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.

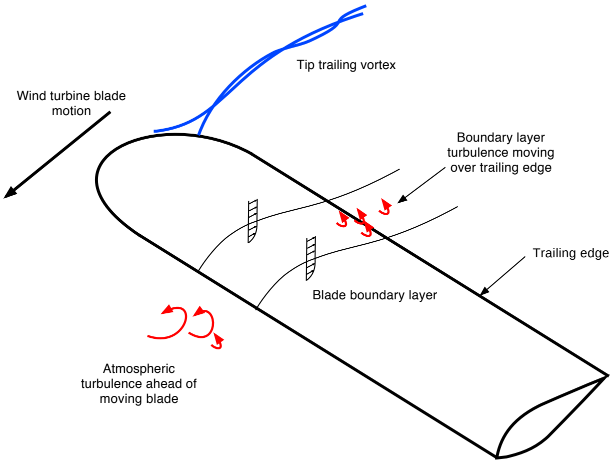

Figure 1. The flow over a wind turbine blade tip

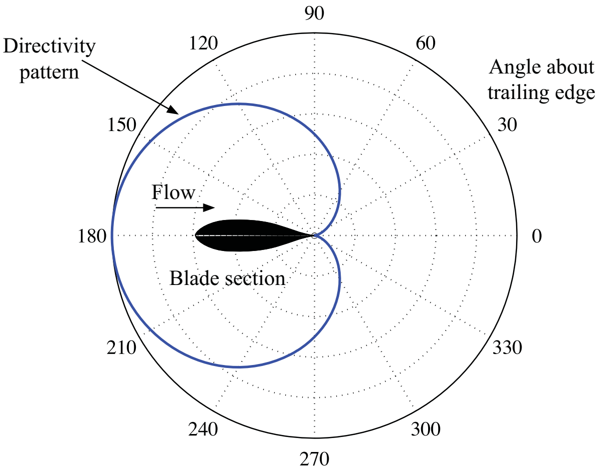

Figure 2. Trailing edge noise directivity (high frequency case)

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

$$f_{peak} = \frac{StV_{tip}}{h - 0.7R} \qquad (1)$$

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.

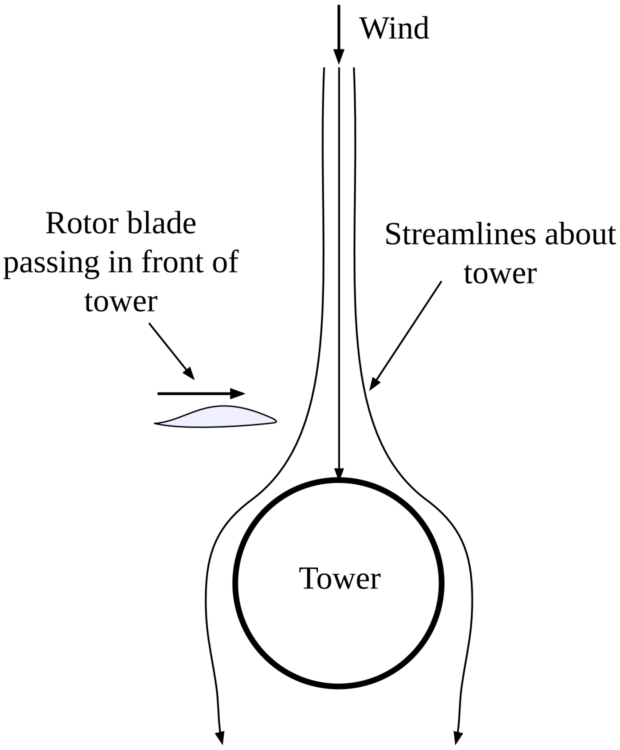

Figure 3. Blade tower interaction

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} ~ 0.6 (11 Hz).

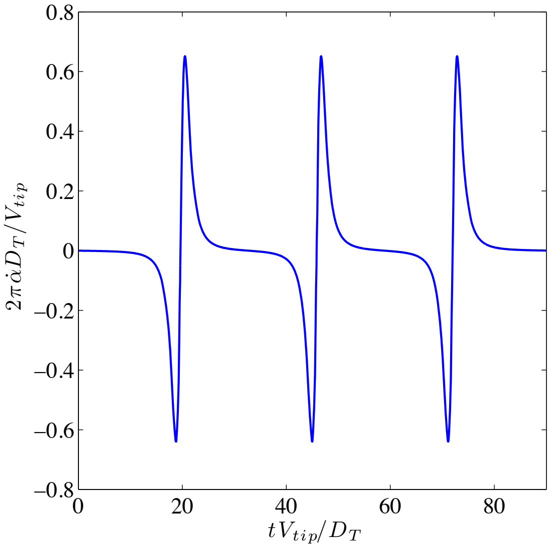

Figure 4. Time variation of BTI noise source strength over one revolution of the GE prototype wind turbine

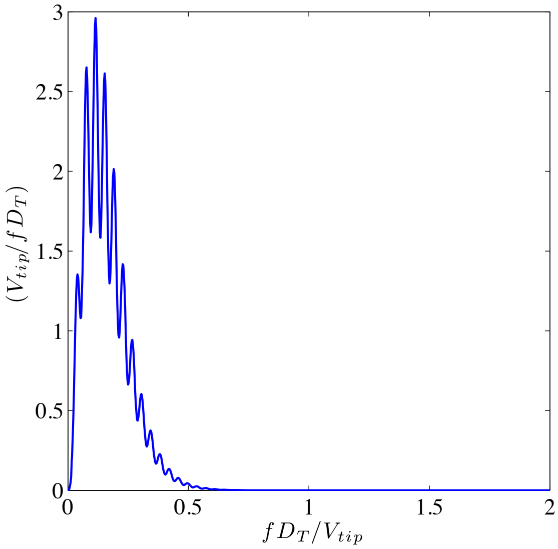

Figure 5. Autospectrum of the BTI noise source signal

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.

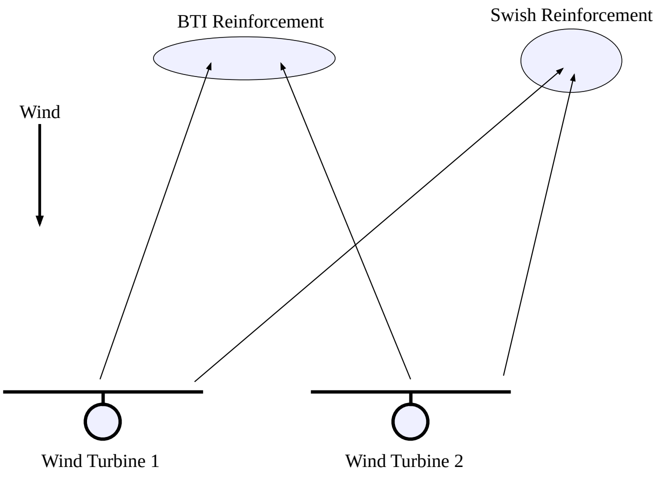

Figure 6. Plan view of two wind turbines with possible zones of noise reinforcement

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.

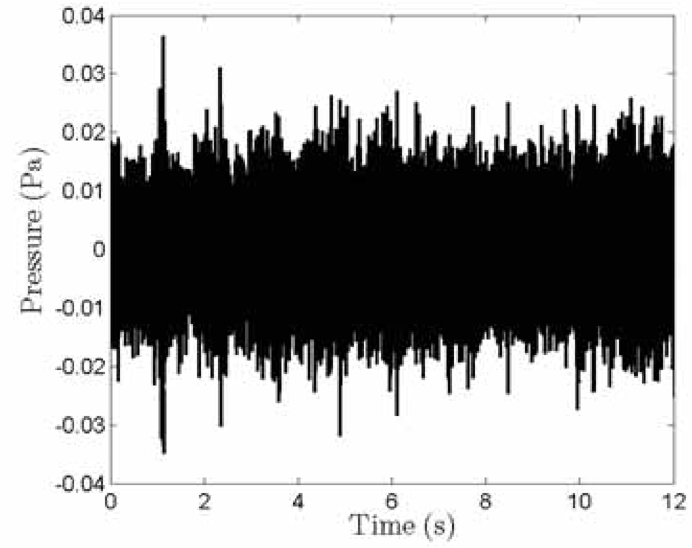

Figure 7. Time series of acoustic data

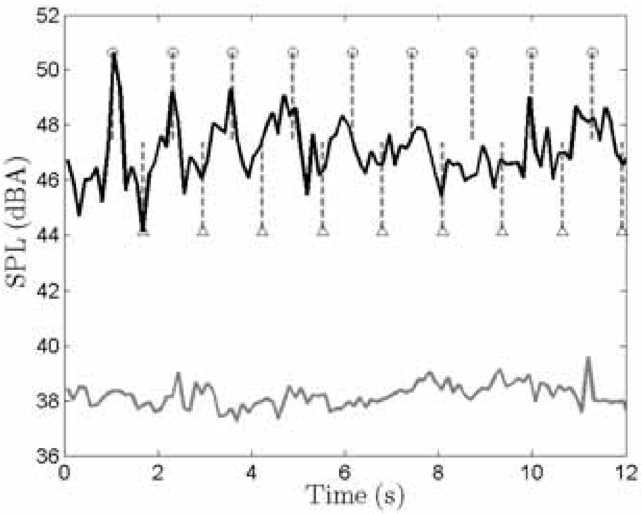

Figure 8. A-weighted SPL with 125 ms FFTs (FAST): near-turbine measurements (black) and measurements (not simultaneous) at a nearby location where wind turbines were not audible (grey). Circles and triangles with dashed lines represent expected signal maxima and minima corresponding to blade pass frequency,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