andresen, "Loudness of pure tones at low and infrasonic frequencies", *Journal of Low Frequency Noise and Vibration* **3**(2), 78-87 (1984)

[7] International Organization for Standardization ISO 389-7:2005 *Acoustics - Reference zero for the calibration of audiometric equipment - Part 7: Reference threshold of hearing under free-field and diffuse field listening conditions*

[8] N.S. Yeowart and M.J. Evans, "Thresholds of audibility for very low-frequency pure tones", *Journal of the Acoustical Society of America* **55**(4), 814-818 (1974)

[9] T. Miyazaki, K. Kono, Y. Inoue, T. Nakao, H. Kato, H. Matsuzaki, H. Sakino and H. Shiraishi, "Noise characteristics generated form wind turbine generators" *Proceedings of Inter-Noise 2011*, Osaka, Japan, 4-7 September 2011

[10] T.H. Pedersen, *Low Frequency Noise from Large Wind Turbines - A procedure for evaluation of the audibility of low frequency sound and a literature study*, Danish Electronics Light and Acoustics (DELTA) Report AV 1098/08, April 2008

[11] S. Lee, S. Lee and S. Lee, "Numerical prediction of acoustic pressure radiated from large wind turbines", *Proceedings of Inter-Noise 2011*, Osaka Japan, 4-7 September 2011

[12] New Zealand Standard NZS 6808:2010 *Acoustics – Wind farm noise*

[13] *Draft NSW Planning Guidelines: Wind Farms*, NSW Department of Planning and Infrastructure, December 2011

[14] International Electrotechnical Commission IEC 61400-11:1998, *Wind turbine generator systems – Part 11: Acoustic noise measurement techniques*

Technical Note

Note: Technical notes are aimed at promoting discussion. The views expressed are not necessarily those of the editors or the Australian Acoustical Society. Contributions are not formally peer-reviewed.

WIND TURBINE SYNDROME – AN ALTERNATIVE VIEW

Dick Bowdler

The Haven, Low Causeway, Culross, Fife, UK, dick@dickbowdler.co.uk

There is a view in many countries that there is something "different" in wind turbine noise, usually considered to be infrasound, that makes people ill even at distances up to 10km. This paper presents the view that there is a simpler explanation and one which many acousticians know about from personal experience. Apart from the level and the character of turbine noise, non-acoustic factors contribute to the annoyance people feel. That annoyance brings stress which produces the symptoms described. The non-acoustic factors are largely attributable to the manner in which wind farms are developed, in particular, governments' dismissal of a few people with a real problem as antisocial.

INTRODUCTION

Pedersen et al. [1] established that wind turbine noise annoys more than most other noise with similar loudness. Some people have put that down to some feature of turbine noise that we do not understand. In particular there is a body of opinion centred mainly round the work of Alves-Pereira and Castello-Branco [2], Harry [3], Pierpont [4] and the Waubra Foundation in Australia [5] that there is some special factor in wind turbine noise that directly causes illness called, for convenience using Pierpont's name, Wind Turbine Syndrome. The most commonly stated culprit is infrasound. A recent paper by Ambrose and Rand [6] suggests that the authors have proved an infrasound link to health effects in part because they were themselves so affected. There is a wide range of symptoms that are claimed to be the effect of turbine noise including sleep disturbance and attendant day time tiredness, headache, tinnitus, memory loss, depression, migraine, dizziness, tachycardia, irritability, loss of concentration, hyperacusis and anxiety. Ambrose and Rand [6] themselves relate that they experienced "*unpleasant symptoms of motion sickness, including ear pressure, headache, nausea, dizziness, vertigo, especially when moving about." They go on to say "We had a sense that the room was moving or slightly displaced from where it appeared. We experienced a loss of appetite, cloudy thinking, fatigue, some anxiety and an inexplicable desire to get outside; similar to motion sickness we have experienced on a boat or plane*." Headlines such as "The Wind Turbine Syndrome has become pandemic [7]" are becoming more common.

I do not think that the proponents of Wind Turbine Syndrome in its various forms have proved their case but this paper does not discuss that. It offers an alternative explanation to the undoubted symptoms people display which are similar to the symptoms that experienced acoustic consultants have observed with many types of noise – that the level and character of the noise are only part of the explanation. The strength of reaction to noise is brought about by non-acoustic factors moderating the perception of noise. One of the conclusions reached by Wolsink et al. [8] in their study of annoyance from wind turbines was that *the amount of annoyance was hardly related to the objective sound level*.

There is no doubt in my mind, from some of the work above and from the author's own experience that there are people who live near wind farms who have the symptoms that have been described above. I also have no doubt (because I have met some of them) that there are some people blighted directly by noise from poorly sited wind farms. But the number of people it is suggested that Wind Turbine Syndrome effects, at distances of up to 10km, cannot be explained simply by the noise level. My view is that there are three factors. First the measured noise level and second the character of the noise – in the case of wind farms mostly the presence of amplitude modulation but sometimes tones. Finally people's perception of the whole development and its implementation and of governments' stated attitude to wind turbine noise. This paper considers primarily the UK approach to wind farm development but many of the comments apply to a greater or lesser extent to other countries.

NOISE LEVEL

The first factor in the effect of wind turbine noise on people is the sound level and, in particular, the sound level relative to the background noise before the development. Some wind farms are simply too close to housing. Although Pierpont [4] does not quote noise levels to which her subjects were exposed, I have no doubt that most of the subjects in her investigation had a genuine grievance related simply to the sound level of the noise. Half were less than 750m away from a turbine and the nearest 305m. In the same way I do not doubt that most of those people who were the subject of Harry's report [3], 70% of whom were less than 750m away, had a genuine grievance related directly to the sound levelof the noise even though again, no noise levels were quoted. Most of these are in rural areas and turbine noise would be up to 40 or even 45dBA compared with a background noise level of less than 30dBA.

The effect of noise in many of these cases, because they were relatively close to turbines was probably exacerbated by amplitude modulation.

BS 4142 [9] is a British Standard that has been in existence for over 40 years. It is widely used throughout the UK as an assessment tool for planning purposes. Indeed it is so widely used that hardly any local authority in the country does not use it for some types of assessment and most require it for assessments of developments where a new noise is introduced into an area. In Ref. [10], the authors say "*The result of an assessment carried out to BS4142 would normally be relevant to the deliberations of any court considering whether or not a nuisance exists.*" The principle is simply that the projected new noise is compared with the existing background noise. If the difference is around 10dB or more then complaints are likely and if the difference is 5dB then the situation is marginal.

When ETSU-R-97 [11] – the wind turbine noise assessment method used in the UK – was written, the version of British Standard BS 4142 current at the time said that it was not applicable when background noise levels were below 30dBA. The ETSU-R-97 Working Group interpreted this as meaning that there was some lower limit (30dBA) below which background noise did not matter. In other words they assumed that, in very low background noise levels, people are not sensitive to the margin of the intruding noise above the background noise. It is just as likely, perhaps more so, that the reverse is true. People who live in very quiet rural areas (where wind turbines are often erected) may have a heightened sense of noise. They value the quiet – that is why they live there. It is quite possible to have an external ambient noise level of 25dBA and an external level of 30dBA from turbines, well below the accepted standard, that would easily be heard and might be found by some people in a tranquil area to be annoying. Most other countries adopt standards that are either a fixed limit or contain a fixed limit. It may be necessary, for the development of renewable energy, that such levels of wind turbine noise should be adopted but developers and government should make clear why they are necessary and should not be surprised if residents complain.

AMPLITUDE MODULATION

The second factor influencing reaction to turbine noise is the character of the noise. The dominant characteristic of turbine noise that cannot always be mitigated completely is amplitude modulation. All modern large turbines exhibit amplitude modulation and this has been explained by Oerlemans and Schepers [12] when the observer is close to the turbines and at greater distances in specific directions as due merely to the directivity and Doppler amplification of the noise. Upwind or downwind of the turbine the amplitude modulation reduces quite rapidly with distance but Oerlemans and Schepers has shown that it can project over longer distances in the cross wind directions. This is what is often called "swish".

However, there appears to be another type of amplitude modulation. It is sometimes called "thump" on the basis that some people including Salford University [13] and van den Berg [14] have suggested that it has a faster rise time than the swish described by Oerlemans and Schepers [12]. It seems possible now that this fast rise time is not a feature but that the fundamental difference is that there is a low to mid frequency component (125 to 250Hz) to the amplitude modulation in thump which does not occur in swish [15]. It seems, anecdotally at least, to be penetrating and relentless. The University of Salford Report [13] found that, of the 27 wind farms in the UK about which there had been complaints, four were due to amplitude modulation. In fact the headline figure of four was the result of asking environmental health officers whether there was "enhanced amplitude modulation" not whether there was amplitude modulation at all. Table 2 of the report shows that at least half of the sites where there were complaints had noise that was described with such words as thumping, swishing and so on and so was clearly modulated.

If amplitude modulation is present in the noise at a receiver, the noise is perceived as being more annoying than if the noise has no modulation. It can become impossible ignore the noise which might otherwise be acceptable.

PERCEPTION AND FAIRNESS

The third factor that is critical in understanding the reaction of people to wind farm noise is perception and, in particular perception of fairness. It is the contention of the author that it is this issue of fairness that has become the primary problem with wind farm noise. This might not have happened if developers and governments had paid more attention to the level and to the character of the noise when it was clearly unacceptable at some sites in the early stages of wind farm development.

A number of large surveys of noise annoyance from aircraft were published in the late 1960s and in the 1970s when there was a big expansion of jet aircraft movements. An American study [16] concluded that people who were highly annoyed by aircraft noise had a high fear of aircraft crashing, high susceptibility to noise, felt that there was some misconduct on the part of the airport or airline staff and did not rate the airport as important as most people. The noise level to which they were exposed did not correlate highly with their annoyance. Fields [17] looked at 282 social surveys of environmental noise. He says *Over 50 percent of the surveys found that, after controlling for noise level, noise annoyance increases with a fear of danger from the noise source, a sensitivity towards noise generally, the belief that the authorities can control the noise, the awareness of non-noise impacts of the source, and the belief that the noise source is not important*. In an international study of wind farm noise at 16 locations in three countries in 1993 [8], when not many people actually lived near turbines, it was found that the relationship between noise annoyance and sound level is not strong. Flindell and Stallen [18] state *It is almost universally recognised that noise exposure level never accounts for more than a small proportion of the variance of any outcome variable considered*.

Maris [19] wrote that *Based on a meta-analysis of several survey studies, it has been estimated that the effects of acoustical (e.g., the loudness, pitch, predictability) and non-acoustical variables (e.g., perceived control, personality traits like noise sensitivity, and attitudes towards the sound and its source) each account for about one third of the variance in annoyance scores (e.g., Job, 1988; Fields, 1993; Guski, 1999).*

The final 33% of the variance is considered error variance. She carried out research to test this hypothesis which identifies the issue of fairness. Participants are told that they are engaged in a study on effects of sound on people's performance during exams. As part of the experiment, they will take an exam while being exposed to sound. Half the participants are taken through a "fair" procedure in which three types of aircraft noise are described and asked to select the one which they think will cause them least annoyance. The other half are given a "neutral" procedure where they are not asked to choose. In the second test half the participants are given an "unfair" test. They are informed that they will be listening to a 15-min sample of their choice: nature sounds, a radio programme, or aircraft sound. They make their choice of sounds (not usually aircraft) and the experimenter then selects aircraft noise irrespective of the subject's choice and leaves the test booth saying "I have set the computer to aircraft sound." Maris established that when the exposer was unfair, annoyance was higher. In her conclusion she says *A person's evaluation of the sound is affected by the social process between themselve(s) and the operator(s) of the source. The results from the laboratory experiment confirm that the unfairness of the sound management procedure influences the evaluation of the sound. Relative to a neutral sound management procedure, an unfair procedure is found to yield collective excess annoyance*.

So it has been suggested for at least two decades that noise level is only one factor in determining people's reaction to noise.

PERCEIVED UNFAIRNESS IN TURBINE DEVELOPMENT

The stated government policy in the UK and in many other countries is that renewable energy projects should be driven by the private sector and that any environmental or other impacts in applications will be controlled by the planning system. This is a part of the democratic process of the country – the developer on the one side and the planning process representing ordinary people. If there are no objections to a proposal going through the planning system then it will be approved. So objectors to wind farms are doing more than exercising their right, they are exercising their obligation to take part in the democratic process. Only by people objecting can there be any chance of testing whether or not the application meets all the reasonable standards for developments – imposed, after all, by the Government in the first place. Otherwise any development would go ahead however damaging. The author believes that Government and developers in the UK have forgotten this. Ed Miliband, now leader of the opposition in the UK but then minister in charge of dealing with climate change, said in 2009 "Opposition to wind farms should become as socially unacceptable as failing to wear a seatbelt" [20]. In November 2010, RenewableUK – the trade and professional body for the UK wind and marine renewables industries - said that "England stands to lose over £1.3bn in investment that will directly create jobs and opportunities for local companies, funds for community activities and increased business rates for local authorities because of the actions of anti-windfarm campaigners" [21]. Let us look at these two statements. In the first one we have a government minister saying that people who exercise their democratic rights should be made social outcasts. In the second, we have the developers association suggesting that if developers did not have to go through the democratic process they could create more jobs. The author contends that it is these sorts of comments that build up resentment in people who are near wind farms or potential wind farms and the key attitude of authorities that makes people perceive that the system is unfair.

The author observes that people are now so suspicious of developers and government that it seems that even the most benign scheme faces opposition. Some developers – even the most unexpected – insist on confrontation. In the UK the raw noise and wind data is almost always made available by developers to Councils and third parties on request for checking. Sometimes it is put on the planning portal for anyone to download. It is one of the few moves towards transparency that has taken place in the last 5 years. Almost the only exception is St Andrews University, who, when requested for the raw data treated it as a Freedom of Information request and refused it. When it was appealed they turned it down again [22]. It is hardly surprising that people think they have something to hide.

The author observes that the result of all this is that people perceive, rightly or wrongly, that

- their lives will be blighted by these developments,
- they will gain no benefit,
- they pay subsidies in the form of Tax,
- they pay more for electricity,
- developers make all the money.

Wasserman and Parnell [23] set out the elements of good noise communication. The list is comprehensive but one element is *Noise communication is successful only to the extent that those involved are satisfied that they are adequately informed within the limits of available knowledge through a transparent process*. They further explain that there is often a lack understanding amongst noise consultants of public perception of noise and the frequent view of consultants that *meeting criteria is an acceptable outcome and will not result in an unacceptable impact* merely perpetuates problems. This seems to be particularly true with wind farm noise where, in the UK, even though ETSU-R-97 does not claim to be a measure of significance, compliance with it is still sometimes translated in an environmental statement as "insignificant impact" even when the turbine noise level might be 45dBA and the background noise 30dBA. Wasserman and Parnell go on to say that no matter how serious a noise is and no matter how much technical detail is used to explain it, the degree of "outrage" (whether people feel that the procedure is fair in effect) is likely to determine much of the public's response. Schomer [24] takes the view that *adjustment for "public relations,". . . . can range from a 5dB penalty to a 5dB bonus depending on the quality of the relations between the noisemaker and the community*. So community engagement from an early stage is extremely important.

STRESS

Pedersen [25] says in a summary of the three surveys quoted above that *Stress was in these studies not directly* *associated with A-weighted sound pressure levels, but with noise annoyance. There was a remarkable consistency among the studies for the relationship between feeling tense or stressed and annoyance. This should however not be taken as evidence for a causal relationship from wind turbine noise to stress, mediated by annoyance. The finding could be explained in the light of Lazarus and Folkman's cognitive stress theory [1984] where an individual appraises an environmental stressor, such as noise, as beneficial or not, and act on behalf of this. An individual already in a strenuous situation possibly appraises the noise as an additional threat to psycho-physiological restoration. As in the present case wind turbine noise can not be controlled by the individual, no action can be taken and the response is manifested as annoyance. Being interrupted in the sleep could possibly further increase the feeling of wind turbine noise as a threat*.

What this suggests is that when people near wind farms become annoyed and believe it is because of the noise level it may instead be because of non-acoustic moderating factors. This annoyance then leads to stress. The symptoms of stress are, like the symptoms of Wind Turbine Syndrome, numerous. They are also very similar and, particularly, include headache, dizziness, irritability, loss of concentration, and anxiety [26], to which we can add sleep disturbance and consequent day time tiredness. These stress symptoms are ones that acoustic consultants have observed in people strongly affected by intruding noise of all types and particularly where bad feeling has built up between the resident and the noise maker.

The evidence suggests that illness has not been caused by anything peculiar to wind turbine noise or anything mysterious that we cannot hear or we cannot measure. It has been caused in many cases because it is too loud and has a character that is objectionable. But increasingly, in many countries, such illness could be due to bad project management by developers brought about by an ill thought out procurement procedure and complete lack of any noise management system promoted by government. In a nutshell, a lack of transparency and involvement.

DOES IT MATTER?

Does bad management matter? Governments could just continue to tough it out in the way many do now and essentially ignore the problem. The author believes that it does matter, for three reasons.

- First because it is a public health problem. Not one of enormous scale but nevertheless one which could be avoided.
- The second reason is that it polarises communities. Rural communities that have lived in reasonable harmony for decades are suddenly divided into two camps. Each camp may be stronger knit than before but they no longer talk to each other and sometimes, at the extreme, vandalise each other's property and threaten young people [27]. Facing the problem of climate change, the challenge of the century that ought to have drawn communities together, has instead polarised them.
- The third is that it stifles development. In countries where the development procedure includes close collaboration with local communities **before** the selection of a site and the design of the wind farm, the record of wind energy development is far better, though this will be due to multiple reasons [28].

Nothing in this paper is intended to suggest that people who are made ill by exposure to wind turbine noise are in any way trying to mislead. People who are exposed to wind farm noise and are ill are genuinely ill. Wolsink et al. [8] concluded that, whilst sound level had hardly any effect on annoyance, *This conclusion must not be misunderstood. The fact that sound level is not predicting annoyance does not mean that people are "not really annoyed" when they are reporting it*. The author's recommendation is that much more attention should be paid to the management of the impact of wind farm noise in the community at the planning stage of projects.

REFERENCES

[1] E. Pedersen, F. van den Berg, R. Bakker and J. Bouma, "Response to noise from modern wind farms in The Netherlands", *Journal of the Acoustical Society of America* **126**(2), 634-643 (2009)

[2] M. Alves-Pereira and N. Castello-Branco, "In-home wind turbine noise is conducive to vibroacoustic disease", *Proceedings of the Second International Meeting on Wind Turbine Noise*, Lyon, France, 20-21 September 2007

[3] A. Harry, *Wind turbines, noise and health*, 2007, Available at http://docs.wind-watch.org/wtnoise_health_2007_a_harry.pdf (Last accessed 13 March 2012)

[4] N. Pierpont, Wind Turbine Syndrome, http://www.windturbinesyndrome.com/wind-turbine-syndrome/ (Last Accessed 13 March 2012)

[5] Waubra Foundation, http://waubrafoundation.com.au/ (Last accessed 13 March 2012)

[6] S.E. Ambrose and R.W. Rand. *The Bruce McPherson infrasound and low frequency noise study: Adverse health effects produced by large industrial wind turbines confirmed, 2011* http://randacoustics.com/wind-turbine-sound/wind-turbines-published-articles/the-bruce-mcpherson-ilfn-study/ (Last accessed 13 March 2012)

[7] Canada Free Press, 11 December 2011

[8] M. Wolsink, M. Sprengers, A. Keuper, T.H. Pedersen and C.A. Westra, "Annoyance from wind turbine noise on sixteen sites in three countries", *Proceedings of the European Community Wind Energy Conference*, Lübeck-Travemünde, Germany 8-12 March 1993, pp. 273-276

[9] British Standard BS 4142:1997, *Method for rating industrial noise affecting mixed residential and industrial areas*

[10] N.D. Porter, I.H. Flindell and B.F. Berry, "Health effect based noise assessment methods: A review and feasibility study", National Physical Laboratory *NPL Report CMAM 16*, 1998 http://www.persona.uk.com/coggeslr/Core_docs/CD-64.pdf

[11] The Working Group on Noise from Wind Turbines, *The assessment and rating of noise from wind farms*, Energy Technology Support Unit, ETSU-R-97, 1996

[12] S. Oerlemans and G. Schepers, "Prediction of wind turbine noise directivity and swish", *Proceedings of the Third International Conference on Wind Turbine Noise*, Aalborg, Denmark, 17-19 June 2009

[13] A. Moorhouse, M. Hayes, S. von Hünerbein, B. Piper and M. Adams, *Research into aerodynamic modulation of wind turbine noise: Final report*, University of Salford, Contract No NANR233, 2007

[14] G.P. van den Berg, "Effects of the wind profile at night on wind turbine sound", *Journal of Sound and Vibration* **277**, 955-970 (2004)

[15] Recording of Swish and Thump available on www.dickbowdler.co.uk (Last accessed 13 March 2012).

[16] *Community reaction to airport noise*, Tracor, Inc., NASA contractor report No. CR-1761, 1971

[17] J.M. Fields, *Effect of personal and situational variables on noise annoyance*, Office of Environment and Agency, Washington DC, 1992 http://www.dtic.mil/dtic/tr/fulltext/u2/a260041.pdf

[18] I.H. Flindell and P.J.M. Stallen, "Non-acoustical factors in environmental noise", *Noise and Health* **1**(3), 11-16, (1999)

[19] E. Maris, *The social side of noise annoyance*, Thesis available at https://openaccess.leidenuniv.nl/bitstream/1887/13361/3/Thesis_Maris_A4.pdf (Last accessed 15 March 2012).

[20] The Guardian, Tuesday 24 March 2009

[21] Anti-windfarm campaigners stand to cost England over £1.3bn at local and regional level, http://www.bwea.com/media/news/articles/pr20101102-2.html (Last accessed 15 March 2012)

[22] Letters from University of St Andrews to Graham Lang (unpublished)

[23] J. Wasserman and J. Parnell, "The art of noise communication", *Proceedings of Acoustics 2008*, Geelong, Australia, 24-26 November 2008

[24] P.D. Schomer, "Criteria for assessment of noise annoyance", *Noise Control Engineering Journal* **53**(4), 132-144 (2005)

[25] E. Pedersen, "Effects of wind turbine noise on humans", *Proceedings of the Third International Meeting on Wind Turbine Noise*, Aalborg, Denmark, 17-19 June 2009

[26] National Health Service in the United Kingdom "Symptoms of stress" http://www.nhs.uk/Conditions/Stress/Pages/Symptoms.aspx (Last accessed 15 March 2012)

[27] Barrhead News, Scotland, 25 January 2012

[28] M. Wolsink and S. Breukers, "Contrasting the core beliefs regarding the effective implementation of wind power. An international study of stakeholder perspectives", *Journal of Environmental Planning and Management* **53**(5), 535-558 (2010)

Technical Note

A REVIEW OF THE DRAFT NSW PLANNING GUIDELINES: WIND FARMS

Justin Adcock, Christophe Delaire and Dan Griffin
Marshall Day Acoustics, Collingwood, VIC 3066

The recently published NSW Planning Guidelines - Wind Farms (the draft Guideline) presents a planning and assessment framework for a range of issues including recommendations for the assessment of noise impacts. These recommendations build upon existing assessment methods used throughout Australia, and helpfully include prescriptive guidance for a number of issues that are not well defined in existing guidance documents. Conversely, the draft Guideline introduces significant new requirements which may add a high level of complexity to the planning process. This technical note presents a discussion of some of the important features of the noise assessment recommendations proposed in the draft Guideline, including proposed noise criteria, measurement techniques, prediction methods and assessment of specific noise characteristics.

INTRODUCTION

Noise assessment criteria for wind farms play a vital role in balancing the protection of amenity for neighbouring communities and supporting a planning framework which enables the development of commercial scale renewable energy projects. Importantly, unlike many other types of noise sources, wind farm noise criteria can have a direct impact on the viability and productivity of proposed wind energy developments. Seemingly small changes in noise criteria or assessment methods can impact significantly on the potential renewable energy yield of a site, despite equating to subjectively minimal changes in wind turbine noise levels at receptor locations.

Selecting the right balance between different wind farm noise policies should therefore consider the broader renewable development implications. For example, could a proposed noise policy create an inadvertent incentive for a smaller number of larger projects, or conversely, a larger number of smaller projects?

The *NSW Planning Guidelines - Wind Farms* (the draft Guideline) [1] were released by the Department of Planning and Infrastructure as a public consultation draft in December 2011. The stated purpose of the draft Guideline is to:

- *provide a clear and consistent regulatory framework for the assessment and determination of wind farm proposals across the state*
- *outline clear processes for community consultation for wind farm developments*
- *provide guidance on how to measure and assess potential environmental noise impacts from wind farms*

The draft Guideline presents a planning and assessment framework for a range of issues including recommendations for the assessment of environmental noise impacts. These recommendations build upon existing assessment methods used throughout Australia, and helpfully add prescriptive guidance for a number of issues that are not well defined in existing guidance documents. Conversely, the draft Guideline introduces significant new requirements including those relating to separating distances and low frequency noise which may add a high level of complexity to the planning process.

This technical note presents a discussion of some of the important features of the noise assessment recommendations proposed in the draft Guideline, having regard to their stated objectives. For ease of reference, the headings in this paper are titled and ordered as per the draft Guideline. All references to noise metrics in this paper adopt the international standard convention of designating frequency weightings and measurement metrics as subscripts (e.g. L_{Aeq} dB). All references to decibels are therefore presented as dB (e.g. not dBA or dBC) unless directly quoting from a reference which adopts an alternative standard.

KEY MATTERS IN THE ASSESSMENT PROCESS

One of the most important, and potentially most stringent, features of the draft Guideline is the introduction of requirements based on separating distances. Specifically, if a wind farm proposal seeks to place turbines within 2km of existing residences, and written consent for the proposal has not been obtained from the residences, an initial study focussed on noise and visual impact considerations is required, including the prediction of low frequency noise levels.

Whilst subsequent sections of the draft Guideline provide objective criteria to assess noise, there is no indication that these criteria would be used as the test of adequacy for residences within 2km of a proposed turbine location. Instead, the draft Guideline indicates that the Government may seek advice from independent experts considering the acceptability of noise. The absence of clearly defined criteria for this initial study appears to be inconsistent with the stated objective of providing a clear and consistent regulatory framework for the assessment and determination of wind farm proposals.

As a result, the adoption of the draft Guideline could arbitrarily prevent wind farm proposals which seek to place turbines within 2km of a proposed residence. Key considerations in relation to the 2km separating distance include the following:

- In most instances it is likely that a 2km separating distance will be significantly more onerous than the objective noise criteria proposed in the draft Guideline. As a result, situations where a separating distance is enforced will render many aspects of the objective noise criteria redundant.
- The level of wind farm noise experienced at this distance will be dependent on the turbine noise emission characteristics, the proposed turbine layout, and the terrain of the surrounding environment. As a result, the level of noise at 2km will vary and therefore a separating distance cannot provide a consistent level of protection of amenity.

APPLICABILITY OF GUIDELINE

The draft Guideline appears to be primarily concerned with new wind farm proposals and their impact on existing residential dwellings. Their application to the following scenarios could benefit from further clarification. For example:

- Could the assessment criteria be potentially applied to existing wind farms, particularly in terms of the measurement methodologies and the assessment criteria proposed for the investigation of alleged low frequency noise or amplitude modulation?
- Could the draft Guideline be used to assess the acceptability of new residential development proposed near to approved or operational wind farms?

NOISE CRITERIA

The proposed criteria presented in Appendix B of the draft Guideline are similar to those presented in the SA EPA Guidelines 2003 [2], which have been previously used to assess wind farm noise in NSW, and recommend that:

For a new wind farm development the predicted equivalent noise level ($L_{eq,10\,minute}$), adjusted for any excessive levels of tonality, amplitude modulation, or low frequency, but including all other normal wind farm characteristics, should not exceed 35dB(A) or the background noise (L_{90}) by more than 5dB(A), whichever is the greater, at all relevant receivers not associated with the wind farm, for wind speed[s] from cut-in to rated power of the WTG [Wind Turbine Generator] and each integer wind speed in between. The noise criteria must be established on the basis of separate daytime (7am to 10pm) and night-time (10pm to 7am) periods.

The draft Guideline explains that the 35dB L_{Aeq} minimum limit value is derived from NSW noise amenity goals which provide distinct amenity levels for day, evening and night periods. The proposed minimum limit value of 35dB has been selected to satisfy the lowest, night amenity values but it is also applied to the day and evening periods. Given that the draft Guideline concurrently requires separate background analysis for day and night periods, there could be merit in considering different noise limits for day and night. This would be consistent with the NSW noise amenity goals which indicates higher noise levels are acceptable during the day and evening periods, and could potentially allow a greater renewable energy yield during the day.

In addition to the above, the draft Guideline explains that criteria were chosen to "*ensure that the amenity of an area is not compromised*". Whilst this may be a reasonable assertion in planning and policy terms, an individual's perception of amenity is highly subjective. Claims of this nature can therefore create unrealistic expectations of the level of protection provided by the criteria. Specifically, it would be helpful for the draft Guideline to clearly state that whilst wind farm noise are to be restricted to relatively low levels, the aim of the criteria is not inaudibility.

UNDERTAKING MEASUREMENTS

The draft Guideline requires that both prediction and measurement compliance be assessed in terms of L_{Aeq} noise levels. This is similar to the approach adopted by AS4959:2010 [3] and is a significant point of difference to the SA EPA Guidelines 2003, the more recent SA EPA Guidelines 2009 [4] as well as both of the relevant NZS6808:1998 [5] and NZS6808:2010 [6] where compliance measurements are predominantly based on statistical noise levels (L_{A90}, L_{A95}).

AS4959:2010 requires "*a minimum adjustment of +1.5 dB(A) to account for the difference between the L_{A90} and L_{Aeq}*". The draft Guideline is more prescriptive, requiring a fixed rather than minimum adjustment of +1.5dB rather. In practice, the difference between the L_{A90} and L_{Aeq} of wind turbine noise will vary. However, defining a single value offers the benefit of a prescriptive assessment methodology. To consider the proposed 1.5dB adjustment, the differences between L_{Aeq} and L_{A90} noise levels for several sets of data measured near wind turbines are presented in Table 1.

Table 1. Difference between measured L_{Aeq} and L_{A90}

Set	Distance from turbine (m)	Number of data points	Measurement time period (min)	L_{Aeq} - L_{A90}	
				Average	**Standard deviation**
1	100-150*	215	1	1.0dB	0.3dB
2	100-150*	327	1	1.6dB	0.6dB
3	100-150*	366	1	1.4dB	0.4dB
4	250	161	10	3.4dB	1.7dB
5	500	161	10	4.1dB	2.1dB

* Measured in accordance with IEC 61400-11:2006 [6]

It can be seen from Table 1 that at distances up to 150m where the noise of the turbine is dominant, the $L_{Aeq} - L_{A90}$ difference is comparable to the 1.5dB draft Guideline value. At measurement positions located further away the difference increases significantly, likely due to the increasing contribution of fluctuating ambient noise with increasing distance, rather than changes in the character of the noise from the wind turbines.

From this type of analysis, it is not possible to directly determine the $L_{Aeq} - L_{A90}$ difference for wind turbine noise at typical separating distances from residential dwellings. In practice, this difference is likely to be similar to 1.5dB in many instances, particularly where the received noise is the combination of multiple turbines producing similar noise levels. However, instances may also arise where wind turbine noise gives rise to $L_{Aeq} - L_{A90}$ differences greater than 1.5dB, due to factors such as atmospheric effects or occasional variations in the nature of the noise emission from the wind turbines.

Notwithstanding the above, the example results presented in Table 1 illustrate the difficulty associated with the direct measurement of L_{Aeq} wind turbine noise levels at increased separating distances where dwellings are located. Accordingly, it would seem likely that compliance measurements will inevitably rely on L_{A90} measurements.

In light of this, a more practical and transparent approach may be for the draft Guideline to apply the '$L_{Aeq} - L_{A90}$' correction to the noise limit rather than the measured noise levels, such that the limit is re-expressed in terms of the L_{A90}. Alternatively, additional clarification on how the 1.5dB correction should be applied solely to the contribution of wind turbine noise may assist in avoiding potential confusion regarding this matter.

NOISE DATA COLLECTION

Extraneous Noise

The draft Guideline recommends that data "*affected by extraneous noise should be excluded from the final data set*", proposing that identifying data where the L_{Aeq} exceeds the L_{A90} by 5dB or more can be a suitable screening method. Such a method may be reasonable to filter extraneous noise when measuring a constant noise source which is higher than the background noise level at the measurement location. However, it may be less successful when considering wind farm noise at typical residential separation distances, particularly using a 10 minute measurement interval, where the ambient noise level can often be higher than the wind farm noise level.

Listening to audio recordings is also a proposed screening method in the draft Guideline. Whilst audio records are a useful reference, the volume of data involved in assessing compliance at multiple locations around a wind farm is large, and therefore listening tests can only ever be practically adopted for a very small component of the datasets.

Measuring noise levels in one-third octave bands may prove helpful in filtering certain types of extraneous noise. For the particular case of insect noise, a one-third octave band filtering method has recently been proposed by Terlich [8] which involves removing all one-third octave bands in the range 3.15-8kHz during periods affected by insect noise. An assumption of such a method is that noise levels in the range 3.15-8kHz have little influence on the A-weighted background noise when insects are not present. However, applying this method to an example set of rural ambient noise level data, which has not been affected by insect noise, causes the A-weighted noise levels to drop by an average of 3dB indicating that the method may require some further refinement. Nonetheless, one-third octave band analysis may prove helpful in some cases.

Number of Data Points

The Guideline is helpful in its specification of a minimum number of data points to be collected during the monitoring period:

Sufficient data is considered to be approximately 2,000 valid measurement intervals […] where at least 500 of these points should be from the worst-case wind direction.

The Guideline defines a "*wind direction spread of 45° either side of the direct line between the nearest actual or proposed wind turbine and the relevant receiver*" as acceptable for assessing worst-case wind directions.

While it is considered sensible for compliance assessment measurements to include reasonable worst case conditions, the choice of a minimum 500 down wind points seems arbitrary. Beyond satisfying the minimum 500 and 2,000 data point requirements, it would seem that one could influence the outcome of monitoring by manipulating the ratio of worst case downwind directions to other directions.

WIND DATA COLLECTION

This draft Guideline describes wind monitoring requirements for microphone locations and for the wind farm site at hub height. Whilst the wind farm site data is stated to be the reference for producing correlations between background noise levels and wind speed, the purpose of wind speed measurements at the microphone is not explicitly defined and may lead to confusion. Table 2 summarises the interpreted purpose of the draft Guideline requirements.

Table 2. Wind speed monitoring locations

Location	Interpreted purpose
Near the microphone	Solely to determine the potential influence of wind induced noise over the microphone. Note that the requirement for a measurement accuracy of +/-0.5ms^{-1} or better may infer a requirement to monitor wind speed at every microphone location, rather than a single candidate location as is common practice.
Hub height, at the wind farm site	The sole reference for correlating background noise levels and wind speeds.

The draft Guideline notes that wind speeds "*should be measured at the proposed wind turbine hub and relevant intermediate heights for the range of meteorological conditions expected*". This suggests that monitoring at hub height is mandatory and that it may not be acceptable to measure wind speeds at intermediate heights and extrapolate these up to hub height. However, the final paragraph in this section states:

> *Final wind turbine design may result in different heights to those originally proposed. In these cases the measured data can be extrapolated to the final design hub height using the equation below. In all cases atmospheric stability conditions should be taken into account to ensure accurate conversion of the data.*

It may be helpful for the draft Guideline to clarify when extrapolation of wind speed data is considered appropriate. In addition, it is unclear how atmospheric stability conditions should be specifically accounted for. Various options for wind shear factors include real-time, short-term average, long-term average, filtering by wind sector, etc. Further guidance on selecting suitable factors would be helpful.

DATA ANALYSIS

The draft Guideline presents a discussion of data analysis and refers to three specific noise characteristics: Tonality, Amplitude Modulation and Low Frequency Noise. The draft Guideline provides relatively prescriptive advice with respect to when and how penalties should be applied for the presence of specific noise characteristics. Comments of this nature are often lacking in guidance documents and their inclusion in the draft Guideline may provide greater certainty during the various assessment stages of a project.

The methods proposed by the draft Guideline for assessing specific noise characteristics do not involve any subjective assessment of the character of the noise, implying that the proposed methods:

- have a very strong correlation with peoples subjective impressions of the noise, and;
- do not result in a specific noise characteristic penalty being incorrectly applied, for example, as a false positive.

As highlighted by the discussions which follow, the available objective assessment methods possess inherent limitations and therefore the observations of an experienced practitioner should still be required to determine the need for objective assessment.

Amplitude Modulation

The draft Guideline recommends the following assessment method for amplitude modulation:

> *An excessive level of modulation is taken to be a variation of greater than 4dB(A) at the blade passing frequency.*

It is not clear whether the 4dB variation refers to the peak-to-trough difference in sound level, or the variation from the average. The requirement may also be misinterpreted as relating to modulation of sound frequencies equal to the blade passing frequency, rather than higher frequencies of sound being modulated at a rate equivalent to the blade passing frequency. Further clarification would be helpful.

No comment is provided to indicate the reliability of this assessment method. Indeed, the absence of such a discussion would suggest that the method is robust. A recent article by Bass [9] investigates the use of a comparable assessment methodology for amplitude modulation, with a 3dB peak-to-trough trigger. The paper identifies an 'unacceptably high rate of false positives' for the test method. It is plausible that a similar return on false positives is possible for the method proposed by the draft Guideline. However it should be noted that the Bass paper investigates amplitude modulation within rural ambient noise and the results may or may not translate to a sound environment where wind turbine noise dominates.

The draft Guideline also notes that the absence "*of excessive modulation in noise emissions measured at an intermediate location is sufficient proof that the modulation is not a feature of the wind farm*". The certainty that this comment can offer during a wind farm assessment is advantageous. However, the comment suggests that the mechanism(s) for amplitude modulation is sufficiently understood and, by inference, is not unduly influenced by propagation effects. By contrast, a recent presentation by Smith [10] suggests that propagation effects may be significant in the occurrence of amplitude modulation in some cases.

Amplitude modulation is the subject of a considerable UK research effort which is nearing completion. This research has highlighted a number of complexities to the causes (see Smith [10]), identification and assessment of amplitude modulation. In advance of this study being completed, it would be prudent for any future guideline to allow the flexibility to accommodate new approaches and findings when available.

Low Frequency Noise

The draft Guideline acknowledges low frequency noise is present in all types of environmental noise and that measurement data supports that low frequency noise is typically not a significant feature of modern wind turbines. However, community concerns about proposed wind farm developments frequently include questions about potential low frequency noise and how the planning process can be used to control it.

The draft Guideline attempt to address these concerns by introducing objective criteria. The first element of the proposed criteria is an external screening test based on the following:

> *If it is shown that the C-weighted noise (measured from 20Hz upwards) from a wind farm (excluding any wind induced or extraneous C-weighted noise) is repeatedly greater than 65dB(C) during the daytime or 60dB(C) during the night-time a more detailed low frequency noise assessment should be undertaken.*

Introducing this screening test offers the benefit of communicating a clear test of adequacy for low frequency noise, and is consistent with the stated aim of promoting a clear regulatory framework. However, the introduction of low frequency noise criteria presents several issues:

- The chosen thresholds appear to have been derived from work largely related to combustion power stations. Evidence to support these values as suitable thresholds for wind farms appears to be limited. A paper by Hessler [11] indirectly referred to by the draft Guideline specifically indicates design limits or regulatory goals are not warranted for low frequency noise from wind farms. Hessler further notes "*a maximum regulatory limit of 70dBC is recommended if one must have a low frequency limit*".

- The draft Guideline acknowledges that low frequency noise is particularly difficult to measure in windy environments. This point is emphasised by Hessler who states "*it must be strongly cautioned that C-weighted sound levels do not mix well with wind turbine applications because it is extremely difficult to accurately measure C-weighted noise levels in the presence of any kind of wind*". Hessler further notes the likelihood of measured levels in excess of 60-65dB L_{Ceq} as a result of extraneous influences in windy conditions. These observations have been confirmed by our own analysis of ambient noise level data collected in rural locations as summarised in Table 3. The data was collected at locations away from wind turbines using a conventional monitoring set-up including a 90mm wind shield around the microphone. Whilst the draft Guideline' proposed criteria are based on L_{Aeq} levels, Table 3 also presents an analysis in terms of L_{A90} levels for information.

Table 3. Application of draft Guideline proposed low frequency noise external screening criteria to measured data (rural site – no wind turbines)

Dataset	**Monitoring duration**	**Percentage of noise levels exceeding the proposed Low Frequency Noise external screening criteria**	
		$L_{Ceq,\ 10min}$	$L_{C90,\ 10min}$
A	20 days	38.4%	0.2%
B	28 days	9.1%	0.0.6%

This sample analysis indicates equivalent noise levels regularly exceed the proposed threshold of the draft Guideline, demonstrating potential limitations and practical challenges to the measurement of outdoor equivalent C-weighted noise levels (L_{Ceq}) in windy conditions. Detailed statistics on wind noise at each microphone and/or enhanced microphone shielding systems could reduce false positives if further related advice was provided in the draft Guideline. However, the draft Guideline states that if these values are exceeded, a more detailed low frequency noise assessment should be undertaken based on a procedure which requires measurements inside non-associated residences. Whilst it is generally agreed that the most appropriate way to investigate low frequency noise is to measure internal noise levels, this type of requirement in a noise policy presents several considerations:

- Enforcement of a low frequency noise permit condition based on the draft Guideline would require the cooperation of a resident to provide access to their home for extensive and potentially intrusive surveys. Unlike external measurements, if permission is not granted there is not the same option to measure noise levels at an alternative representative location.
- Low frequency noise levels within dwellings are highly prone to the influence of domestic equipment and activity inside the home. Identifying this type of influence often requires the use of audio recordings to examine the source of noise, however this may be seen as an intrusion on privacy.
- An increased low frequency noise level inside a dwelling may be a consequence of the specific sound insulation characteristics of the dwelling under investigation; a factor which is beyond the control of a wind farm developer, and which may not be able to be reliably accounted for in the design and planning of a wind farm.

Notwithstanding the above, the draft Guideline recommend the UK Department of Environment Food and Rural Affairs (DEFRA) document *Proposed criteria for the assessment of low frequency noise disturbanc*e [12] as the relevant reference to assess internal low frequency noise levels. The DEFRA document is well researched and includes a recommended methodology and proposed criterion which are valuable references for the assessment of low frequency noise levels inside residential dwellings.

Subsequently, the draft Guideline propose that the DEFRA criterion be used to determine if the noise levels are excessive, and where found to be excessive, to apply a 5dB penalty to the measured or predicted L_{Aeq} noise level. However, applying the DEFRA criterion in this manner, as a definitive test for excessive noise levels, extends beyond its intended application. Specifically, the DEFRA document states:

"*It is suggested the proposed criterion be used not as a prescriptive indicator of nuisance, but rather in the sense of guidance to help determine whether a sound exists that might be expected to cause disturbance. Some degree of judgement is required by the EHO [Environmental Health Officer] is both desirable and necessary in deciding whether to class the situation as a nuisance, and is likely to remain so. One of the main reasons is that, from the control cases, it is clear that problems do not necessarily arise when the criteria are exceeded. Indeed, we can conjecture that genuine LFN complaints occur only in a few such cases. Therefore, factors like local knowledge and understanding of the broader situation are likely to remain important aspects of the assessment. [...]*"

Therefore, whilst the DEFRA document is a helpful reference for low frequency noise investigations, the adoption of their criterion as a definitive test of acceptability, as proposed in the draft Guideline, is not advocated by the authors of the DEFRA document.

NOISE PREDICTIONS

The draft Guideline require noise predictions to be determined for 'worst-case' conditions at all relevant receivers and proposed intermediate points, but does not endorse any specific approved method. Instead, they note that ISO 9613-2

[13] and the CONCAWE noise propagation model [14] are commonly used. It is correct that both of these methods are in common use in Australia for wind farm noise assessments. However, for a given assessment condition, these methods can often produce different prediction outcomes. The issue of sound propagation from wind farms has been the subject of considerable investigation. In 1998, a comprehensive study [15], part funded by the European Commission, considered the merits of alternative modelling methods. This study found that the ISO 9613-2 model provided a robust representation of upper noise levels which may occur in practice. Conversely, the study demonstrated that alternative methods such as CONCAWE and ENM tended to significantly over predict the measured noise levels in practice. The study also demonstrated CONCAWE and ENM to be overly sensitive to the selected input parameters, resulting in a range of predicted noise levels vastly greater than the measured variation observed in practice. Since this time, other publications have lent support to the use of the ISO 9613-2 as a preferred methodology for predicting noise levels from wind farms:

- In 2009, the UK Institute of Acoustics journal [16] published a joint agreement between practitioners in the field of wind farm noise assessment, including consultants routinely employed on behalf of both developers and community opposition groups. This agreement advocated ISO9613-2 as the appropriate calculation method, accompanied by recommendations on the selection of suitable input parameter for factors such as ground and atmospheric conditions.
- New Zealand Standard NZS6808:2010, which is currently used in Victoria, designates ISO 96132 as the appropriate prediction method
- Australian Standard AS 4959-2010 provides general advice on predictions and notes that a number of complex methods are available for the prediction of noise from wind turbines. Of the more detailed available methods, ISO 9613-2 is the only calculation standard referred to directly.

The available evidence, including studies carried out with the involvement of the authors of this paper [17, 18], provide support for the ISO 9613-2 standard as a preferred method for the prediction of A-weighted noise levels. The selection of a preferred method in any future NSW guidelines, along with relevant input parameters, would provide helpful clarity on the subject and enable more consistent assessment outcomes.

The above matters solely relate to the prediction of A-weighted noise levels from the operation of a wind farm. However, the draft Guideline also requires the prediction of low frequency noise levels at dwellings within 2km where consent has not been obtained. To be able to present this information requires:

- Turbine manufacturers' noise emission data at frequencies below the minimum range that may be available. Specifically, the international test standard IEC 61400-11:2006 which is widely used for rating turbine noise emissions, requires the determination of one-third octave band sound levels in the range from 50Hz to 10kHz. The standard does include provision for determining sound levels at lower frequencies, however, the extended measurement range is not mandatory and, as such, the additional data may not be available in many cases. In cases where data is available, the test uncertainty associated with the emissions will considerably greater than that of overall A-weighted sound power levels.
- Prediction of noise levels at frequencies below the validated range of the methodologies referred to in the draft Guideline, ISO 9613 and CONCAWE. Alternative methods are available for predicting noise at lower frequencies, most notably the Danish method NORD 2000. However, to our knowledge, such methods are not routinely applied in Australasia, either for wind farm or other general applications.

Accordingly, whilst it is possible to provide predicted C-weighted noise levels, the resulting values will be subject to greater uncertainty as a result of both the input information and the prediction methodologies employed. The draft Guideline does not provide any advice to address these complexities and therefore places the onus on industry to develop new procedures and methodologies specific to the assessment of wind farm noise in NSW.

CONCLUSIONS

The draft Guideline presents a comprehensive and stringent set of criteria to control the design, planning and commissioning of commercial scale wind farm developments. The draft Guideline offers useful prescriptive advice on certain aspects of wind farm noise assessment, and in turn offers the benefit of increased certainty. However, in relation to matters such as the assessment of noise characteristics, the advice is prescriptive beyond the present state of understanding of wind turbine noise. This has the potential to result in unnecessary penalties and operational curtailments to completed wind farm developments. Noise compliance assessments during commissioning also have the potential to become protracted and costly as a result of default requirements to assess noise characteristics at each site. In its present form, the draft Guideline will be significantly more stringent than noise policies previously used to date in NSW. The potential amenity protection benefits this could translate to, must be balanced against the corresponding loss in energy yield from each new development (see reference [18]), and the subsequent impact this could have on the NSW government's broader objectives with respect to renewable energy.

REFERENCES

[1] NSW Department of Planning and Infrastructure, *Draft NSW Planning Guidelines: Wind Farms*, 2011

[2] South Australia Environment Protection Authority, *Environmental noise guidelines: Wind farms*, 2003

[3] Australian Standard AS 4959:2010 *Acoustics – Measurement, prediction and assessment of noise from wind turbine generators*

[4] South Australia Environment Protection Authority, *Wind farms environmental noise guidelines*, 2009

[5] New Zealand Standard NZS 6808:1998 Acoustics – *The assessment and measurement of sound from wind turbine generators*

[6] New Zealand Standard NZS 6808:2010 *Acoustics – Wind farm noise*

[7] International Electrotechnical Commission IEC 61400-11 *Wind turbine generator systems – Part 11: Acoustic noise measurement techniques*, edition 2.1 2006-11

[8] M. Terlich, “The peril of ignoring insect noise in the assessment of ambient noise levels”, *Proceedings of Acoustics 2011*, Gold Coast, Australia, 2-4 November 2011

[9] J. Bass, “Investigation of the ‘Den Brook’ amplitude modulation methodology for wind turbine noise”, *Acoustics Bulletin,* **36**(6), November-December 2011, pp. 18-24

[10] M. Smith, “Mechanisms of amplitude modulation in wind turbine noise”, *Institute of Acoustics Wind Turbine Noise Conference*, Cardiff, UK, 26 January 2012

[11] D.M. Hessler and G.F. Hessler, “Recommended noise level design goals and limits at residential receptors for wind turbine developments in the United States”, *Noise Control Engineering Journal* **59**(1), 94-104 (2011)

[12] A. Moorhouse, D. Waddington and M. Adams, *Proposed criteria for the assessment of low frequency noise disturbance*, University of Salford, Report prepared for the Department for Environment, Food, and Rural Affairs (DEFRA) Contract No. NANR45, 2005

[13] International Organization for Standardization ISO 9613-2:1996, *Acoustics – Attenuation of sound during propagation outdoors Part 2: General method of calculation*

[14] CONCAWE Report 4/81, *The propagation of noise from petroleum and petrochemical complexes to neighbouring communities*, Netherlands, 1981

[15] J.H. Bass, A.J. Bullmore and E. Sloth, *Development of a wind farm noise propagation prediction model*, The European Commission, Joule III, Contract JOR3-CT95-0051, Final Report, 1998

[16] G. Leventhall, A. Bullmore, M. Jiggins, M. Hayes, A. McKenzie, D. Bowdler and B. Davis, “Prediction and assessment of wind turbine noise – Agreement about relevant factors for noise assessment from wind energy projects”, *Acoustics Bulletin* **34**(2), March-April 2009, pp. 35-37

[17] A. Bullmore, J. Adcock, M. Jiggins and M. Cand, “Wind farm noise predictions and the risks of conservatism”, *Proceedings of the 2nd International Meeting on Wind Turbine Noise*, Lyon, France, 20-21 September 2007

[18] C. Delaire, D. Griffin and D. Walsh, “Comparison of predicted wind farm noise emission and measured post-construction noise levels at the Portland Wind Energy Project in Victoria, Australia”, *Proceedings of the 4th International Meeting on Wind Turbine Noise*, Rome, Italy, 11-14 April 2011

The 2012 conference of the Australian Acoustical Society will be held in Fremantle, Western Australia, from 21 to 23 November 2012. Acoustics 2012 Fremantle will be another great opportunity for Australian and International guests to get together to discuss all aspects of acoustics. Below are some updates on key presentations, workshops and dates.

Plenary and keynote presentations

The conference will include many interesting plenary and keynote presentations. Guest speakers include:

- Dr Irene van Kamp of the National Institute of Public Health and the Environment (Netherlands).
- Dr Ross Chapman of the School of Earth and Ocean Sciences, University of Victoria, Canada.

Pre-conference workshops

A variety of specialist workshops/short courses will take place prior to the event, including:

- *Active Noise Control*, University of Western Australia
- *Underwater Passive Acoustic Monitoring*
- *Advanced Machine Diagnostics and Condition Monitoring*, (2 day course), the course will be given by Em. Prof. Bob Randall from UNSW and will be held at Curtin University.

The key dates for the Acoustics 2012 Fremantle conference are:

Papers		**Registrations**	
Abstract acceptances	28 April	Registration begins	1 July
Full papers due	11 June	Late registration fees apply	1 September
Reviews released	27 August	Conference begins	21 November
Final papers due	19 September		

Please refer to the conference website for all the up-to-date information regarding the conference:
http://www.acoustics.asn.au/joomla/acoustics-2012.html

If the conference website does not answer any of your queries, please contact the WA Division AAS secretary via e-mail (wa-secretary@acoustics.asn.au)

Technical Note

DEVELOPMENT OF THE DRAFT NSW PLANNING GUIDELINES: WIND FARMS

Jeff Parnell
Noise Specialist, NSW Department of Planning and Infrastructure

INTRODUCTION

On 23 December 2011 the NSW Department of Planning and Infrastructure released its *Draft NSW Planning Guidelines: Wind Farms* (the *Draft*) [1] for public consultation. The period for consultation was until 14 March 2012, which had not been reached at the time of writing this Technical Note. As you would be aware in this special edition of Acoustics Australia, there has been some reference to these guidelines. Given the deadline for this edition of Acoustics Australia predates the end of consultation period it is not possible at this time to discuss the issues raised, however at the time of writing there had been approximately 400 submissions.

The intent of this Technical Note is therefore to elaborate in more detail the science and thinking behind the development of the *Draft*. Those readers with a working knowledge of the current standards and guidelines used in Australia will recognise that the *Draft* adopts aspects of the methodologies and practices presented in the 2009 South Australian document *Wind farms - environmental noise guidelines* [2] and Australian Standard AS4959 – 2010 *Acoustics – Measurement, prediction and assessment of noise from wind turbine generators* [3]. This document also draws on experience gained in the assessment and operation of wind farms in NSW and from community input. As a result it is believed that the process undertaken in developing the *Draft* will achieve the objective of developing a final document that meets the needs and expectations of both industry and community.

FRAMEWORK OF DRAFT GUIDELINE

The noise component of the *Draft* is based upon 6 fundamentals listed below. The reasoning and science underpinning these proposed fundamentals is discussed in some detail however it needs to be remembered that the status of these guidelines is still draft, and any final document may be subject to change.

Identification of monitoring locations

Site selection is important, particularly as these sites may be revisited for compliance over the life of the wind farm. Whilst this should be a basic consideration for an acoustician, the draft gives some guidance on positioning, particularly in relation to trees. It is generally considered that extraneous noise from foliage is not a significant problem for low scrubs and bushes, however tall trees such as eucalypts and poplar trees which seem to be common in high wind areas can cause difficulties in collection valid noise data. Whilst monitoring procedures for other environmental noise exclude periods of higher wind, this is not the case for wind farm measurements. The *Draft* therefore allows for monitoring locations to be moved away from existing or proposed trees to a position between the trees (and residence) and the wind turbine providing the noise exposure is approximately the same.

In the knowledge that it can be extremely difficult to separate wind turbine noise from the ambient when at large distances, the *Draft* allows for supporting noise data to be collected at intermediate locations where the signal-to-noise ratio is much higher. This concept is not new and has previously been accepted in similar situations in the NSW Industrial Noise Policy (INP) [4]. The *Draft* however describes in more detail how the practice can be used to supplement data collected at the sensitive receiver and can also be used to confirm compliance. It is suggested that these intermediate locations be used to confirm the presence or otherwise of any specific audible characteristics which are more easily identified in closer proximity to the turbines where the improved signal-to-noise ratio assists the data analysis.

Establishment of background noise levels

In recognition that wind farm noise will be substantially masked as wind levels at the receiver increase, the *Draft* adopts the use of regression analysis to establish the median levels at each integer hub height wind speed from cut in speed (generally around 4 m/s) to the rated power (generally around 11 m/s). Similar to the SA 2009 Guideline, the *Draft* recommends 2000 valid data points, with 500 of those to be from the most adverse wind direction. Where the adverse wind direction is one that does not occur commonly, then data from a minimum of 6 weeks of monitoring is deemed to be sufficient.

The regression line approach used to determine the background level is considered both valid and appropriate, particularly given that the threshold noise criteria are established independent of the existing background noise levels.

Development of noise criteria

When developing noise criteria, there are two aspects that need to be considered:

- What is the level of noise acceptance that is considered appropriate for the area? and;
- What is the noise amenity that one is trying to establish for the area?

In response to the first aspect, it is a general NSW objective to set where possible noise goals that will ensure at least 90% of the population are protected from being highly annoyed for

Percentages of highly annoyed					
L_{den}	Road	Rail	Aircraft (revised estimate)	Industry	Windturbine
55 dB	6 %	4 %	27 %	5 %	26 %
50 dB	4 %	2 %	18 %	3 %	13 %
45 dB	1 %	0 %	12 %	1 %	6 %

Figure 1. Comparison of L_{den} values for different sources with respect to annoyance [5]

at least 90% of the time [4]. To establish the noise levels at which these impacts may be expected, reference was made to dose/response studies. In particular, the studies presented in the following three figures were used to gain a perspective of annoyance levels. Note: the noise levels in all figures are measured or predicted outside of the residence.

Acknowledging that an L_{den} noise metric incorporates an evening and night time penalty into this single noise descriptor, Table 1 shows the approximate dose response compared to a L_{eq} using a 6.4 dB reduction from the L_{den} for a constant noise source and extrapolation from the source studies. From data contained in Table 1 it can be shown that 90% of the population can be expected not to be very or highly annoyed at 40 dB(A). In examining the second aspect of noise criteria development, reference is made to the amenity noise goals established in the INP [4] for various land use classifications. From Table 2 it can be seen that 40 dB(A) is an accepted night time noise level for a rural area.

It can therefore be concluded that both contemporary dose/response relationships and acceptable amenity noise goals identify a level of 40 dB(A) as meeting NSW noise objectives for protection of the community and maintaining the amenity of a rural area. Notwithstanding, it was determined that the threshold criteria set in the *Draft* should be discounted by 5 dB to a level of 35 dB(A) to allow for any other industrial noise sources and to ensure that NSW objectives were easily met.

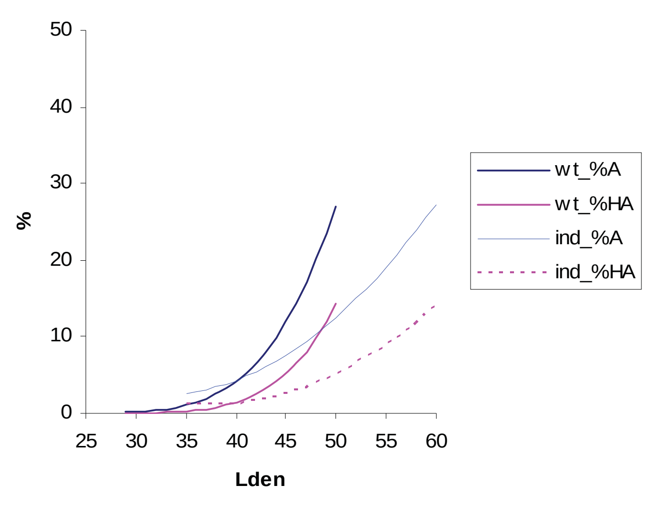


Figure 2. Comparison of the percentage (highly) annoyed persons indoors (%A indoors and %HA indoors) due to wind turbine noise (wt) and industrial noise (ind) [6]

Response outdoors	Sound pressure levels, dBA					
	<30	30-35	35-40	40-45	>45	Total
Do not notice	124 (75%)	92 (46%)	30 (21%)	7 (12%)	2 (10%)	255 (44%)
Notice, but not annoyed	34 (21%)	71 (36%)	52 (37%)	22 (37%)	5 (24%)	184 (31%)
Slightly annoyed	4 (2%)	20 (10%)	30 (21%)	16 (27%)	8 (38%)	78 (13%)
Rather annoyed	2 (1%)	13 (7%)	19 (14%)	4 (7%)	3 (14%)	41 (7%)
Very annoyed	2 (1%)	3 (2%)	9 (6%)	11 (18%)	3 (14%)	28 (5%)
Total	166 (100%)	199 (100%)	140 (100%)	60 (100%)	21 (100%)	586 (100%)

Figure 3. Response to wind turbine sound outdoors in relation to 5 dB(A) intervals of sound levels (all respondents) [7]

Table 1. Summary of dose / response studies

Study	**% Very or Highly Annoyed**				
	30 dB(A)	**35 dB(A)**	**40 dB(A)**	**45 dB(A)**	**50 dB(A)**
EEA	0	4	10	20	35
Janssen	0	3	10	20	-
Wind Perception	1	3	9	12	-

Table 2. NSW Amenity Noise Criteria [4]

Noise Amenity Area	Time of Day	Recommended L_{Aeq}. Noise Level dB(A)	
		Acceptable	**Recommended Maximum**
Rural	Day	50	55
	Evening	45	50
	Night	40	45
Suburban	Day	55	60
	Evening	45	50
	Night	40	45
Urban	Day	60	65
	Evening	50	55
	Night	45	50

Setting of penalties for excessive levels of specific noise characteristics

As with all types of natural and anthropogenic noise, there are identifiable levels of tonality, low frequency and modulation, NSW noise criteria are developed inclusive of a certain level of these characteristics. The objective of the *Draft* is therefore not to completely eliminate these characteristics, but to ensure that excessive levels are managed. The basis for establishing what would be considered 'excessive' levels of specific audible characteristics is given below.

Tonality

The proposed method for identifying excessive tonality is the same as that used in the INP [4] and is based on 1/3rd octave band analysis. Whilst not considered a perfect measure of tonality, a review of methods used by other States has not revealed a better indicator. The method in the INP has been established since 2000 and few, if any issues have been raised with its implementation.

To overcome difficulties with measuring 1/3rd octave bands at large distances where the signal may be compromised by local extraneous noise, the *Draft* allows for levels of tonality to be established at intermediate location points. This is based on the rational that any tonal impacts will not be enhanced at greater distances.

Amplitude modulation

The aerodynamic noise from a wind turbine's blades is sometimes referred to as 'swish' [8] or 'thump' and can be explained by the amplitude modulation of the wind turbine noise level. The modulation is generally distinct at short distances from the wind turbine generator (WTG) and may not be audible at a greater distance [9].

Whilst there has been some investigation of a modulated noise signal, there have been few recommendations on how to objectively evaluate or set management levels. Based on advice given by van den Berg (and agreed by Tonin) at the Land and Environment Court hearings into Taralga wind farm [10], the *Draft* has proposed that an excessive level will be identified as when a variation of greater than 4 dB(A) exists. It is however recognised that this is an area where contemporary studies are likely to inform future procedures for assessing and managing amplitude modulation.

Low frequency

Much has been raised regarding the level and impact of low frequency noise particularly that of infrasound (< 20 Hz). When considering the potential of wind farms to cause low frequency noise impacts, there are three important aspects that must be considered.

1. The sound power level of a turbine is only around 105 dB(A)
2. At distances of around 1km the frequencies below about 100 Hz will be inaudible [11]
3. Low frequencies are extremely difficult to measure, particularly outdoors and even more so in the presence of even small levels of wind.

An examination of detailed work by Møller and Pedersen [12] shows that wind turbines have a very similar spectral signature, regardless of the turbine capacity. When normalised, the signature band becomes even narrower and supports the work of Jakobsen [13] and Colby et al. [14] in stating definitively that wind turbines do not generate excessive levels of low frequency noise. Furthermore, the graphs show that the relationship between the lower frequencies, including the infrasound band, are such that controlling a higher frequency or range of frequencies will have the effect of controlling the lower end of the noise spectra.

When compared to the UK Department of Environment Food and Rural Affairs (DEFRA) acceptability curves [15] in Figure 7 it can be seen that most wind turbines are well below the acceptable levels for all low frequency noise, particularly below 31.5 Hz, when the outside noise is kept to around 35 dB(A).

It is therefore considered unnecessary to establish the full spectral signature of all wind turbines, but rather to rely on triggers to identify any anomalies such as a mechanical problem. To achieve this, the *Draft* recommends the use of dB(C) measurements at intermediate locations to identify a need for any further investigation. Trigger levels of 65/60 dB(C) as suggested by Broner [16] have been adopted.

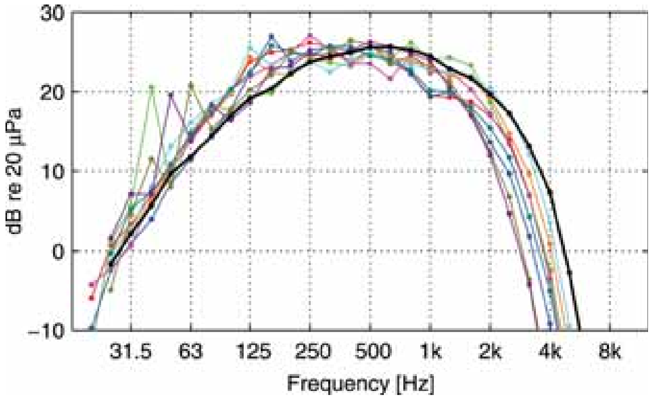


Figure 4. A-weighted sound pressure levels in 1/3rd octave bands at distances, where the total A-weighted sound pressure level is 35 dB. 2.3 – 3.6 MW turbines [12]

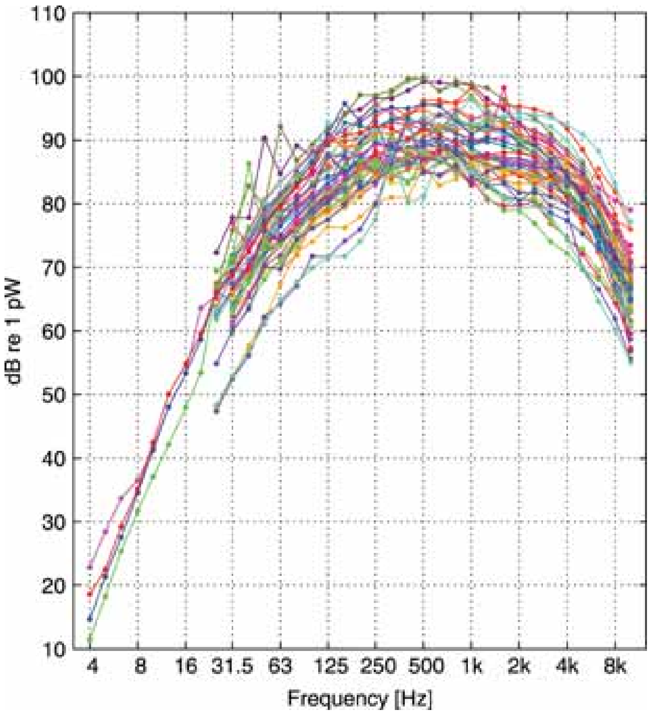


Figure 5. A-weighted apparent sound power levels in one-third-octave bands. 45 turbines with nominal electric power 75 kW–3.6 MW [12]

Predictions of noise impacts

Predictive noise modelling for wind farms is not considered to be overly difficult given that in most instances the noise source is highly elevated with direct line of sight to receivers. The *Draft* aims not to be prescriptive in the type of predictive noise model used and it is expected that advances in modelling will result in improved models during the lifetime of the final guideline. The focus of the *Draft* is therefore demonstrating that the particular model used can be validated for site specific scenarios.

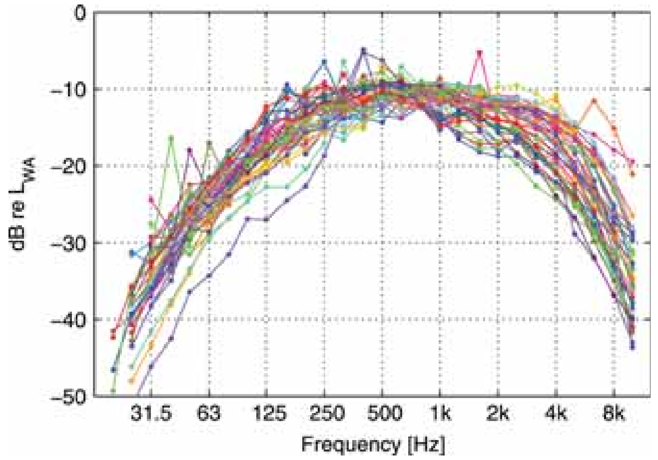


Figure 6. Normalized A-weighted apparent sound power levels in 1/3rd octave bands. 45 turbines with nominal electric power 75 kW–3.6 MW [12]

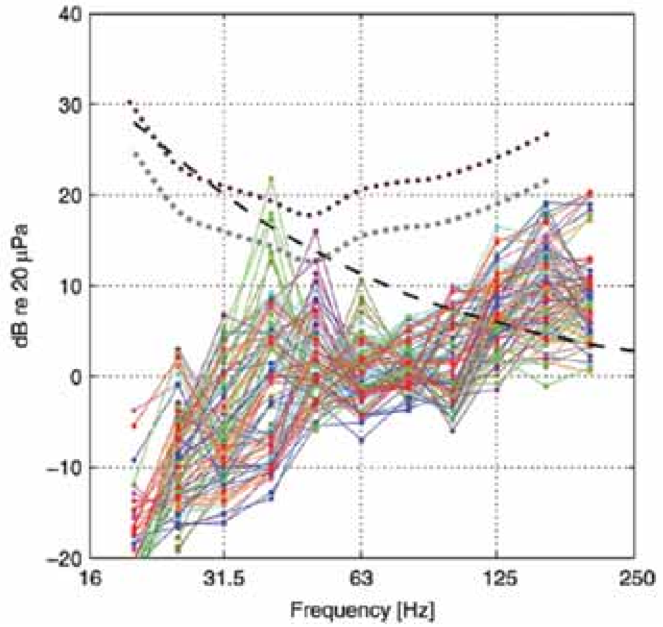


Figure 7. Indoor SPL in dB(A) where the total outdoor SPL is 35 dB(A). Adapted from [12]

– – – – ISO 389-7 (audibility) [11]

········ DEFRA fluctuating (acceptability) [15]

┈┈┈┈ DEFRA steady signal (acceptability)

Compliance

An important component of the *Draft* is the requirement for compliance monitoring. As with other major developments in NSW, the *Draft* sets out the procedure for establishing compliance once the wind farm is operational. It is recognised that measuring a level of say 35 dB(A) in a windy environment up to 2 km from the noise source can be difficult. Whilst it would be expected that low pass filters and possibly directional microphones would be used to improve the collection of compliance data, the *Draft* also describes how useful supporting data can be collected from intermediate locations where the signal-to-noise ratio is more favourable. The use of data collected at a proximity of say 400 m where an L_{eq} of around 45 - 50 dB(A) can be expected, may be useful in supporting receiver collected data when extrapolated to the receiver location using established relationships. Moreover, the presence of specific audible characteristics can much more easily be confirmed or denied at these intermediate locations.

Similar to AS 4959, the *Draft* allows for the conversion of some L_{90} data to L_{eq} where collection of uncontaminated L_{eq} data is shown to be problematic. The *Draft* however, differs from AS 4959 in that it prescribes the relationship between the L_{90} and the L_{eq} as being +1.5 dB.

ACKNOWLEDGEMENTS

The Department is appreciative of all the submissions it has received and particularly the advice of those with whom there has been personal correspondence.

This Technical Note does not necessarily describe sections of what will be a final guideline as these may change substantially following the input from the consultation process. Any opinions expressed are those of the author and do not necessarily reflect those of the NSW State Government.

REFERENCES

[1] NSW Department of Planning and Infrastructure, *Draft NSW Planning Guidelines: Wind Farms*, 2011

[2] South Australia Environment Protection Authority, *Wind farms environmental noise guidelines*, 2009

[3] Australian Standard AS 4959:2010 *Acoustics – Measurement, prediction and assessment of noise from wind turbine generators*

[4] NSW Environment Protection Authority, *Industrial Noise Policy*, 2000

[5] European Environment Agency, *Good practice guide on noise exposure and potential health effects*, EEA Technical report No 11/2010

[6] S.A. Janssen, H. Vos, A.R. Eisses and E. Pedersen, "Exposure-response relationships for annoyance by wind turbine noise: a comparison with other stationary sources", *Proceedings of EuroNoise 2009*, Edinburgh, Scotland, 26-29 October 2009

[7] F. van den Berg, E. Pedersen, J. Bouma R. and Bakker, WINDFARMperception: *Visual and acoustic impact of wind turbine farms on residents*, Project no. 044628, Final report, University of Groningen and University of Gothenburg, 2008

[8] A. Moorhouse, M. Hayes, S. von Hünerbein, B. Piper and M. Adams, *Research into aerodynamic modulation of wind turbine noise: Final report*, University of Salford, Contract No NANR233, 2007

[9] V.V. Lenchine, "Amplitude modulation in wind turbine noise", *Proceedings of Acoustics 2009*, Adelaide, Australia, 23-25 November 2009.

[10] *Taralga Landscape Guardians Incorporated vs Minister for Planning and RES Southern Cross Pty Ltd*, NSW Land and Environment Court Proceedings No. 10196 of 2006

[11] International Organization for Standardization ISO 389-7:2005 *Acoustics - Reference zero for the calibration of audiometric equipment - Part 7: Reference threshold of hearing under free-field and diffuse field listening conditions*

[12] H. Møller and C.S. Pedersen, "Low-frequency noise from large wind turbines", *Journal of the Acoustical Society of America* **129**(6), 3727–3744 (2011)

[13] J. Jakobsen, "Infrasound emission from wind turbines", *Journal of Low Frequency Noise, Vibration and Active Control* **24**(3), 145-155 (2005)

[14] D.W. Colby, R. Dobie, G. Leventhall, D.M. Lipscomb, R.J. McCunney, M.T. Seilo and B. Søndergaard, *Wind turbine sound and health effects: An expert panel review*, American Wind Energy Association and Canadian Wind Energy Association, 2009, http://www.awea.org/learnabout/publications/upload/awea_and_canwea_sound_white_paper.pdf (Last accessed 18 March 2012)

[15] A. Moorhouse, D. Waddington and M. Adams, *Proposed criteria for the assessment of low frequency noise disturbance*, University of Salford, Report for Department for Environment, Food and Rural Affairs, DEFRA, UK, Contract no NANR45, 2005

[16] N. Broner, "A simple criterion for low frequency noise emission assessment", *Journal of Low Frequency Noise, Vibration and Active Control* **29**(1), 1-13 (2010)

BOOK REVIEWS

Wind Turbine Noise

Editors: Dick Bowdler and Geoff Leventhall

Publisher: Multi-Science Publishing Co Ltd, 2012, 215 pages

ISBN: 978-1-907132-30-8 (paperback)

As we are very aware throughout Australia, the noise from wind turbines is a major constraining factor in the location of individual turbines and in particular wind turbine farms. The outcomes from the Senate Select Committee in 2011 and the more recent guidelines from State environmental agencies attest to the extent of interest in this topic. Investigation, understanding and reduction of noise from wind turbines is a necessary progression in the development and increased use of this form of renewable energy. The book provides a single stop reference on the topic and it has been authored by an international group of experts.

The first of 8 chapters starts at the beginning with a discussion on basic acoustics by Geoff Leventhall and in a mere 11 pages takes the reader from sound pressure to frequency analysis. Chapter 2 by Stefen Oerlemans from the National Aerospace Authority discusses the various primary noise sources in wind turbines – their prediction and techniques for reduction. Andrew Bullmore follows with the sound propagation from wind turbines with some very nice colour graphics to highlight particular concepts. Chapter 4 on wind turbine noise at the receiver is written by Bo Søndergaard and deals with measurement and assessment of noise in the vicinity of buildings and inside rooms. A major source of complaints about wind turbine noise is the variability, ie. amplitude modulation in the sound and this is discussed by Frits van den Berg and Dick Bowdler. Chapter 6 is continued by Frits van den Berg and deals with effects of sound on people including not only the data from noise surveys but also non auditory effects on reactions such as changes in property values. The penultimate chapter is by David Hessler on the measurement and analysis of wind turbine noise. The concluding chapter by Mark Bastasch summarises criteria for wind turbine noise in different countries. This is probably the chapter that will draw most attention as people try to compare the relevant guidelines in their region with others around the world. It is also the section that will need frequent updating as criteria and guidelines change as the data from more studies become available and are taken into consideration by the regulatory authorities.

So this book provides an excellent overview of the aspects related to wind turbine noise. It is reasonably well indexed so the casual user can go directly to the section that may provide the guidance they are seeking. The primary audience for this book is the scientific, regulatory and planning community, but it will also be of relevance to those in the wind power industry and to environmental organisations and all those with an interest in the topic of noise from wind turbines.

Marion Burgess

Clay's Handbook of Environmental Health - 20th Edition

Editor: Stephen Battersby

Publisher: Routledge, 2011, 942 pages

ISBN: 978-0-415-49285-0 (hardcopy)

This is the 20th edition of a substantial reference book, 942 pages, and covers thoroughly two domains of public health within the remit of the UK Charted Institute of Environmental Health – namely health improvement and health protection. Of the 21 chapters, the first 8 cover the knowledge base for all aspects of environmental health including human physiology and health. The subsequent chapters deal with different aspects of environmental health and in particular the legal aspects. The chapter on 'Noise and Vibration" has been written by Andrew Colthurst and Steve Fisher both from WSP Acoustics (a design engineering and management consultancy based in UK).

Overall the chapter is easy to read and introduces clearly the basic concepts of sound with particular relevance to environmental noise measurement. The metrics discussed are biased to those applicable in Europe. And there is a greater emphasis on the UK legal and regulatory requirements. However this all provides a concise summary as well as criteria for outdoor and indoor spaces which can be compared with Australian guidelines. There is even a small section on wind turbines and one on occupational noise. Very general guidance on the options for mitigation complete the chapter.

This would be a very useful handbook for the resources of a large consulting company where staff need to have a general overview understanding of issues outside their main field of work. It would also be valuable for those undertaking projects outside Australia as it provides a ready source of comparative 'acceptable' guidelines and approaches to environmental noise for UK and Europe.

Marion Burgess

Marion Burgess is a research officer in the Acoustics and Vibration Unit of UNSW, Canberra

NEWS

Rail Infrastructure Noise Guideline Draft

The NSW Interim guideline for the assessment of noise from rail infrastructure projects (IGANRIP) was first published in 2007. Its purpose was to assist the ongoing expansion of rail transport by streamlining the approvals process for rail infrastructure projects, while ensuring that potential noise and vibration impacts are assessed in a consistent way and minimised as far as possible. The Draft *Rail Infrastructure Noise Guidelin*e (RING) is an update to IGNARIP. It has been amended to reflect feedback from transport, planning, infrastructure construction and rail industries. Advice from the broader community is now sought prior to finalising this guideline.

For more information see www.environment.nsw.gov.au/noise/railnoise.htm

NSW Planning Guidelines: Wind Farms

The Draft NSW Planning Guidelines: Wind Farms have been prepared to ensure effective consultation with local communities and to deliver improved consistency, transparency and rigour in the planning assessment process. The guidelines have been prepared in consultation with the community and energy industry to provide a regulatory framework to guide investment in wind farms across NSW, while minimising and avoiding any potential impacts on local communities. The draft was available for comment till March but the draft and the submissions can be viewed at the NSW Planning & Infrastructure website

www.planning.nsw.gov.au

Citation for commitment to female progression

An ongoing commitment from professional technical services firm AECOM to the advancement of women within its ranks has resulted in its Australian business being recognised as an Employer of Choice for Women (EOCFW) for 2012 by the Federal Government's Equal Opportunity for Women in the Workplace Agency (EOWA). Citation recipients are non-government organisations with gender diversity programs that encourage and support the pursuit of excellence amongst female team members striving to succeed in their chosen careers. Acknowledgement as an EOCFW is welcome recognition for AECOM. The business has recently brought gender imbalance into sharper focus, introducing a number of initiatives under the umbrella of a wider Diversity and Inclusion program that aims to create further opportunities for female professionals in its 4500-strong Australian workforce.

The Noise Compass - A New Approach to Directional Noise Monitoring

The latest noise monitoring system in development at Acoustic Research Laboratories Pty Ltd (ARL) employs an innovative approach to the age old problem of directional noise measurement. ARL have combined advanced acoustic signal processing methods, employed for decades in complex military sonar systems, with a multi-microphone array allowing calibrated noise level and compass bearing information to be determined.

The multi-octave array comprises three nested horizontal planar sub-arrays each containing sixteen microphones as illustrated in Figure 1. The spatial filtering provided by each sub-array is specifically optimised for operation in three separate low frequency octave bands.

The noise signals received by each of the nested sub-arrays are processed using conventional time domain beamforming techniques. A total of 216 beams are produced by the beamformer, covering the full range of compass bearings in each octave band.

The spatial filtering provided by the beam pattern is highly dependent on microphone array geometry. In the design of any receiver array, trades-offs are necessary between array maximum size and microphone count. The sixteen element sub-arrays selected for the Noise Compass yields the beam pattern illustrated in figure 2.

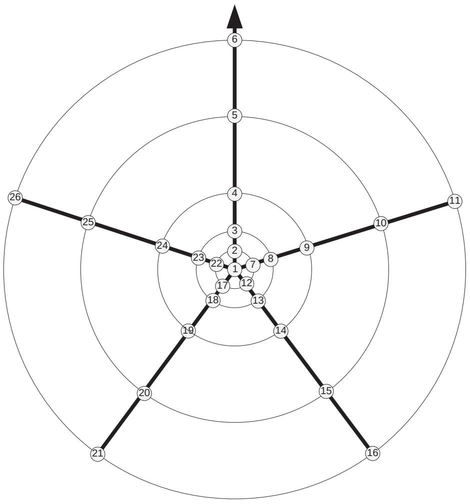


Figure 1 - Microphone Array Layout

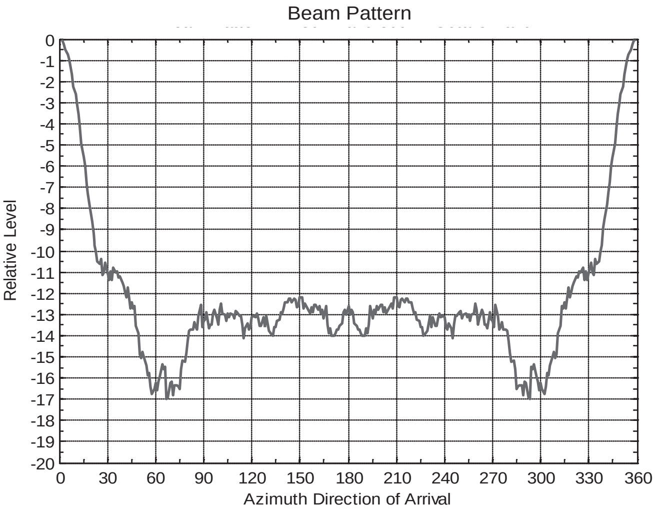


Figure 2 - Beam Pattern

Each beam output is a time-domain signal representing a particular 'look' direction in a designated frequency band. These directional signals are processed using high-speed classical sound level measurement algorithms based upon ARL's Firefly acoustic processing, enabling reliable measurement of multiple simultaneously emitting noise sources.

The processing also supports calculation of interval-based percentile statistics (including L_{eq}) for every directional beam as well as the standard omni-directional measurements.

All system components can be calibrated and maintained to relevant sound level meter standards. This includes the octave band filtering used in the time domain beamforming, thus supporting calibrated directional measurements.

In operational use, the Noise Compass system automatically conducts microphone serviceability checking and reporting, and due to the large number of sensors, degraded mode operation is possible with up to three failed microphones. Support functions include automated report generation, alarm condition triggering and real-time IP streaming of directional audio and noise levels.

For further information, contact:

Acoustic Research Laboratories
Proprietary Limited
A.B.N. 47 050 100 804

Noise and Vibration Monitoring Instrumentation for Industry and the

www.acousticresearch.com.au

Level 7, Building 2 423 Pennant Hills Road
Pennant Hills NSW 2120 AUSTRALIA
Telephone: +61 2 9484 0800
Facsimilie: +61 2 9484 0884

New module in Education Program

The Professional Education in Acoustics program has been established in Australia with the aim of providing appropriate short courses to meet the needs of those embarking on a career in acoustics. It is primarily intended for those entering or who have recently entered the acoustic consulting field. The program has been developed with assistance from of the Association of Australian Acoustical Consultants. The program is offered in distance learning mode under the short course program of UNSW, Canberra. Three modules corresponding to (i) General Principles of Acoustics (ii) Acoustic Measurement and (iii) Room and Building Acoustics (a new module) are available. For more information on the program see www.aaac.org.au/au/aaac/education.aspx or email Marion Burgess at m.burgess@adfa.edu.au

New work health and safety laws

New work health and safety legislation commenced in New South Wales, Queensland, the Australian Capital Territory, the Commonwealth and the Northern Territory on 1 January 2012. This consists of an integrated package of a model Work Health and Safety (WHS) Act, supported by model Work Health and Safety (WHS) Regulations, model Codes of Practice and a National Compliance and Enforcement Policy. For details and the situation in the other jurisdictions see www.safeworkaustralia.gov.au/Legislation/Pages/ModelWHSLegislation.aspx

Code for prevention of work-related hearing loss

In relation to prevention of work-related hearing loss, the final version of the model Code of Practice for Managing Noise and Preventing Hearing Loss at Work can be found at http://www.safeworkaustralia.gov.au/AboutSafeWorkAustralia/WhatWeDo/Publications/Pages/Managing-Noise-Preventing-Hearing-Loss-COP.aspx

Update to AS/NZS 1270

The NZ Dept of Labour publication on *Attenuation data for hearing protectors* was updated in Nov 2011. As the data comes from tests to AS/NZS 1270, it is of use to Australian workplaces. It now contains colour photos of most of the protectors and can be viewed at

http://www.osh.dol.govt.nz/publications/booklets/classified-hearing/index.asp

Noise management poster

The WA Department of Mines and Petroleum has a good poster on noise management on its website available at

http://www.dmp.wa.gov.au/documents/Misc/MSH_Poster_ProtectAtWorkAtHome.pdf

NEW PRODUCTS

Noise Compass - A new approach to directional noise monitoring

The latest product from Acoustic Research Laboratories Pty Ltd (ARL) employs a new approach to the problem of directional noise measurement. ARL have combined proven acoustic signal processing methods, employed for decades in complex military sonar systems, with a large microphone array allowing calibrated noise level and compass bearing information to be determined for multiple simultaneous noise sources. The multi-octave array comprises nested multi-microphone sub-arrays each providing spatial filtering in azimuthal bearing. The noise signals received by each of the nested sub-arrays are processed using conventional time domain beamforming techniques. A total of 216 time domain beams are produced, covering the full range of compass bearings in each of three octave bands. The beams are available to the operator as directional audio streams, and are also further processed using classical sound level measurement algorithms based upon ARL's Firefly high-speed acoustic processing engine. The system calculates interval-based percentile statistics (including L_{eq}) for all directional beams, providing accurate and reliable measurement of multiple simultaneously emitting noise sources. All system components can be calibrated and maintained to relevant sound level meter standards, including the octave band filtering thus supporting calibrated directional measurements. In operational use, the Noise Compass system automatically conducts microphone serviceability checking and reporting, and due to the large number of sensors, degraded mode operation is possible with up to three failed microphones. Support functions include automated report generation, alarm condition triggering and real-time IP streaming of directional audio and noise levels. Further information contact: Acoustic Research Laboratories Pty Ltd, tel. (02) 9484 0800 or visit http://www.acousticresearch.com.au

Fantech TD Silent In-Line Fans

The Fantech TD Silent 250mm and TD Silent 315mm models are high performance, high capacity fans that are quieter than any other fan in their class. Noise reduction is due to a technically advanced design and internal construction. Sound waves produced inside the fan are captured by a sound-absorbent internal membrane resulting in an efficient low profile fan that operates very quietly. The Silent Series fans have specially designed aerodynamic inlet to improve air-flow performance and further reduce noise. At 3 metres, the TD Silent 250mm has a sound pressure of 42dB(A) in low speed and 47dB(A) in high speed. The TD Silent 315mm has a sound pressure of 44dB(A) in low speed and 50dB(A) in high speed. The Silent Series fans are compact and ideal for installations in false ceilings where space is often restricted. For further information visit

www.fantech.com.au/silent

SAVTek Wireless noise monitoring system

SAVTek have released a new wireless noise monitoring system developed by Munisense of the Netherlands. The system can be set up with as few as one or as many as one hundred noise monitoring stations. The monitoring stations may be either Type 1 or Type 2 and are solar powered. The units monitor A and C weighted noise levels in the form of statistical parameter levels such as L_{90}, L_{10} and L_{eq} as well as streaming audio. The data is uploaded via a 3G gateway to a secure server. The results can be accessed from any computer with an internet connection and the noise levels can be viewed in real time. Audio recorded by the units can be listened to in real time or as recorded files. Reports of noise data can be viewed on the computer or downloaded for historic periods (days, weeks or months). The Munisense noise monitoring system is ideal for monitoring city noise levels to verify noise modelling predictions. The system is also well suited to monitoring the noise from construction sites, transportation, concerts and events, operational noise from industry, manufacturing facilities and quarries. Weather units can also be included in the system. For further information contact Darryl Watkins, tel. (07) 3300 0363 or email

dwatkins@savtek.com.au

PRIZES & AWARDS

NSW Division Travel Award

The New South Wales Division of the Australian Acoustical Society is offering up to three (3) awards to research students to attend the Acoustics 2012 conference at the Esplanade Hotel, Fremantle, Perth, 21-23 November 2012. The amount of each award is $1200 and is to be spent towards the conference registration fee, travel to and from the conference venue, and accommodation. The award is open to all research students who are AAS student members of NSW Division as well as research students endorsed by AAS members of the NSW Division. The closing date for the applications is 25 May 2012. For more information and the application form go to http://www.acoustics.asn.au/joomla/notices.html

Excellence in Acoustics Award

The CSR Bradford Insulation Excellence in Acoustics Award aims at fostering and rewarding excellence in acoustics. The entries will be judged on demonstrated innovation from within any field of acoustics. The prize

Vale Warren Renew

1934 - 2012

The Australian Acoustical Society mourns the loss of Warren Renew.

Warren Douglas Renew MAAS passed away on 1 March 2012.

One of seven children, Warren was born and spent his early years in South Townsville and in Kelvin Grove when his family moved to Brisbane. Warren's career in engineering and noise abatement commenced in 1952, when he joined Commonwealth Engineering (Comeng) as a cadet engineer, latterly, having completed an Associate Diploma in Electrical and Mechanical Engineering, Warren worked as an industrial engineer in their rolling stock division.

In 1961, Warren left Comeng, to undertake full time study at the University of Queensland, graduating in 1965 with a Masters in Engineering Science. His thesis was entitled A periodic method of determining thermal diffusivity. While at UQ, Warren assisted as a tutor in Applied Mechanics (the lecturer was Bob Hooker). In the years 1996 to 1968, Warren worked for AMPOL at their Lytton refinery. After a stint as a consultant engineer, Warren spent the years 1970 to 1972 with BP in London. Warren's interest in noise control seems to have developed during his time at UQ and the Refinery. Later when Bob Hooker introduced an undergraduate course in Engineering Noise Control, Warren was amongst several practicing engineers who undertook the course as an extension. In the UK he was a member of the group which supervised the specification and testing of noise control elements for BP's refineries and contributed to the 1971 OCMA specification Procedural Specification for the limitation of Noise from Plant and Equipment for use in the Petroleum Industry. (Related work was eventually to result in the CONCAWE noise modelling study). Returning from the UK, he assisted with the (then) Queensland Institute of Technology's environmental health noise extension course and worked as an engineer in private practice. During the years 1974 to 1979 he was a process engineer at Evans Deakin. With the passage of the Queensland Noise Abatement Act (1978), the then "Division of Air Pollution Control" added Noise Abatement to its title and in 1979, Warren joined Queensland government service as their first noise inspector and 'senior noise control officer'. Warren remained with the Division through its multiple reorganisations and changes of acronym until the latter part of 2011 when health issues forced his retirement.

Warren was an early member of the Society in Queensland (when he joined, there were only three other Queensland members) in the then, wider New South Wales Division of the Australian Acoustical Society. In the early 1980's the Director of the Queensland Division of Noise Abatement and Noise Control was determined to hold a Noise Conference in Queensland and it seemed a good idea if the Conference was conducted under the auspices of the AAS, thus in 1984 a meeting of interested persons was held (39 attendees and 25 apologies), with the intent of forming a new Division. From that meeting, a group of three, Warren Renew, Noela Eddington and Bob Hooker, prepared a submission which was delivered to Federal Council in November 1984 in Perth. The submission was accepted and in November of the following year the Queensland Division was established. At the commencement of the Division on 24 November 1985, Warren and Bob Hooker joined Federal Council as the first Queensland Councillors. The planned noise conference was held in Toowoomba in 1986 and was a great success. Warren and Bob remained on the Council (and the Divisional committee) through to 1993, with Warren serving as Federal Treasurer during Bob's term as President (1991 – 1993).

Warren contributed to many acoustic conferences in Australia and internationally, including as a member of the organising committees of the 1986 Toowoomba conference, 1991 Westprac IV, Brisbane and Acoustics 2004 at Surfers Paradise. He was the Australian representative on the International Institute of Noise Control Engineering Technical Study Group on Assessment of the Effectiveness of Noise Policies and Regulations: this was a long standing commitment and Warren had the challenging task of trying to obtain the relevant information on noise policy in the many and disparate Australian jurisdictions and massage the key elements into a format that would fit with the needs of the international study group report. An early exponent of the large scale use of automatic noise logging equipment, Warren was amongst the first to make wide use of the then 'new technology' in the field work for the Brisbane Noise Survey 1986 – 1988. (The Brisbane noise survey, 1986 to 1988, Duhs T, Renew WD, Eddington N, 1989). In recent years Warren enrolled to undertake a PhD with the school of Geography, Planning and Environmental Management at UQ, his research concerned the economic effects of industrial and transportation noise on adjacent residential areas. It is understood the draft thesis was submitted in 2011, at the time of his passing, the work remained in review.

Professionally, Warren is remembered for his calm gentle manner, his willingness to provide mentoring to colleagues and his practical approach to the resolution of noise problems. In a great many cases, Warren's role was one of key technical input, using his experience and understanding of the technicalities of noise control to cut through and achieve reasonable, practical and prudent outcomes to difficult industrial noise issues. Indeed there were many instances where, acoustical consultants would prevail upon the Noise Abatement Division/ DEH/DoE/EPA and DERM, to have Warren participate in negotiations between the Department and industry to find the, up to that point, elusive common ground for the setting of appropriate and practical noise conditions. In such matters, things were looking up when Warren's participation was agreed.

Warren was always helpful, pleasant, polite and respectful to all - a true gentleman. He will be sorely missed.

Warren Middleton, Russ Brown, Marion Burgess, Ian Hillock includes a trophy and a gift to the value of $1,500. Entries are open to any professional, student or layperson involved or interested in any area within the field of acoustics who is a member of the Australian Acoustical Society at an appropriate grade. Group entries are also allowed. As this is an award that recognises excellence and innovation it is important that all submissions are representative of up to date technology, creativity and relevancy. Thus entries need to be recent and normally no older than three years at the time of submission. Projects which commenced prior to this time need to demonstrate important developments within the last three years. An entry form is to be completed with all relevant particulars included. The submission should be forwarded as an electronic word document attachment to the AAS General Secretary. Presentation of the Award will be made at the Annual Conference of the Australian Acoustical Society. Entries close 5.00 PM 31 August 2012. For more information go to http://acoustics.asn.au/joomla/excellence-in-acoustics-award.html

MEETING REPORTS

NSW Division

On 22nd February, Yolande Stone, Director of Policy Planning Systems and Reform, NSW Department of Planning and Infrastructure, and Jeff Parnell, a Noise Specialist also within the NSW Department of Planning and Infrastructure, gave an overview on the Draft NSW Planning Guidelines for Wind Farms. The guidelines were prepared to ensure effective consultation with local communities and to deliver improved consistency, transparency and rigour in the planning assessment process. The guidelines were prepared in consultation with the community and energy industry to provide a regulatory framework to guide investment in wind farms across NSW, while minimising and avoiding any potential impacts on local communities. Yolande gave an overview of the NSW planning process and how issues such as noise from wind farms become a major priority for the Government. Jeff discussed the science underpinning the draft guidelines and the objective of the document. The document is available on the Department website at: http://www.planning.nsw.gov.au/Development/Onexhibition/tabid/205/ctl/View/mid/1081/ID/66/language/en-US/Default.aspx

On 20th March, Paul Maddock, Noise Policy Section, Office of Environment and Heritage, gave an overview on the Draft Rail Infrastructure Noise Guideline. The Draft Rail Infrastructure Noise Guideline (RING) is an update to IGNARIP. It was amended to reflect feedback from transport, planning, infrastructure construction and rail industries. Advice from the broader community was also sought prior to finalising the guideline. The document is available on the OEH website at: http://www.environment.nsw.gov.au/noise/railnoise.htm

VIC Division

A technical presentation on the new Noise in Regional Victoria guidelines was held at the Melbourne EPA office on 7th March. Approximately forty members of the AAS VIC Division attended the seminar given by Elaine Just, Noise Project Officer, Policy Regulation, EPA. The non-statutory guidelines are used for setting the recommended maximum acceptable levels for industry noise impacting on sensitive areas outside the Melbourne metropolitan area. The NIRV has now replaced the N3/89 Interim Guidelines. In larger regional cities and at the urban fringe of Melbourne, NIRV uses the procedures already established in SEPP N–1 to set recommended levels. In ‘rural areas’, including small towns, NIRV presumes that the background levels will be low. Therefore, background levels are only checked where there is a prominent local noise source such as a freeway or highway. NIRV sets the recommended levels primarily according to the land-use zoning. However, factors such as: the “base noise level”, the distance from the receiver to the zone boundary, the effect of multiple noise sources and noise due to mines, quarries or landfills may vary the limit. Noise emission from the site is measured at noise-sensitive areas using the procedures in SEPP N–1. This sets out how to measure the noise and make appropriate adjustments to the measurement to obtain an ‘effective noise level’ which can then be compared to the recommended level. The NIRV is available from the EPA website at: www.epa.vic.gov.au/noise/industry_noise.asp

QLD Division

The Queensland Division had the pleasure of hearing a technical talk on 7th March by Dr Elizabeth Beach, a Research Psychologist at the National Acoustic Laboratories (NAL). Dr Beach spoke about Leisure Noise and presented the results of some of the recent research by NAL. She provided information on how both the physical studies and opinion surveys were constructed and executed and outlined the results of these. The studies focused on common Leisure Noise sources such as nightclubs and music concerts as well as some other not so obvious sources such as exercise classes. The results presented by Dr Beach showed significant risk to those exposed to a high level of Leisure Noise, especially nightclubs and the results of surveys conducted showed a low opinion and take-up of mitigation options such as ear plugs. The talk was very interesting and provided insight into an area that the typical society member may not commonly work in.

FUTURE CONFERENCES

ACOUSTICS 2012 Fremantle

The annual conference of the Australian Acoustical Society will be held at the Esplanade Hotel in Fremantle, Western Australia, from 21-23 November 2012. The theme for this conference is “Acoustics, Development, and the Environment” and the conference will include plenary sessions addressing acoustical and vibration aspects of major infrastructure projects from transportation and construction in the urban context through to mining. In addition to papers on this theme, papers on all aspects of acoustics are welcome including Transportation noise and vibration, Noise and Health and Underwater Acoustics. The conference will also include sessions and workshops on acoustical topics that fall outside of the main theme. More information at www.acoustics.asn.au/joomla/acoustics-2012.html

ICSV19

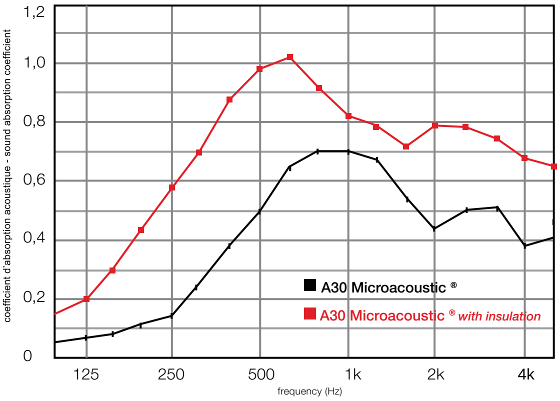
The 19th International Congress on Sound and Vibration (ICSV19), sponsored by the International Institute of Acoustics and Vibration (IIAV) and Vilnius University, will be held from 8-12 July 2012 at Vilnius University in Vilnius, Lithuania. The Scientific Program includes invited and contributed papers and a series of keynote lectures. More information at www.icsv19.org

Inter-Noise 2012

Inter-Noise 2012 will be held at the Marriott Marquis Hotel in New York City, USA, 19-22 August 2012. This large congress of over 1000 delegates will include: Three days of technical papers spanning many areas of noise and vibration, including the congress theme: Quieting the world’s cities, Three plenary sessions on City noise codes, The effects of noise on children, and Airport noise, and a large exhibition and series of short courses on noise and vibration control. More information at www.internoise2012.com

ISMA 2012

The 25th edition of the international ISMA Noise and Vibration Engineering Conference (ISMA2012) will be held in Leuven, Belgium, from 17-19 September 2012. It will be organised in conjunction with the 4th International Conference on Uncertainty in Structural Dynamics (USD2012). More information at
http://www.isma-isaac.be/conf/


1,2
1,0
0,8
0,6
0,4
0,2
0
coefficient d'absorption acoustique - sound absorption coefficient
125
250
500
1k
2k
4k
frequency (Hz)
■ A30 Microacoustic ®
■ A30 Microacoustic ® with insulation

DIARY

2012

13 – 18 May, Hong Kong, China
Acoustics 2012 Hong Kong
http://acoustics2012hk.org

10 – 13 June, Prague, Czech Republic
Euronoise
http://www.euronoise2012.cz

20 – 22 June, Chicago, USA
Music Induced Hearing Disorders
http://www.aes.org/conferences/47/

2 – 6 July, Edinburgh, UK
11th European Conference on Underwater Acoustics (ECUA 2012)
http://www.ecua2012.com

8 – 12 July, Vilnius, Lithuania
19th International Congress on Sound and Vibration (ICSV19)
http://www.icsv19.org

22 – 27 July, Porto, Portugal
15th International Conference on Experimental Mechanics (ICEM15)
http://paginas.fe.up.pt/clme/icem15

12 – 15 August, New York, USA
Inter-Noise 2012
http://www.internoise2012.com

19 – 24 August, Beijing, China
23rd International Congress on Theoretical and Applied Mechanics (ICTAM2012)
http://www.ictam2012.org

9 – 13 September, Portland, USA
nternational Conference on Noise and Vibration Engineering (ISMA 2012)
http://www.isma-isaac.be/conf/

17 – 19 September, Leuven, Belgium
ISMA Noise and Vibration Engineering Conference (ISMA2012)
http://www.isma-isaac.be/conf/

21 – 23 November, Perth, Australia
ACOUSTICS 2012 Fremantle
http://www.acoustics.asn.au/joomla/acoustics-2012.html

2013

26 – 31 March, Vancouver, Canada
IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP)
http://www.icassp2013.com

2 – 7 June, Montréal, Canada
21st International Congress on Acoustics (ICA 2013)
http://www.ica2013montreal.org

7 – 11 July, Bangkok, Thailand
20th International Congress on Sound and Vibration (ICSV20)

26 – 28 August, Denver, USA
Noise-Con 2013
http://www.inceusa.org/nc13

27 – 30 August, Denver, USA
Wind Turbine Noise 2013
http://www.windturbinenoise2013.org

15 – 18 September, Innsbruck, Austria
Inter-Noise 2013
http://www.internoise2013.com

2014

25 – 30 May, Florence, Italy
IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP)
http://www.icassp2014.org

6 – 10 July, Beijing, China
21st International Congress on Sound and Vibration (ICSV21)

17 – 19 November, Melbourne, Australia
Inter-Noise 2014

2015

10 – 15 May, Metz, France
International Congress on Ultrasonics (2015 ICU)
http://www.me.gatech.edu/2015-ICU-Metz/

Meeting dates can change so please ensure you check the conference website: http://www.icacommission.org/calendar.html

VIBRATION ISOLATORS FOR NOISY ELEVATORS

In a new luxury 20-storey residential tower in downtown Taipei City, Taiwan, vibration from the motor driving four Mitsubishi elevators was causing significant structure-borne noise. This noise transferred through walls and into living units whenever the lifts were running, which was very often.

The problem was extremely noticeable on the upper levels of the building, including the most expensive apartment. The residents of the building had complained loudly to Mitsubishi about the effect of lift noise on their sleep and quality of life.

In accord with common industry practice, the original design of the elevator relied on straight rubber to isolate the motor from its mount. However this material didn't adequately handle the vibration in this case.

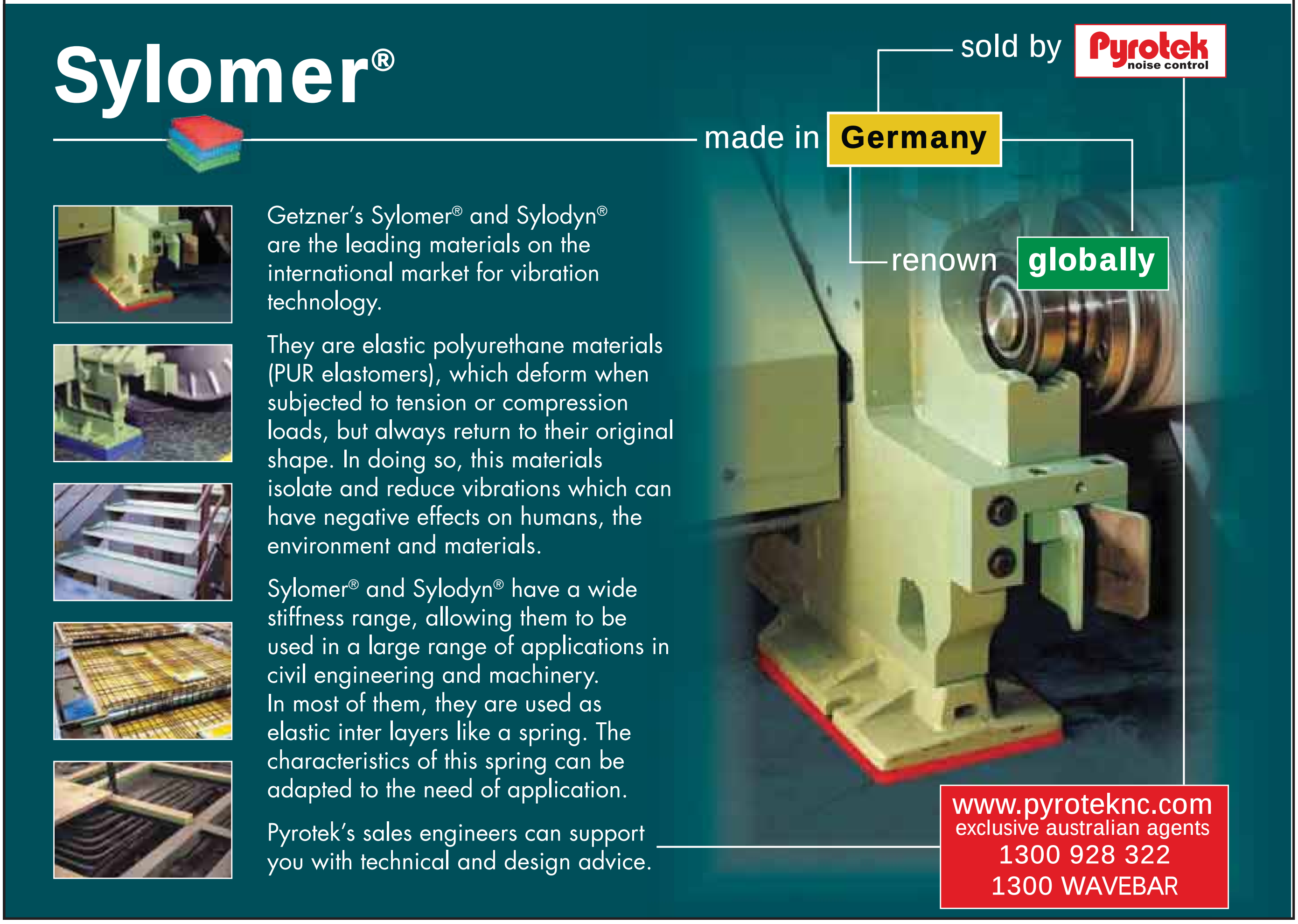
In an attempt to remediate the problem, Mitsubishi spent substantial time and money trying two other kinds of rubber isolator, without success. A vibration damping product was required to provide good isolation from 50 to 160 Hz. Further noise and vibration tests revealed a peak frequency around 400 Hz. Thus, an isolator material that would flex at low loads but remain strong at high loads was needed.

In consultation with Pyrotek Noise Control in Taiwan and Pyrotek's Product Development in Melbourne, an isolation material called Sylomer was selected. Sylomer is an elastic polyurethane material that deforms under tension and compression loads, but always returns to its original form. The results illustrating the improvement in noise levels before and after installation of the Sylomer vibration isolators in the four Mitsubishi elevators are given in Table 1.

The acoustic performance of the Mitsubishi elevators was significantly improved, much to the delight and relief of the building tenants.

Table 1. Noise levels before and after installation of the Sylomer isolator pads

	Frequency Range					
	50 – 400 Hz			Overall		
Lift	Before dBA	After dBA	Improvement dBA	Before dBA	After dBA	Improvement dBA
1 & 2	39.0	34.2	4.8	48.7	39.5	9.2
3 & 4	42.9	28.9	14.0	45.8	38.6	7.2



SUSTAINING MEMBERS

The following are Sustaining Members of the Australian Acoustical Society.
Full contact details are available from http://www.acoustics.asn.au/sql/sustaining.php

3M AUSTRALIA
www.3m.com

ACOUSTIC RESEARCH LABORATORIES
www.acousticresearch.com.au

ACRAN
www.acran.com.au

ACU-VIB ELECTRONICS
www.acu-vib.com.au

ADAMSSON ENGINEERING
www.adamsson.com.au

AERISON PTY LTD
www.aerison.com

ASSOCIATION OF AUSTRALIAN ACOUSTICAL CONSULTANTS
www.aaac.org.au

BARRISOL AUSTRALIA
www.barrisol.com.au

BORAL PLASTERBOARD
www.boral.com.au/plasterboard

BRUEL & KJAER AUSTRALIA
www.bksv.com.au

CSR BRADFORD INSULATION
www.bradfordinsulation.com.au

EMBELTON
www.vibrationisolation.com.au

HOWDEN AUSTRALIA
www.howden.com.au

IAC COLPRO
industrialacoustics.com/australia

NSW DEPT OF ENVIRONMENT & CLIMATE CHANGE
www.environment.nsw.gov.au

PEACE ENGINEERING
www.peaceengineering.com

PYROTEK NOISE CONTROL
www.pyroteknc.com

SINCLAIR KNIGHT MERZ
www.globalskm.com

SOUND CONTROL
www.soundcontrol.com.au

SOUND SCIENCE
www.soundscience.com.au

VIPAC ENGINEERS AND SCIENTISTS
www.vipac.com.au

AUSTRALIAN ACOUSTICAL SOCIETY ENQUIRIES

NATIONAL MATTERS

- * Notification of change of address
- * Payment of annual subscription
- * Proceedings of annual conferences

Richard Booker - General Secretary
Australian Acoustical Society
PO Box 1843 Toowong DC QLD 4066
Tel: (07) 3122 2605
email: GeneralSecretary@acoustics.asn.au
www.acoustics.asn.au

SOCIETY SUBSCRIPTION RATES

For 2011/12 Financial Year:

Fellow and Member	$130.00
Graduate, Associate and Subscriber	$100.00
Retired	$40.00
Student	$30.00

Including GST

DIVISIONAL MATTERS

Enquiries regarding membership and sustaining membership should be directed to the appropriate State Division Secretary

AAS - NSW Division
Laura Allison
c/- AECOM
Level 21, 420 George Street
Sydney, NSW 2000
Tel: (02) 8934 0035
Fax: (02) 8934 0001
Laura.Allison@aecom.com

AAS - Queensland Division
PO Box 760
Spring Hill Qld 4004
Sec: Richard Devereux
Tel: (07) 3217 0055
Fax: (07) 3217 0066
rdevereux@acran.com.au

AAS - SA Division
AECOM,
Level 28, 91 King William St
ADELAIDE S.A. 5005
Sec: Darren Jurevicius
Tel: (08) 7100 6400
Fax: (08) 7100 6499
darren.jurevicius@aecom.com

AAS - Victoria Division
c/- Simon de Lisle
Arup Acoustics
Level 17, 1 Nicholson Street
Melbourne VIC 3000
Tel: (03) 9668 5580
Fax: (03) 9663 1546
simon.delisle@arup.com.au

AAS–WA Division
Unit 3
2 Hardy Street,
SOUTH PERTH 6151
Sec: Norbert Gabriels
Tel (08) 9474 5966
Fax (08) 9474 5977
gabriels@iinet.net.au

ACOUSTICS AUSTRALIA INFORMATION

GENERAL BUSINESS

Advertising Subscriptions

Mrs Leigh Wallbank
PO Box 70, OYSTER BAY 2225
Tel (02) 9528 4362
Fax (02) 9589 0547
wallbank@zipworld.com.au

PRINTING, ARTWORK

Cliff Lewis Printing
91-93 Parraweena Road
CARINGBAH NSW 222
Tel (02) 9525 6588 Fax (02) 9524 8712
email: matthew@clp.com.au

ARTICLES & REPORTS NEWS, BOOK REVIEWS NEW PRODUCTS

The Editor, Acoustics Australia
c/o Nicole Kessissoglou
School of Mechanical & Manufacturing Engineering
University of New South Wales
NSW 2052 Australia
Mobile: +61 401 070 843
acousticsaustralia@acoustics.asn.au

SUBSCRIPTION RATES

	Aust	Overseas
1 year	A$77.20	A$88.33
2 year	A$133.10	A$157.30
3 year	A$189.00	A$227.27

Australian rates include GST.
Overseas subscriptions go by airmail
Discounted for new subscriptions
20% Discount for extra copies
Agents rates are discounted.

ADVERTISING RATES

B&W	Non-members	Sus Mem
1/1 Page	$784.00	$699.15
1/2 Page	$509.40	$457.40
1/3 Page	$392.00	$352.90
1/4 Page	$326.70	$294.00

Spot colour:	available
Prepared insert:	$424.70 Conditions apply
Column rate:	$26.40 per cm (1/3 p 5.5cm width)

All rates include GST

Discounted rates for 3 consecutive ads in advance

Special rates available for 4-colour printing

All enquiries to: Mrs Leigh Wallbank
Tel (02) 9528 4362 Fax (02) 9589 0547
wallbank@zipworld.com.au

ACOUSTICS AUSTRALIA ADVERTISER INDEX - VOL 40 No 1

Kingdom	Inside front cover
Belcur	4
Cliff Lewis Printing.	4
Matrix	4
SAVTek	6
Bruel & Kjaer	36
HW Technologies	44
Renzo Tonin & Associates	56
Renzo Tonin & Associates	71
Sound Level Meters	71
Odeon	83
ARL	85
Barrisol	89
Peace Engineering	90
Pyrotek	91
Thermo Fisher Scientific	93
ACU-VIB	inside back cover
Bruel & Kjaer	back cover

NEW HAND-HELD SOUND INTENSITY SYSTEM TYPE 2270-G

SOUND POWER AND NOISE SOURCE LOCATION USING SOUND INTENSITY?

EASY!

EASY
Sound power
Fulfils ISO, ANSI and ECMA standards

EASY
Noise source location
Number, curve or contour plot on the grid

EASY
Measurement organisation
See rows and columns overlaid on a photo of your surface

EASY
Results before you leave the job site
Overall sound-power calculated automatically

TRADE-IN OPPORTUNITIES AVAILABLE NOW

Contact your local Bruel & Kjaer office for more details

FREE COURSES

Attend free noise source identification and sound power courses

Register online at www.bksv.com/courses

EASY source location using 2D and 3D contour maps mode with PULSE Noise Source Identification software

www.bksv.com/Type2270G

BN 0885 – 12

HEADQUARTERS: DK-2850 Naerum · Denmark · Telephone: +45 4580 0500
Fax: +45 4580 1405 · www.bksv.com · info@bksv.com

Bruel & Kjaer Australia
Suite 2, 6-10 Talavera Road, PO Box 349, North Ryde NSW 2113 Sydney
Tel: +61 2 9889 8888 • Fax: +61 2 9889 8866 • www.bksv.com.au • auinfo@bksv.com

MELBOURNE: Suite 22, Building 4, 195 Wellington Road, Clayton VIC 3170
Tel: +61 3 9560 7555 Fax: +61 3 9561 6700 • www.bksv.com.au • auinfo@bksv.com

Local representatives and service organisations worldwide.

Brüel & Kjær
creating sustainable value