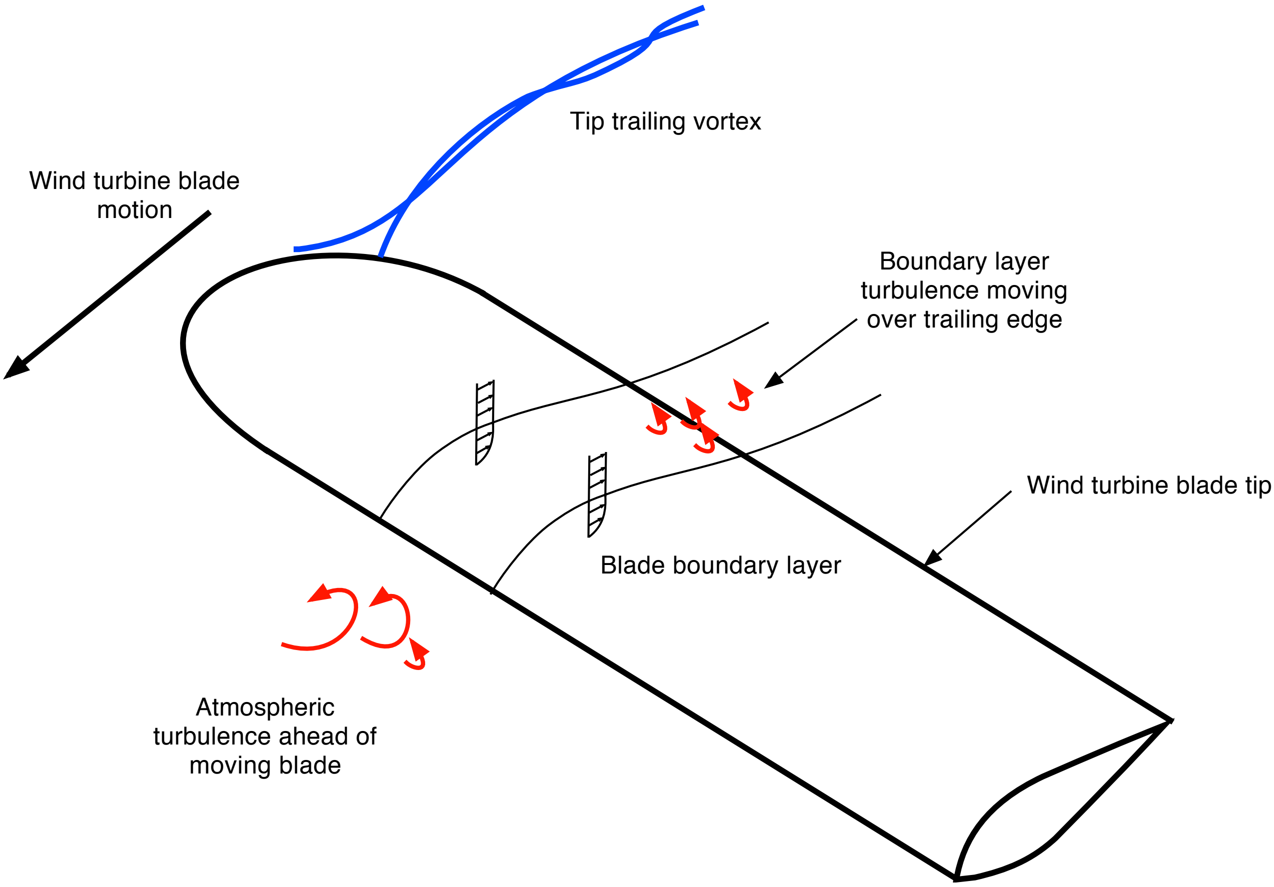

Figure 1: The flow over a wind turbine blade tip.

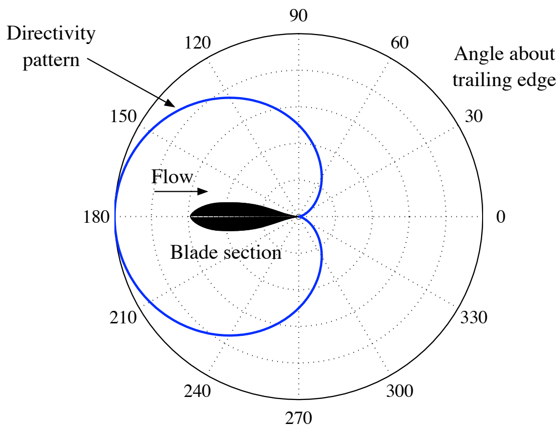

Figure 2: Trailing edge noise directivity.

There are two other, important noise sources that should be mentioned in this brief review. The first is airfoil tip noise that is generated by flow over the blade tip that results in the trailing edge 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, however more work needs to be done in this area.

The second is airfoil tonal noise (Arcondoulis et al. 2010). Here, discrete vortices form either in the boundary layer or wake to create intense tonal noise, with or without a self-reinforcing feedback loop (Moreau et al. 2011). Tonal noise occurs at low-to-moderate Reynolds numbers, hence is not usually a problem for large wind turbines that operate at high 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 wind turbine noise sources 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 leading 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	Turbulence 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 (2009) 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 (Cebeci and Bradshaw 1977) 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 boundary layer height was estimated at the rotor tip to be 24 mm.

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 (Wagner et al. 1996) for this type of noise is contained at a frequency

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

with St = 16.6, h is hub height, V_{tip} is the rotor tip speed and R is blade radius. Using the wind turbine described above and by Oerlemans and Schepers (2009), 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 (Howe 1978). 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 (2004). 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 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 Equation 2, the trailing edge noise generated by the blades will have most energy at about 465 Hz. This is in agreement with the A-weighted noise measurements of Oerlemans and Schepers (2009), which show most acoustic energy contained within the 250-1000 Hz frequency range. Note that these are time averaged, A-weighted results.

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 (1955) 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.

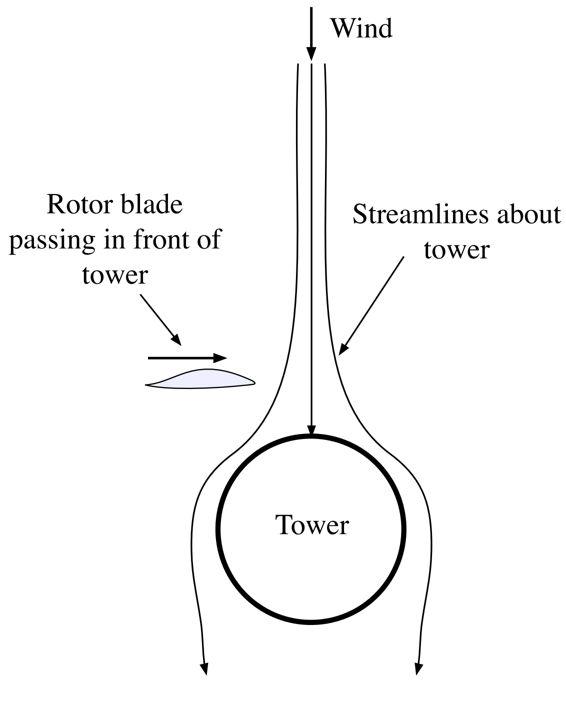

Figure 3: Blade tower interaction.

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 1 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} = 0.23 or 4 Hz and multiple components from fD_T/V_{tip} = 0.075 (1.3 Hz) to fD_T/V_{tip} = 1.38 (24Hz).

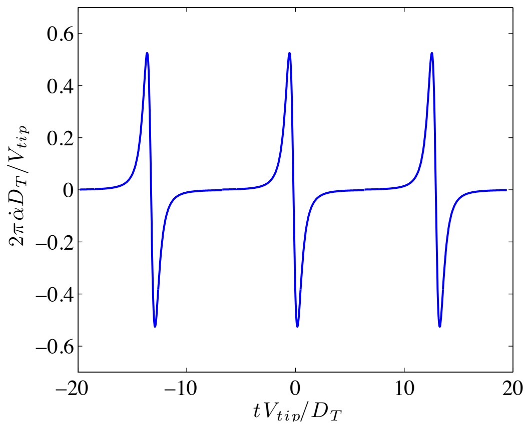

Figure 4: Time variation of BTI noise source strength over one revolution of the GE prototype wind turbine.

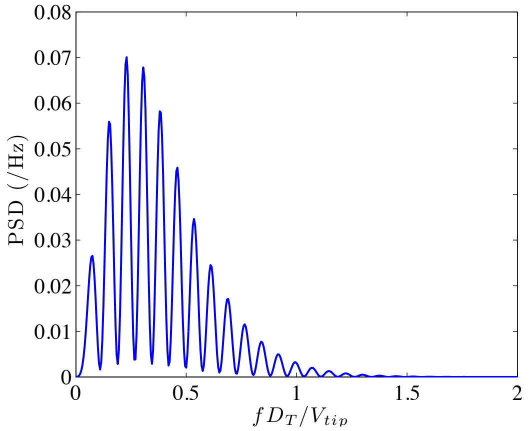

Figure 5: Autospectrum of the BTI noise source signal.

WIND TURBINE NOISE MEASUREMENTS

The above analysis gives an indication of the frequency scales that we can expect from a wind turbine from three dominant aerodynamic 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 (approx. 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 (Hubbard et al. 1983, Oerlemans and Schepers 2009) 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 above. Recent measurements and observations taken at a European wind farm (Van den Berg 2004) show a marked difference between day and night. During a summer's 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 up to between 500-1000 m 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 (i.e. close to the turbines) audible swish-like noise was observed day and night however, no thumping or pile-driving noise was observed.

To explain some of these observations, Van den Berg (2004) pointed out that the state of the atmosphere at night is different to that in the day. In fact, when the stability of the atmosphere changes to a certain state, the wind at ground level (and at 10 m) 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 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. 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 (2004) 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 (2004) 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 can only contain 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 (2004) 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 (2005).

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 suspect that the same may be true for BTI noise. Currently, there is no methodology or data 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.

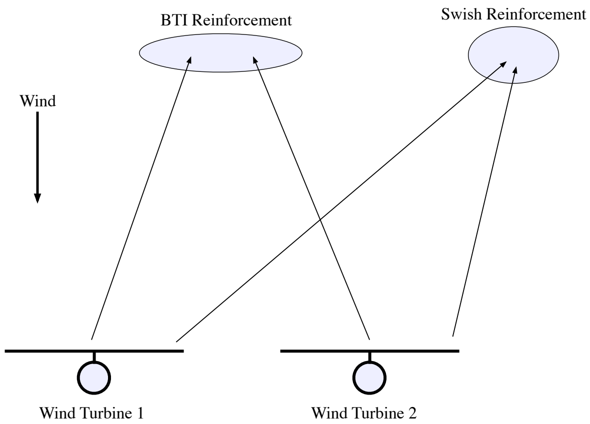

Figure 6: Plan view of two wind turbines with possible zones of noise reinforcement.

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 only (other directions are omitted for clarity) of the turbines 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. 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 understand BTI and swish reinforcement, the model presented provides a framework for understanding and addressing public concerns about wind turbine noise.

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 (Marsden et al. 2007, Lutz et al. 2007). Recently, Jones et al. (2011) developed an optimisation procedure using a semi-empirical model of trailing edge noise to develop new, low noise airfoil designs. Figure 7 illustrates an example of a family of low-noise designs based upon NACA 0012 airfoil. The final design (labelled 7D) achieved a 2.9 dB OASPL noise reduction (over the original NACA 0012) 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 (1991), 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 provide this level of noise reduction (Gruber et al. 2010), and this may be due to the production of additional turbulent noise by the serrations themselves. Porous trailing edge inserts (Geyer et al. 2010) 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. This requires 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 ensure that noise reinforcement does not occur. While this seems a simple and cost effective solution to the problem, it may be difficult to implement

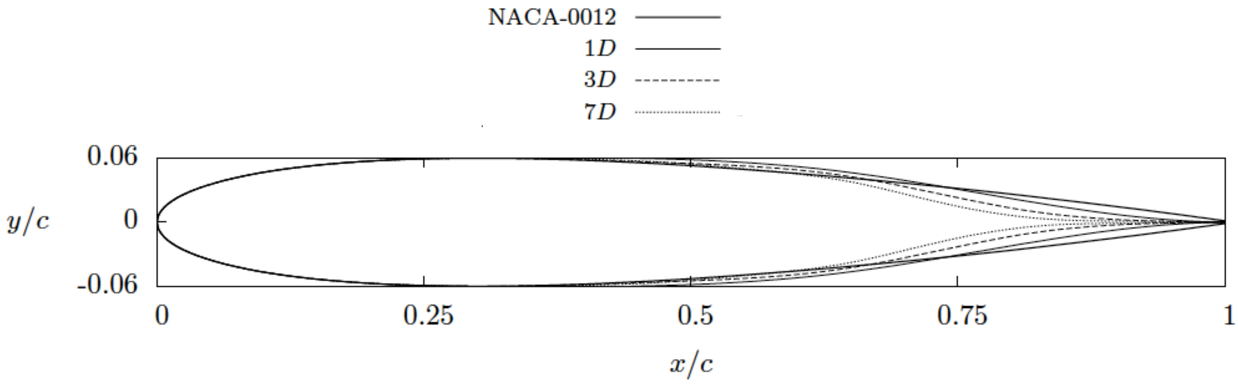

Figure 7: Low-noise, optimised airfoil design of Jones et al. (2011)

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 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 approximately 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 it was found its frequency content had maximum energy at about 4 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 only contain noise from the broadband swish (trailing edge) component. 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.

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