Technical Note

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CONSTRUCTIVE INTERFERENCE OF TONAL INFRASOUND FROM SYNCHRONISED WIND FARM TURBINES: EVIDENCE AND IMPLICATIONS

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SUMMARY

Noise from wind farms is contentious: people who live nearby complain of annoyance, and yet broadband measurements of infrasound seem to indicate the noise is generally not above audibility criteria. The paradox can be resolved by supposing that wind farms generate a strong tonal signal at the blade passing frequency, 0.8 Hz, and that this infrasound, with a wavelength of 400 m, can constructively interfere if two or more wind turbines operate in synchrony and the path lengths differ by a multiple of 400 m. Coherent infrasound at 0.8 Hz could propagate many kilometres, would tend to carry many harmonics due to the rapid changes within its waveform, and the high harmonics in the 20–30 Hz band have the potential to be heard by human ears. The existence of coherent infrasound from wind turbines has not been specifically recognised, but evidence of the phenomenon can be discerned in two anomalies contained in data from recent infrasound monitoring of wind farms in South Australia. This paper interprets the anomalies in terms of a model which suggests that wind farms produce enhanced sound pressure levels when the blades of multiple machines become mutually entrained and the sound from them becomes coherent. The inference is that acoustic measures, which assume wind turbine signals are stationary, may not be accurate indicators of peak noise levels.

BACKGROUND

There has been much debate about the impact of wind turbine noise on people living next to wind farms. In Australia, some of that debate has been conducted in the pages of this journal (e.g. [1]). While there have been many complaints of annoyance from neighbouring residents, the complaints have often been dismissed because acoustic measurements indicate the levels of infrasound should be inaudible since they do not rise above background noise levels [2]. The National Health and Medical Research Council recently commissioned a systematic review of the problem [3], and it issued for comment a Draft Information Paper summarising its findings [4]. The paper states that "Evidence suggests that levels of infrasound are no higher in environments near wind turbines than in a range of other environments. For example, a South Australian study [Evans et al. 2013] observed similar levels of infrasound at rural locations close to wind turbines, rural locations away from wind turbines, and at a number of urban locations" ([4], p.12).

This paper assesses the Evans et al. measurements, along with some related findings, and finds there are certain limitations which may put a question mark over such a conclusion. The synthesis here highlights the relevant measurements, describes possible limitations in interpretation, and recasts the findings in terms of coherent infrasound. It is pointed out that the waveform generated by blade–tower interaction (BTI) carries many harmonics that can reach into the audible range, and it is suggested that these high harmonics, when emitted by synchronised wind turbines, could be a major cause of the problem. A recent proposal [5] for minimising the infrasound problem by desynchronising the blades is endorsed.

INFRASOUND

As stated by the NHMRC, "infrasound is considered by some to be an important component of noise from wind farms" (p.12 of [4]). In this context the recent work of Thorne [6, 7] is particularly relevant, for he points out how constructive interference from synchronised wind turbines can lead to "heightened noise zones", a term developed by him in conjunction with Bakker and Rapley [8]. Thorne considers the synchronous rotation of wind turbines (p.42), although he appears to be more concerned with amplitude modulation of blade swish than with direct propagation of 1 Hz infrasound and its harmonics. His simulations were done with emission frequencies of 20, 48, and 66 Hz (p.51). The work of Doolan et al. (2012) [5] is also of interest, for they theoretically consider BTI, and derive a curve (shown here as Figure 1) for how the amplitude of the generated pressure varies over time. This theoretical waveform indicates that the signal has a large and sudden variation in pressure at the blade passing frequency (1 Hz). A spectrum of this waveform (their Fig. 5) shows the expected sequence of multiple harmonics.

Doolan and colleagues note that there is currently no methodology to accurately quantify BTI noise, but they say it could be important. They draw a diagram of how two BTI sources, which they describe as "temporally coherent", may constructively interfere (their Fig. 6), perhaps at a residence, and suggest that actively desynchronising the turbine blades may be a way to avoid the heightened pressure pulse.

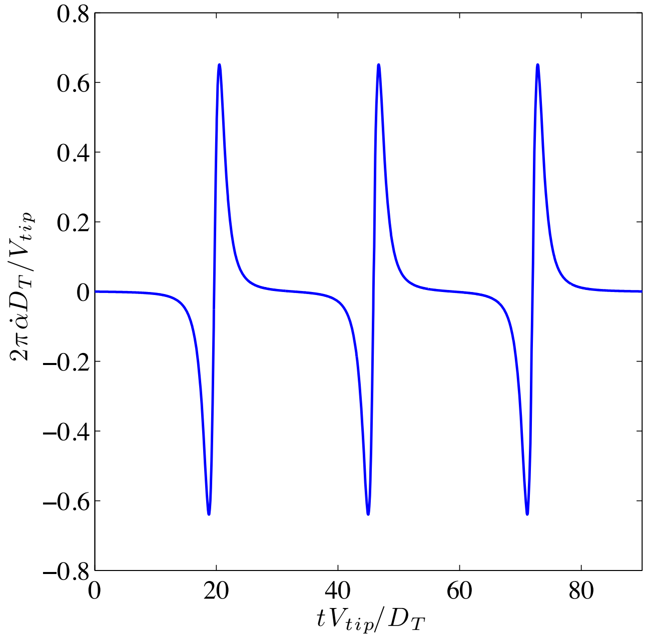

Figure 1. The acoustic waveform generated by a wind turbine as its blades pass the supporting tower (theoretical calculation of blade–turbine interaction from Doolan et al. (2012) [5], with permission). The frequency of the waveform is about 1 Hz and is tightly controlled, creating the possibility of the pressure pulse from one set of turbine blades to entrain another set. The steeply rising portion of the waveform makes it well suited for synchronisation with other such waveforms; it also produces many harmonics.

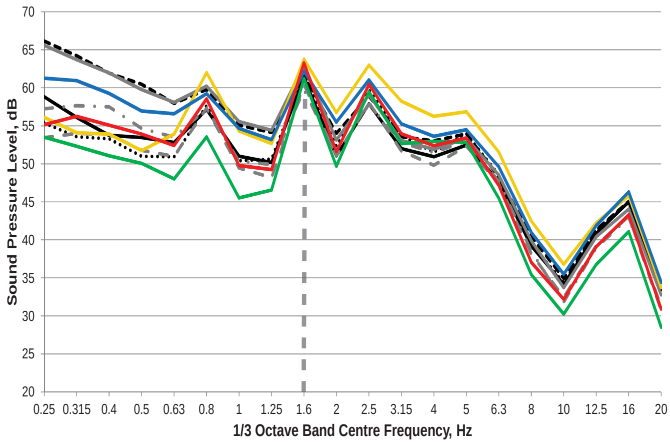

Figure 2. Absolute sound pressure levels in 1/3-octave bands from 0.25 Hz to 20 Hz measured by Evans et al. at Bluff Wind Farm, South Australia. Note the distinct peaks at 0.8 Hz, 1.6 Hz, and 2.5 Hz. The different traces are for different times, 4 with the wind farm operating (coloured lines), and 6 with it switched off (black and grey). Note the apparent anomaly that at 1.6 Hz (added vertical line) there is less than 3 dB difference between all measurements, *including between on and off*. Modified from [9], with permission.

This paper validates the idea that strong 1 Hz infrasound can arise by constructive interference of many wind turbines emitting signals such as in Figure 1. It also adds the idea that synchronisation of wind turbines may be promoted by the tendency of oscillators of closely matching frequencies to become physically entrained. The possibility that the blades of multiple wind turbines become locked together is a hypothesis that this technical note puts forward for further discussion.

Below, the implications for audibility of multiple entrained turbine blades are set out, and a mechanism is described whereby the BTI harmonics may be sensed by the ear. The paper emphasises that the control circuits used in South Australian wind turbines to regulate power output act to bring many turbines to almost the same rotational frequency, and hence are liable to produce entrainment and increase infrasound energy levels. Supporting evidence from recent South Australian monitoring data [9, 10] is discussed.

Signature of the blade pass frequency

Evans et al. (2013) [9] measured infrasound emitted from two wind farms, Bluff and Clements Gap, and the former showed particularly interesting results. The researchers found that at Bluff the infrasound contained clear peaks at the blade pass frequency of 0.8 Hz and at its harmonics of 1.6 Hz and 2.5 Hz, and the authors describe how these spectral peaks are a characteristic signature of a wind turbine's revolving blades. The peaks can be clearly seen in Figure 29 of their work, and are shown here in Figure 2. They are also visible in their Figures C3–C8, and in one figure for Clements Gap (the lower trace of Figure C9).

There are two important properties of these peaks which should be emphasised. First, these infrasonic signals have very long wavelengths – a frequency of 0.8 Hz, for example, has a wavelength of about 400 metres.

Second, these signals have a narrow bandwidth because the turbine blades in a wind farm are, for reasons of generation efficiency, regulated to maintain a constant rotational speed. The Suzlon S88 turbines installed at the wind farm measured by Evans and colleagues maintain a relatively constant rotational speed of 15–17 rpm, largely independent of wind speed variations (16 rpm = 3.75 sec/rev = 1.25 sec/blade for 3 blades = 0.8 Hz blade pass frequency). This factor deserves greater emphasis. For the Suzlon S88 the set speed at rated power is particularly precise, 15.79 rpm (p.36 of [11]), a speed which is electronically controlled and equivalent to a blade pass frequency of 0.7895 Hz. Therefore, if operating conditions permit, the rotation rate is fixed to a potential accuracy of 1 part in 1500 (a stability of 0.07%). Even if the windspeed fluctuates a little, the electronic controller will attempt to keep the rotational speed fixed at that optimum value. In other words, for windspeeds at and above the rated wind speed (12 m/s for the Suzlon turbine), the unit operates on a nearly *vertical portion* of the rotational speed–torque space, virtually independent of wind speed. The design of the Suzlon S88 allows a degree of slip between the blades and the generator, a factor which smooths out speed fluctuations but also has the side-effect of leaving the turbine (and its neighbours) open to mutual entrainment in which blade rotations become locked together.

Of course, there are a range of turbine types, each with its own operating characteristics set by a controller circuit. However, in South Australia the Suzlon S88 predominates [12]. The controller sets the operating characteristic, essentially a plot of torque against rotational speed, with the aim of optimising the power output as windspeed changes [13]. The controller and its algorithms are proprietary and are kept confidential by manufacturers. Nevertheless, once the wind speed reaches a point at which the turbine has reached its rated output, the general operating strategy is to actively adjust the torque to keep the rotational speed of the blades constant (Ch. 7 of [14]). Most turbines, including so-called 'variable speed' designs, have characteristics with vertical, or steep, portions along which the rotational speed is dynamically regulated for optimum power extraction (e.g., Fig. 4.9 of [13]; Fig. 7.12 of [14]; [15]).

A potential outcome of this tight, but slightly accommodating, regulation is that, for moderate windspeeds and above, all the blades in a wind farm might turn at almost exactly the same speed, making it highly likely, as explained in more detail below, that at least some will become synchronised. It is not uncommon to see the blades of a wind farm passing the tower at the same time (see Figure 3), and the likelihood that this occurs merely by chance are minute. Informal observation of a wind farm near Canberra, where Suzlon S88s are installed, showed that when two neighbouring 3-blade turbines were visually aligned so that one was in front of the other (producing a 6-pointed star), this configuration would sometimes stay perfectly fixed for more than a minute.

Figure 3. Monitoring wind turbine noise at an operating wind farm, Waterloo, South Australia. Notice that the blades of the four turbines have closely matched phase. Considered as a random event, the chance of 4 turbines having all phases equal to within 5° of each other are $(5/360)^3$ = about 1 in 2 million. Photo: EPA South Australia, with permission.

Such synchronisation implies that the blades will act as *coherent sources* of infrasound energy as they pass the towers. Whenever the generators come into synchrony, because of control circuits and physical entrainment, a wind farm could become a strong infrasound source. In this circumstance, it is inevitable that the waves will constructively interfere at various points (and destructively interfere at others). Doolan and colleagues discuss this theoretical possibility [5], and suggest a remedy in terms of adjusting each turbine so that the blades are never synchronous; however, at that time the data was not available to prove their point. This paper brings together findings which give the idea added plausibility. In fact, recent data from the same group [10] points directly to synchronisation at work, and this is evaluated in a later section.

Entrainment produces coherence

The key factor promoting a synchronous state is the universal phenomenon of mutual entrainment. It was first documented by Huygens when he noticed that two small pendulum clocks attached to the same wall became synchronous. Synchronisation of oscillators of closely matched frequency is now widely recognised in many branches of physics. It is therefore to be expected that physical coupling between turbine blades will occur aerodynamically, perhaps giving rise to the synchronicity seen in Figure 3. Interactions via electrical loading of the generators might also contribute to synchrony, and this idea has been explored for fixed-speed generators [16-18]. These studies, together with informal observations and the clear evidence of Figure 3, strengthen the possibilities outlined by Thorne [6, 7] and Doolan and colleagues [5].

Entrainment of a collection of oscillators is relatively simple to grasp intuitively (see the synchronisation of 32 metronomes at http://www.youtube.com/watch?v=kqFc4wriBvE), but in practice it is difficult to predict. It depends on multiple mutual interactions which are essentially chaotic [19]. If a number of wind turbine blades become synchronised and the sources become coherent, sound pressure levels will increase. For example, two wind turbines would have an intensity 6 dB louder than a single turbine, and four might have an intensity 12 dB louder. When one considers that a wind farm may have dozens of wind generators, the chances that some of them will become synchronised increases.

Unlike a set of metronomes, it is not suggested that all the turbines will become synchronous because their spacing may not support it, but the possibility is enhanced by the wavelength of infrasound (0.8 Hz = 400 m) being about the same as the spacing between wind generators, which are often placed in a line along a ridgetop (e.g., Fig. 3 of [20]). Allowance will need to be made for the propagation times between towers and for the distances from the towers to points of constructive interference. Such analysis is beyond the scope of this technical note. Although the analogy is imperfect, a simple comparison that conveys the concept is a swarm of cicadas. Each cicada emits its own regular chirping; however, because of mutual sensing and interaction, at some point the whole swarm can synchronise its sound and sing in chorus. At this point, the sound pressure becomes appreciably louder.

Another relevant factor is that a line of wind generators may be considered a line source rather than a point source. This means that, at right angles to the line, the intensity will fall off much more slowly with distance ($1/r$ rather than $1/r^2$); moreover, in directions along the line, the intensity might reach levels much greater than with a single generator and propagation could extend in a beam for tens of kilometres, especially since atmospheric attenuation of infrasound is small.

Coherence leads to nodes and antinodes

Constructive interference from coherent sources means that infrasound pressure at the blade passing frequency (and its harmonics) could be high, even at locations far away. It is also the case that coherent sources could interfere destructively, but given the generally equi-spaced arrangement of wind turbines in a farm (see for example Fig. 9 of [21]), the actual situation is likely to be an alternating pattern of constructive and destructive points (nodes and antinodes). Thorne [7] illustrates this for low frequency sound (his Figs 21–25), although his analysis does not extend to infrasonic frequencies where the effects will be even more marked. In terms of impact on local residents, the pattern of nodes and antinodes will depend on location and the wavelength of each harmonic, and will shift with wind, temperature, and atmospheric stability. Importantly, there will also be fluctuations in phase on the scale of tens of seconds due to the blades slipping in and out of synchrony – an entrainment effect which will lead to sudden phase jumps.

Broadband infrasound measurements can miss tonal components

If the coherent infrasound hypothesis is true, then the method of measuring the broadband sound pressure level as a single G-weighted measure encompassing energy over 0.15–315 Hz (as done by Evans and coworkers) may not be the most appropriate in terms of infrasound audibility. The authors measured the broadband sound as about 50–60 dB SPL and then compared it to natural sources over the same band. Their conclusion, endorsed by both the Systematic Review [3] and the Information Paper [4], is that there were "similar levels of [broadband] infrasound at rural locations close to wind turbines, rural locations away from wind turbines, and at a number of urban locations" (Section 6.1, paragraph 7). This creates a puzzle, for why is it that people living near wind farms complain of rumbling sounds, often with 1 Hz periodicity, while people in the city do not, and why are the annoyance levels so variable over time? [22]. Adding to the puzzle are some of the authors' one-third octave measurements below 20 Hz: on some occasions there was no difference in recorded level at 1.6 Hz between when the turbines were operating and when they were switched off (see Fig. 2).

There is a possible explanation for both these puzzles, and it is that the G-weighted measures over 0.15–315 Hz are not capturing the audibility of fluctuating narrow-band infrasound that slips in and out of phase. Although G-weighting is a general measure intended to reflect the audibility of low frequency sound, it may not accurately represent the audibility of sounds which incorporate many harmonics that reach into the audible range (20 Hz and above). There is work to show that the perception of tones and broadband noise is similar [23], but this is for single tones only, not sets of harmonics. In the latter case, if all harmonics are in phase, the *peak pressure* will be greater, and ref. 23 suggests that infrasound may be detected via a peak detection mechanism, so that the peak pressure is more important than the RMS pressure. In addition, since the loudness range of infrasound is very compressed, a small rise in pressure can lead to a substantial increase in loudness, and this applies both to constructive interference of multiple coherent infrasound and to the in-phase superposition of its harmonics. Moreover, ref. 23 describes how infrasound may be easily sensed by modulation of low frequency sounds, and so any harmonic content above 20 Hz could promote turbine audibility. More research is needed in this area. A related issue is whether the 1 Hz periodicity people hear derives directly from the infrasound or from modulation of the constant aerodynamic noise emitted by the moving blades (see Fig. 6 of [5] and [24]).

An additional factor that may make low-frequency sound more audible than a single measurement indicates is the use of long averaging times (several minutes). This means that instants when the infrasound is at its loudest (when the sources lock together) are averaged along with the quietest times (when the sources are out of phase). There is therefore the possibility that the measured signal is not stationary, as standard analyses assume, but a fluctuating sequence of in-phase and out-of-phase conditions. The question of the enhanced audibility of such a signal will be considered later, but at this point it is informative to look closer at the evidence that coherent infrasound exists.

DIRECT EVIDENCE FOR INFRASOUND COHERENCE

Two intriguing anomalies have recently been reported. The first, by Evans et al. (2013), is contained in a major report on infrasound measurements from windfarms and other locations in South Australia [9]; the second, by Zajamsek and colleagues [10], was presented to a 2013 conference on wind turbine noise and again concerns infrasound measurements at a South Australian wind farm. It is suggested that both anomalies can be explained by the presence of coherent infrasound.

No difference between 'on' and 'off'

The anomaly found by Evans and colleagues is reproduced here as Figure 2 and is indeed curious. In order to determine whether the Bluff Wind Farm was generating infrasound, it was arranged for the wind turbines to be switched off. As a result, the report found that "At Location 8 near the Bluff Wind Farm (Figure 29), the [0.8 Hz, 1.6 Hz, and 2.5 Hz] peaks were detected *at a similar level* during both operational and shutdown periods" (emphasis added). As shown here in Figure 2, the spectrum at 1.6 Hz shows less than a 3 dB variation between all measurements, which is strange given that the peaks are distinctive signatures of wind turbines. The interpretation suggested by the synthesis here is that the convergence of all the 1.6 Hz measurements must have been due to another wind farm (probably North Brown Hill, 8 km away) and that L8 happened to be at an infrasound antinode at the time.

Evans et al. also conclude that "there is a possibility that the peaks in the spectrum during the shutdown resulted from operation of North Brown Hill Wind Farm", a source which was "very faintly audible" during the shutdown (p.37). However, because the sources were below background levels and therefore not a problem, they did not attempt to resolve the paradox of why infrasound levels from a source 8 km away could be higher than from a source 1.5 km away. However, the coherent infrasound model makes it possible to appreciate how, if the antinodes are aligned correctly, this might happen. The situation has as much to do with the phases of the sources as with the distances.

Similarly, Figures C3–C10 of Evans et al. show the same signature peaks at 0.8, 1.6, and 2.5 Hz at two locations, Bluff and Clements Gap, and more comparisons are presented between when the wind farms were operating and when they were shutdown (pp. 61–65). Again, there was little difference for Bluff, although there was for Clements Gap where there is no adjacent wind farm. Once more, the Bluff anomaly was not considered important because recorded infrasound levels were below background (in a one-third octave band), especially for higher wind speeds. Nevertheless, it is significant that in Figure C3, which includes measurements at Bluff for low wind speeds (0 to 3 m/s, when wind turbines do not rotate – p.58), the distinctive peaks at 0.8, 1.6, and 2.5 Hz are still present, again indicating that infrasound from Brown Hill 8 km away (where the wind must have been above 3 m/s) was still contributing. These measurements point to the presence of coherent infrasound that can propagate considerable distances. The question it raises is whether the elevated infrasound levels could have led to troublesome audible sensations at higher frequencies, and this is now addressed.

High harmonics of the blade pass frequency

Another anomaly that can be interpreted as evidence for the presence of highly coherent infrasound comes from the acoustic monitoring of Zajamsek and colleagues [10]. These workers made continuous sound recordings in homes near the Waterloo wind farm in South Australia and matched the level and spectral content of the sound with occasions when the residents noted its degree of annoyance. Of particular interest, they found using narrow-band (0.1 Hz) analysis that in one 'slightly annoyed' case (their Fig. 11) multiple harmonics of the blade pass frequency were present. The harmonics occurred not only at 0.8, 1.6, 2.4, 3.2, 4.0, 4.8, and 5.6 Hz (corresponding to the 1st–7th harmonics, which have been seen in other work), but also at frequencies corresponding to harmonics in the 20–30 Hz band at 29, 33, 34, 35, 36, 37, and 38 times the fundamental.

Such high harmonics are unusual, although they have been seen in musical acoustics (clarinets, for example, see http://newt.phys.unsw.edu.au/music/clarinet/E3.html). Of more relevance, a recent detailed report on the same wind farm [25] records that, when using a spectral resolution of 0.0017 Hz, "each peak [up to 69 Hz] is an exact multiple of the blade-pass frequency" (p. 71). A theoretical explanation for such high harmonics comes from noting that at least the 14th harmonic is present (at about the –40 dB level re the peak) in Fig. 5 of [5], and that, if the plot were extended logarithmically to –60 dB, further harmonics would become visible. Although perhaps 1000 times smaller than the largest BTI harmonic, it is possible that such high harmonics are selectively amplified by room modes in the same way as a Helmholtz resonator can pick out high partials from a musical sound.

Consider that if the 38th harmonic is evident in a 0.1 Hz analysis, then the associated fundamental must have a bandwidth of 0.1/38 or 0.003 Hz. More explicitly, if the 38th harmonic appears at 30.2 ± 0.1 Hz, which it does in Figure 11 of [10], then the fundamental can be accurately specified as 0.795 ± 0.003 Hz. Curiously, this value, which here derives from Vestas V90 turbines, comes close to the specified 0.790 Hz at rated power for the Suzlon S88 controller (set out above). The similarity in BTI frequency suggests that both machines use a similar, tightly specified rotational frequency, and it is this condition which promotes turbine entrainment.

The conclusion is that the high harmonics are sensitive indicators of a narrow-band synchronised condition, and it is a short step to the hypothesis that these high harmonics may be the cause, or at least contribute significantly to, audible annoyance. It is notable that the levels measured in the 20–30 Hz band are within 10–20 dB of audibility (Fig. 8 of [10]; Fig. 3 of [26]), so it requires only a relatively small increase in sound pressure levels in this band for the sound to become audible. In comparison, the levels at 0.8 or 1.6 Hz are about 50 dB below audibility, so these infrasonic frequencies, in themselves, may be less troublesome than the harmonics they give rise to. However, since Zajamsek and colleagues observe that "the 23.3, 28, and 28.8 Hz frequencies are well below the perception threshold" of ISO:226–2003, could there be any other additional factor – over and above constructive interference – responsible for making the sounds audible?

Short-term amplitude fluctuations

The answer could lie in the particular signal processing used. As Zajamsek et al. note, the recorded signal may include "important characteristics that can be averaged out during normal statistical processing methods" (p.2 of [10]). Indeed, it is suggested here that short-term levels, perhaps over 10–15 seconds, might be higher at certain epochs within the 2-minute averaging window. If the period of in-phase synchronisation occurred for say just 10 seconds during a 10 minute sampling period, and if 5 turbines became coherent, then the peak recorded level would be about 7 dB above the average level. An additional 7 dB would place the identified harmonics close to the average threshold of audibility, especially if the ear uses a peak pressure detection scheme [23] and sensitively hears modulation of higher frequency sounds.

It is worth noting that high harmonics also appear at other occasions when the same resident reported 'high annoyance' (Figure 7) and when another resident in another household also did so. However, one anomaly is that the fundamental and its high harmonics do not always appear (Figures 6, 7, 11) every time a resident reports annoyance. It is possible the lack of correspondence might relate to timing uncertainties: intermittent coherence means the analysis windows may not always neatly correspond with the 'annoyance' windows.

A technique to successfully detect intermittently coherent infrasound might involve a refinement of a method used by Doolan and colleagues [10, 22, 26]. These workers analysed wind turbine noise and correlated it with resident annoyance, finding some weak trends. Circumstantially, their work points to acoustic energy below 10 Hz as a possible cause of objectionable thumping at a repetition rate of about 1 Hz. Significantly, when short-term (0.125 ms) fluctuations were investigated using a peak-detection algorithm, variations in unweighted SPLs of up to 10 dB were found. Such variations are consistent with the presence of coherent infrasound that is fluctuating in and out of phase (and may have been larger if the measurements had been made in the 20–30 Hz band instead of the selected 10–1000 Hz band).

Other wind farm studies have also reported short-term fluctuations, and an analysis by Cummings [27] has highlighted a pronounced low-frequency variability. In a separate English case study, a particular 60-second recording shows a clear 0.8 Hz infrasonic component in the waveform until two-thirds of the way through, at which point the infrasound suddenly fades away (reproduced as Fig. 8 of [7]). At the Macarthur wind farm in Victoria [21], Evans observed a sudden increase in infrasound levels which generally affected scores of 10-minute monitoring windows before suddenly disappearing (p. 33 and Figs 17, 18 of [21]). In this case, because the elevated levels (as high as 75 dB-G over 10 minutes) were not associated with changes in wind speed or direction, he believed they were due to 'extraneous' sources and hence they were systematically removed. The concern raised by the coherent infrasound hypothesis is that these instances of extraneous sources, and multiple other similar occasions (e.g., pp. 2, 30, 35, 40, 43, 45, 50, 51, 52, 58 of [21]), may represent an entrained condition of the wind turbines. It is therefore difficult to decide whether the Macarthur report's conclusion – that wind farms contribute little to infrasound and low frequency noise – is robust. This is especially the case when, curiously, not even the fundamental or harmonics of the blade pass frequency appear in any of the displayed spectral plots.

The major limitation of the analysis methods used so far is that they assume the signal is stationary – an almost universal assumption which tends to obscure infrasound that becomes coherent only intermittently. For example, some Canadian work [28] found that average sound levels increased by about 5–10 dB in the 20–30 Hz band after a wind farm was installed in Ontario; however the data was plotted as long-term averages, not peak readings. There could have been many short periods when sound levels were above the threshold of hearing. In some subsequent Australian monitoring work by Doolan and colleagues [26], the frequency resolution was limited to 2 Hz, which misses narrow harmonics; however, in a later undertaking [22] the frequency resolution was higher (0.1 Hz) but an averaging time of 2 minutes was used as standard. Perhaps because of this, narrow band analysis did not reveal harmonics beyond the 7th, and the harmonics were not always seen. Broad correlations with annoyance were found, but there were inconsistencies as well.

It therefore seems crucial that the selected bandwidth settings and signal processing routines are designed to detect nonstationary infrasonic signals. The analysis needs to be narrow band (so that all the BTI harmonics can be detected) and use little averaging, and this combination will involve some compromises in time and frequency resolution as well as with signal-to-noise ratio.

CONCLUSION

The long-standing puzzle has been that standard acoustic measures do not correlate well with reported wind farm annoyance [26] and that the average detected levels appear to be below the threshold of audibility [9, 22]. To resolve this paradox, the concept developed here has been that wind turbine infrasound can be narrow band, have multiple sources, and occur intermittently as the sources drift in (and out of) phase. When two or more sources become entrained, interference at the fundamental of the BTI frequency (0.8 Hz) will give a pattern of nodes and antinodes, and there will also be a different (but related) pattern of nodes and antinodes for each harmonic. If a particular harmonic in the 20–30 Hz band happens to have two or more sources in phase at the measuring point [5, 7], the increased sound pressure level produced has the potential to be audible, and the proposal here is that the intermittency of the in-phase and out-of-phase conditions might underlie wind turbine annoyance. Whenever the blades become synchronised (perhaps for many tens of seconds) the intensity of the fundamental and some of its harmonics could, at nodes, be at least 6 dB larger, but the levels will revert to baseline when the sources fall out of synchrony (Fig. 8 of [7]).

A lingering puzzle is why some people complain of effects from wind farms which persist for hours, not effects which come and go. Such long-lasting symptoms such as headaches and pressure in the ears might be the outcome of pressure effects within the middle ear [29], a possibility only more research can decide.

Taken together, the evaluations made here provide indications that intermittent coherence could be the physical basis for the annoyance of wind farm noise. One key factor is the precise frequency setting of the wind turbine control circuit, and the other is the universal tendency for coupled oscillators to synchronise. The work builds on the 'heightened noise zone' idea of Thorne and colleagues and gives it added weight by regarding the BTI signal as the primary contributor to the problem – this signal carries most of the acoustic energy and has the power to force entrainment of neighbouring blades that are turning at close to the same frequency. The impulse and its many harmonics generated by BTI could also set off resonant room modes in the 20–30 Hz band. The electronic controllers built into wind turbines are identified as exacerbating the noise problem by increasing the chances of entrainment.

If the human ear can hear wind turbine noise, while the measurements say the noise is inaudible, then the remedy is better measurement techniques. The Information Paper's position – that because instruments do not measure anything above ambient background levels then the sound cannot be a problem – may be giving precedence to measurements that could be inappropriate or incorrectly interpreted. If people living close to wind farms report troublesome noise then the preferred response is to find the source of the problem, not question the validity of the reports.

This paper suggests that the apparent paradox between what is heard and what is measured might be resolved by recognising the tonal nature of infrasound at the blade passing frequency (0.8 Hz) and of its harmonics, which may extend to 20–30 Hz. More measurements need to be made at these frequencies and at distances up to tens of kilometres. Measurements at multiple points are needed so that a map of infrasound nodes and antinodes under various conditions can be established. Theoretical studies of the interference patterns caused by regular arrangements of wind turbines would also provide insight.

A relatively simple solution to the problem of wind farm noise may be the one proposed by Doolan and colleagues:

ensure the blades never operate in synchrony. Synchronisation is inherent in the Suzlon turbines with their fixed speed–variable pitch design, although it is not the case with more modern variable speed designs [12]. Even with modern machines, however, the tendency for any set of physical oscillators to synchronise needs to be recognised.

Hopefully this paper will prompt a re-evaluation of wind farm infrasound and how it might lead to audible disturbances. Some of the statements in the NHMRC Draft Information Paper appear to be questionable and may be better reframed. For example, the NHMRC's statement that infrasound from wind turbines does not differ from other natural sources seems inconsistent with the observation that such infrasound has strong tonal components. Its reported effects, including annoyance and disturbed sleep, might be studied by simulated wind turbine noise generated by a speaker, as the draft report recommends (p.20), although reproducing sound with a flat frequency response down to 1 Hz and with accurate phase would no doubt be challenging.

Similarly, there is mounting evidence that wind farm noise can be heard at much more than the 500–1500 m specified by the NHMRC, particularly at night. The review recommends more research into "wind turbine signature" and for field measurements "ranging from 500 m to 3 km and beyond" (p.20). From the issues raised here of the behaviour of coherent infrasound, distances of 8 km and more may be more appropriate. Although measuring down to 0.8 Hz is possible, an easier approach technically may be to use narrow band analysis to detect high harmonics in the 20–30 Hz band, measurements which might relate directly to reported annoyance.

ACKNOWLEDGEMENTS

The author thanks the reviewer for a wide range of challenging questions which have considerably improved the text.

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