Problems Measuring Low Frequency Sound Levels Near Wind Farms

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ABSTRACT

It is current practice to measure sound pressure levels (SPL) from wind farms at a handful of locations in the surrounding countryside. These can be placed near sensitive areas such as residences to provide an indication of the SPL at that point and are used in conjunction with sound level prediction software to infer sound level throughout the affected areas. This paper reports a literature review of human perception of low-frequency sound before describing investigations into sound levels at the Makara wind farm near Wellington, New Zealand where the interference of low frequency sound from the multiple wind turbines form stable SPL patterns. The low frequency emissions from multiple wind turbines were simulated and validated against measurements from microphone arrays. Ten sound frequencies from 1/3 octave immission spectra were chosen from recorded measurements on the site ranging from 55 Hz to 315 Hz. The simulation used the positions of 14 wind turbines closest to a microphone array as point sources of the sounds. Results show that the combined frequencies from a single turbine produced SPL patterns within a 100 m-by-100 m area that varied by 2–5 dB whereas the combined sounds from all 14 turbines varied by 6-13 dB. Validation of these results was achieved by using three 2-by-4 microphone arrays with 1 m, 2 m and 3 m separation between the microphones. These recorded variations of 6–11 dB in their 15-minute, SPL averages. Additional validation was also shown by direct observation; the sound from the wind turbines was observed to appear and disappear within two to three paces between fixed locations. The conclusion is that measurements of low frequency sound levels can vary considerably over even very short distances and that point measurements may not represent the sound levels throughout their immediate neighbourhood.

INTRODUCTION

The rapid introduction of wind farms in many countries has met with problems as communities complain about the noise emissions from the farms while power companies counter that noise levels are too low to cause significant annoyance.

There are many issues with the understanding of the human perception of noise, particularly the low-frequency noise that is predominantly emitted from wind farms, and what constitutes a reasonable level of noise. This paper therefore begins with a literature review of human perception of low-frequency noise before dealing with sound propagation from wind farms and changes in sound level with position.

The main body of the paper investigates the effects of sound interference from multiple turbines and the creation of Heightened Noise Zones (HNZs). This is done through a simulation of the propagation and interference effects from wind turbines at the Westwind wind farm at Makara in New Zealand backed up with microphone array measurements at the site.

BACKGROUND

Literature Review

Low frequency sound

The increasing predominance of low frequency noise as a source of complaint is occurring world-wide, although many researchers agree that the phenomenon is consistently overrated as an environmental pollutant (Benton and Leventhall, 1994). Leventhall, in a paper entitled: “Infrasound from Wind Turbines - Fact, Fiction or Deception”, goes further stating that infrasound (in particular) is “below audible threshold and of no consequence”. With respect to low frequency sound, which Leventhall defines as 10–100 Hz or possibly 5 Hz to 200 Hz, is “normally not a problem, except under conditions of unusually turbulent airflow”. This viewpoint is not shared by thousands of people world-wide who have been affected by wind turbines being built close to their place of habitation, particularly those with greater sensitivity to low frequencies. Whilst a common belief is that residents complain as a result of not liking the loss of visual amenity, Frey contends that “Oftentimes those affected did not object to the construction, accepting the developer’s assurances that the noise would not be problematic”. (Frey and Hadden, 2007)

That wind turbines produce noise which affects some residents and is deemed annoying is beyond question. It remains a matter of on-going research, world-wide, as to the nature of that noise. While large amounts of low frequency noise are produced by wind turbines, it may be that, technically speaking, the low frequency and/or infrasound components are frequently below normal human audibility. Leventhall (ibid.) attributes the entire argument concerning infrasound with respect to wind turbine installations as a misunderstanding that detracts from the real issue of the repetitive swish observed to correspond to the blade-pass frequency of approximately 1 Hz. His explanation is that the swishing noise reported relates to the amplitude modulation of a higher frequency carrier wave with frequencies in the region of 500–1000 Hz. This modulation results from a change in radiation characteristics as the blades pass the tower, however, the modulation frequencies (approximately 1 Hz) do not have an independent and separate existence.

One of the difficulties of low frequency environmental noise is it does not obey a classical and symmetrical decay with distance. The large numbers of turbines produce emissions that have some of the character of point sources but have also been shown to have characteristics of line sources as well, notably a halving of attenuation with distance beyond 750–900m (Shepherd and Hubbard, 1996) thus displaying different sound distribution modes as a result (Guest, 2003). Added to this is that the higher frequencies attenuate faster with distance, meaning that the immission spectra are dominated by low frequency sound. These issues will produce significant variations in sound levels surrounding wind farms and may result in the unique ‘fingerprint’ of such wind farms.

Low frequency sound has been defined as that lying below 200Hz and is noted as a special environmental noise problem, particularly for those people more sensitive to these frequencies. Frequencies below 75 Hz seem to be particularly distressing (Berglund et al., 1996) and may be exacerbated, for example by rattle or vibration of objects (Leventhall, 2004, Persson and Bjorkman, 1988, Shust, 2004).

In measuring sound levels detected by humans, the A-weighted scale is predominantly used, which is intended to mimic the sensitivity of humans at various frequencies. There is significant evidence that this weighting underestimates the sensitivity of humans at low frequencies and also that sensitivity to sound via direct bone conduction becomes more important (Sloven, 2001). Sloven (Moller and Pedersen, 2004), from the noise Section of the Environmental Protection Agency, Rijnmond, Netherlands, simply states that the A-weighting is an unsatisfactory measure for quantifying the disturbance arising from low frequency noise. Rather he favours the use of dBC and even dBG in some circumstances. There is clearly a need for a simple measurement tool which can be used quickly and reliably and which relates better to human annoyance from LFN. In the absence of such a method, Sloven suggests noise complaints should be investigated by using octave bands. An alternative method might involve the use of a combined value utilising both dBA and dBC weightings or linear weighting.

In Belgium and the Netherlands, the C-weighting has taken on greater significance with respect to monitoring LFN from music festivals. The heavy bass beat travels considerable distances and can be extremely disturbing to people, often kilometres away. In some cases, all noise 32Hz and below is forbidden. While concert goers do not notice much perceptible difference in the music, with these low-frequencies missing, they do however feel less in their stomachs.

The extent to which dBA underestimates LFN is vital to understanding the annoyance from LFN sources. One approach to this underestimation problem would be to load the measured SPL at those frequencies where considerable annoyance is experienced, i.e. low frequencies. Nijmegen in the Netherlands, load SPL levels by 5 dB, for example (Dickinson, 2010). Sloven, (ibid.), proposes a more complex loading system:

$$L = A + (0.84A - 29.44) + 0.04\,(C\text{-}A)\,(41\text{-}A) \qquad (1)$$

where A and C are the normal dB weightings and L is the loading factor. This formula is valid in cases of LFN, type Q, night and evening, inside houses, and is based on a comparison with the Dutch standard of 25 dBA as a good environmental sound level limit. The heart of this formula is the value 'C-A' = 21 dB, giving 'normal' LFN, a value derived from experience. The advantages are

- simplicity,
- not needing to know which of the 1/3 octave levels is dominating the spectrum,
- flexibility and
- it connects A-weighting with LFN.

It is important to note that where SPL is measured outside a residence, one cannot rely on the standard industry assumption that there will be 15 dB attenuation through the walls. The assumption on which this is based (that wall openings are less than 5% of the total) has been demonstrated by Dickinson (Moller and Pedersen, 2004) to be false. Dickinson (ibid.) states that the SPL measured inside rooms can vary markedly, from the centre to the corners, for example. It should be understood that the 15 dB attenuation is based on a 'spatial average' which might bear little resemblance to what a person actually hears in the room, particularly if loud nodes are predominant in the area normally occupied by their head while sleeping.

At low frequencies human sensitivity to sound is reduced as is the dynamic range (van den Berg, 1999). As sound at low frequencies requires far greater SPL to be perceived as above the threshold of hearing, this value comes closer to the threshold of pain. Together these mean that small changes in sound level will result in large, perceived changes in loudness. An additional difficulty of using a single number such as A-weighted SPL is that, notwithstanding the differences between individuals, there also exists a significant difference with respect to age. Much of the research into the annoyance of sound is conducted in laboratory settings, particularly using pure tones, which provides good-quality, accurate information. However, the downside is that it removes the subjects from real-world experiences where habituation and/or sensitisation may occur. It is also common for predominantly young people to be the subject of the laboratory-based research as it is common practice throughout the world that psychology and physiology laboratories, which are based within universities, rely on students to be use as guinea pigs. People under 25 respond differently to those of older age groups and differences of 10 dB are not uncommon in research relating annoyance to sounds (Dickinson, 2010).

Sound from turbines

There are multiple sources of sound from a wind turbine (Dickinson, 2010, Hubbard and Shepherd, 1991) that result from the aerodynamic forces on the blades and between the blades and the tower, the turbulence effects from the helical wakes, as well as the mechanical forces within the turbine hub and gear-train. It is usually the interaction between the blades and the tower that produces modulation close to the 'blade-passing frequency,' which is usually about 1Hz, that is dominant. Others consider that it is the pulses caused by each blade replacing the previous one that creates this 'blade-passing frequency.'

Measurement of sound from wind turbines shows that much of the sound energy lies in the low frequency range with the highest sound levels sometimes occurring in the infrasound region (<20 Hz) . This combination of low frequencies from wind turbines and the human response to these frequencies mentioned earlier may, in part, explain the much lower sound levels required to trigger annoyance due to wind turbines as compared with other noise sources (Hubbard and Shepherd, 1991).

Prediction of sound levels

Sound from wind farms

While single turbines emit noise from several points, e.g. hub, tower and individual blades, at a reasonable distance these can be assumed to be one single, point source. For multiple turbines in a wind farm, which are distributed widely to minimise the reduced efficiency due to wake and turbulence effects, this assumption can no longer be considered tenable. For instance, a section of the West Wind wind farm at Makara, near Wellington, New Zealand is 5 km long, containing 14 turbines. Some houses are only 1.2 km distant.

Beyond about 750 m the propagation of the low frequency sound downwind tends to follow an inverse-distance reduction in sound level rather than an inverse-square relationship (Dickinson, 2010). The sound levels predicted using the inverse-square law will therefore underestimate the true levels significantly (Mosley, 2010) based on current prediction software.

The practice of sound level prediction for multiple turbines is to calculate the sound level from each turbine and add that to the aggregate of all the turbines, as incoherent sound, to find the sound level at any given point. What does not appear to have been considered in any practical sense, is the interference effects that must occur from the interaction of the sound from these multiple sources, i.e. Superposition Theory. Such an analysis is now presented.

Analysis of Turitea and Makara Wind Farms

Both the Turitea (in the Manawatu Disctrict of New Zealand) and Makara wind farms are spread over large areas of land within their respective locales. Both have turbines placed near the ridge-lines of ranges with the houses in valleys below. The Makara wind farm is placed on an extended range of hills with houses in the many winding valleys between.

Analysis of the turbine layout in both locales shows wind turbines installed in straight lines and arcs. The potential effect of these formations at affected homes is to enhance sound emissions and propagation due to the additive effects of turbines operating approximately together. The effect is significant under adverse weather conditions as observed at two New Zealand (e.g. a south-east wind in the case of some homes in the Manawatu and north-west or southerly conditions at Makara) and not significant under different, non-adverse weather conditions.

Residents have noted these weather conditions that cause noise from the turbines to be significantly louder. However, the effects appear to be highly localised, with one house reporting noise while another nearby does not and vice versa. In both cases, sound levels have also been observed to change markedly over several metres, disappearing and reappearing with distance, but not time.

Mosley (Thorne, 2010) has studied the variation of noise levels surrounding a wind farm in the Manawatu, using a postal survey and concluded that heightened noise is found on lines radiating from the wind farm similar to the spokes on a wheel.

Sound Interference

As with all waves, sound waves can interfere with each other, constructively or destructively. In the former case, the compressive portions of the wave arrive at the same time as do the rarefied portions. This results in greater compressive-to-rarifaction pressure differences, which equates to larger amplitude sounds (louder). For destructive interference, compressive and rarefied portions arrive at different times, resulting in some degree of cancellation and thus lower amplitudes (quieter).

While it might be easy to visualise the pattern formed by this effect on sound waves of a single frequency and few sources, the effects can quickly become very complex. For instance, Figure 1 shows the interference pattern for 14 turbines, in phase, at Makara from a single frequency. What is discernible from this figure are the anti-nodal lines, particularly at the ends of the line of turbines, that represent constructive interference occurring over a distance.

When multiple frequencies are also introduced the effects are too complex to visualise *a priori*.

Research into sound level prediction of wind turbine noise has not attempted to investigate this issue, either because it is considered too complex or because it is assumed that the range of frequencies present will wash out any effect of interference. Wind turbine proponents often advance the theory that the ‘noise’ from the turbines will either blend in with, or be drowned out by, other environmental sounds, such as the wind in the trees or the sound of a stream (Hayes and Botha, 2010). Both of these examples produce complex sounds that may, in some respects, be considered broad-band noise. The latter point may be why such proponents feel compelled to make this statement. Such broad-based assumptions are not well supported by the documented noise complaints, world-wide. In particular, the Makara wind farm has generated 787 complaints from 1st June 2009 to 31st January 2010 (Bakker et al., 2009).

HEIGHTENED NOISE ZONE (HNZ)

To understand the reasons for marked changes in sound level with location, the concept of a Heightened Noise Zone (HNZ) is introduced. This is the combined effect of directional sound and vibrations (wave trains) from the towers, the phase between turbines’ blades and lensing in the air or ground. The interference between the noise (audible), or vibration, from different turbines creates very localised patches of heightened (or lowered) noise/vibration (Thorne, 2009).

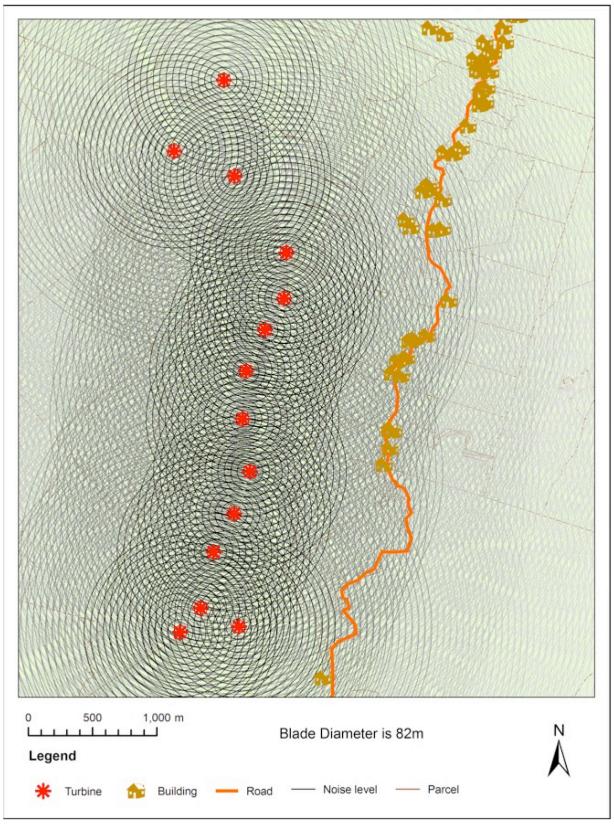

Figure 1. Part of the Makara wind farm showing 14 turbines, buildings along South Makara Road, and a visualisation of sound interference at one frequency. Source: Research graphics by S. R. Summers.

The sounds/vibrations travel outwards from the individual turbines to any affected home. Here the interference can create the larger peaks and troughs of a Heightened Noise Zone. The HNZ is directly affected by the design and operation of the wind farm (location and type of turbines, phase angles between blades), atmospheric conditions and wind conditions. These variables, added to the effects of lensing focussing or acting as a wave guide underground, passage over trees and wind shear, are confounding factors that can be calculated with a degree of reliability (10 dB range) but that can move the HNZ.

It is possible for the HNZs to be small in extent—even for low frequencies—leading to turbine sounds 'disappearing' and 'appearing' in areas only a few metres apart.

These attributes of Heightened Noise Zones—small size and the dependence on time-related factors like wind direction—explain much of the problem of wind farm noise and its variability as heard by residents.

For the simple, single-frequency situation shown in Figure 1, the circle-crossings are seen to occur in straight lines diverging away from the turbines. Between them are the nodal points where a circle meets a space. The former are called anti-nodal lines and the latter are called nodal lines. The Heightened Noise Zones can be seen to lie on the anti-nodal lines.

EXPERIMENTAL

Simulation

Simulations were performed to investigate the variation of sound level with location near a wind farm due to the interference effects from the multiple sound sources. The Makara wind farm was chosen because recordings of wind farm noise were available and because of the simple, fairly linear arrangement of turbines with respect to the site of the later microphone array measurements. The simulations were carried out for unweighted sound as the more common A-weighted sound measure, as noted earlier, underestimates human perception at low frequencies.

The proof of the idea of Heightened Noise Zones is presented as a series of simulations and experiments. The simulations in Figures 2, 4 and 5 are used to visualise the sound amplitudes and sound propagation/dispersion patterns from the turbines at Makara. (Note that this is a very simple simulation and must be taken as being illustrative only of potential effects. For instance, the ground is assumed to be flat—despite the actual topography of steep hills and winding valleys—and there is no wind at the receiving site to provide directionality effects.)

The simulations assist in the prediction of wind farm sound propagation under different weather conditions at homes and turbine loadings.

Sound with a mixture of the frequencies recorded at Makara—namely the 1/3 octave, 1-minute average immission levels recorded near the white square in Figure 2—are simulated being emitted from the wind turbines. These frequencies will determine the properties of the interference at some nearby home and the resulting propagation pattern. Because high frequencies are known to attenuate faster with distance, only the lower frequencies were considered. Another reason this range of frequencies was chosen is because it is representative of the low frequency rumble reported by residents. The frequencies are shown in Figure 3.

The simulation used the centre frequencies (from 25-315 Hz) of the 1/3 octave spectrum with the amplitudes shown in Figure 3. The contributions of each of the turbines and all of their frequencies were summed at each grid point inside the region of interest and the sound level calculated as deciBels for each time step. These values were then used to determine the difference between the maximum sound level and minimum sound level. All results were unweighted sound pressure levels in deciBels. The parameters of the simulation are shown in Table 1. A range of simulations were run in which one parameter at a time was varied to investigate the sensitivity of the simulation. These are listed in Table 2.

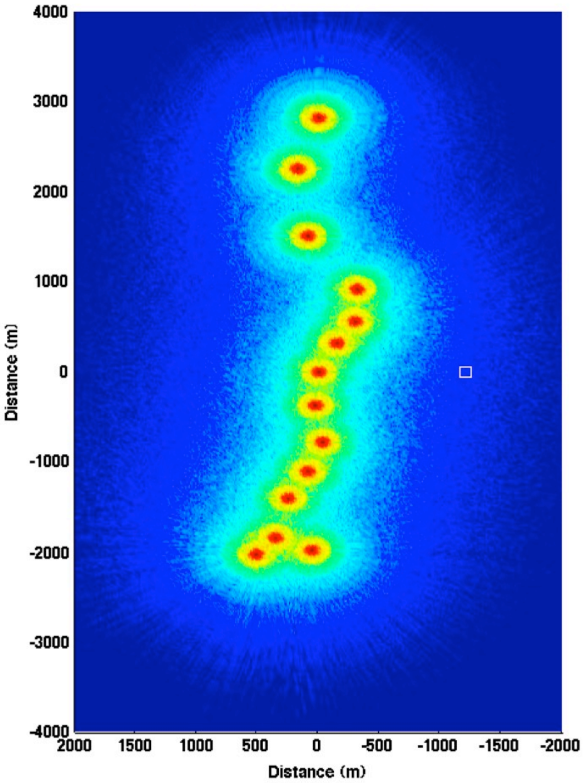

Figure 2. Loudness (SPL) in the area around 14 Makara turbines shown in Figure 1. The white square indicates the area used for further simulation and microphone-array experiments.

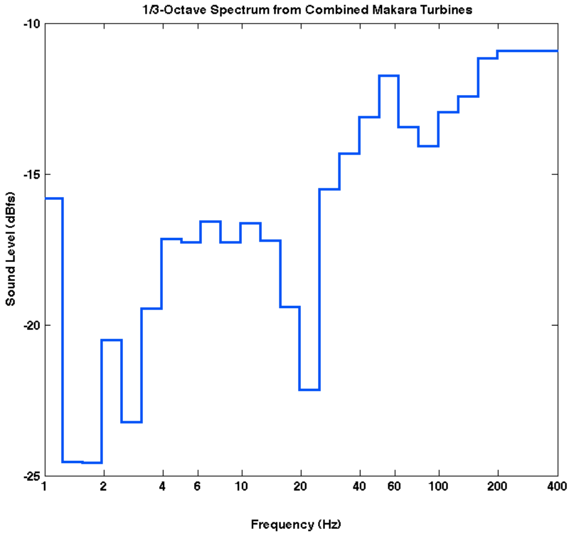

Figure 3. 1/3-octave immission spectrum from the 14 Makara turbines in the study in dB full scale. The frequencies below 20Hz are for modulation as determined by using the Hilbert-transform method.

It was assumed that, during the length of the simulation, the turbine blades would rotate at the same rate, i.e. the same blade-passing frequency. This is a reasonable assumption if the windspeed at each of the turbines was the same over this period. A further assumption was that the relative phase difference of the sound from each of the turbines remained constant. This was not as unreasonable as it might initially appear since the phases at each of the grid points inside the region of interest would depend on the distance to the individual turbines. One of variations (noted in Table 2) was to randomly assign initial phases to each of the turbines and frequencies at the start of the simulation.

Mesh plots of some of the simulations generated using MATLAB are shown in Figures 2, 4 and 5. Figure 2 shows the propagation pattern around 14 wind turbines close to South Makara Road. The small, white square indicates the area of detail for Figures 4 and 5. The sound pressure level (dB SPL, difference ratio) is plotted at positions within a 100 m by 100 m area. The scale on the colour bar to the right of the plots indicates the sound level in decibels that the colours represent.

There are two main features to note from Figure 2. The rays spreading out from the turbines, particularly at the bottom and the top, are the nodal/anti-nodal lines mentioned in the previous section. The dark rays are the nodal lines where the sound level is reduced because of destructive interference between the sounds from the different turbines. The light-coloured rays are the anti-nodal lines or Heightened Noise Zones. On the left and right sides of the turbines note the chaotic nature of the sound levels, seen as 'dithering.' This implies the complex pattern of sound levels seen in the two detail plots following.

A single turbine is shown in Figure 4. The peaks and troughs from the interaction of the different frequencies from the blades and tower are shown as clean, radiating waves with node/antinode sound levels changing by about 5 dB.

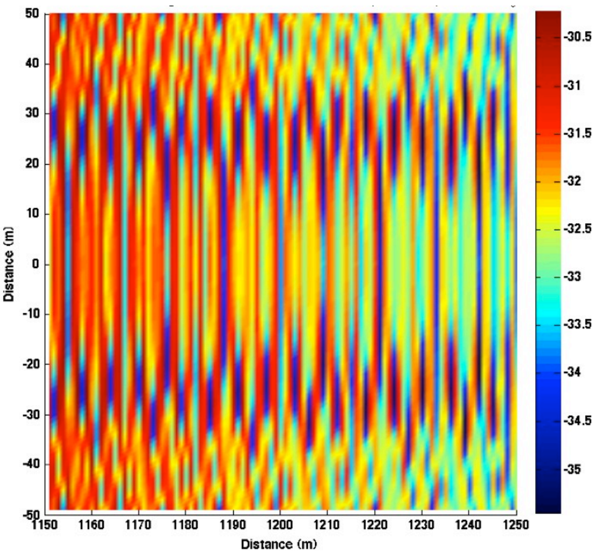

Figure 4. Simulated propagation pattern from a single turbine at 1.2km distance, emitting 25–315Hz sound with the amplitudes shown in Figure 3.

Figure 5 illustrates the highly complex propagation pattern at South Makara Road with 14 turbines operating approximately 1200 metres distant. The node/antinode positions vary but can be about 4 metres apart. This accords well with physical observation at the site. The maximum and minimum levels differ by more than 14 dB between node and antinode over the area.

Experimental Validation

That this complex propagation effect is realised in practice can be determined from observations at both Turitea and Makara. Anecdotal evidence from Makara, including observations by the authors, indicates that the sound of the turbines can change from distinctly audible, to inaudible, to distinctly audible again over a distance of only 4 paces. Also, over time the typical beating or modulating sound of turbines is heard as they synchronise and desynchronise with each other. Similar observations have been made near the Te Apiti wind farm in the Manawatu where the distance between nodes was about 10m (Thorne, 2009).

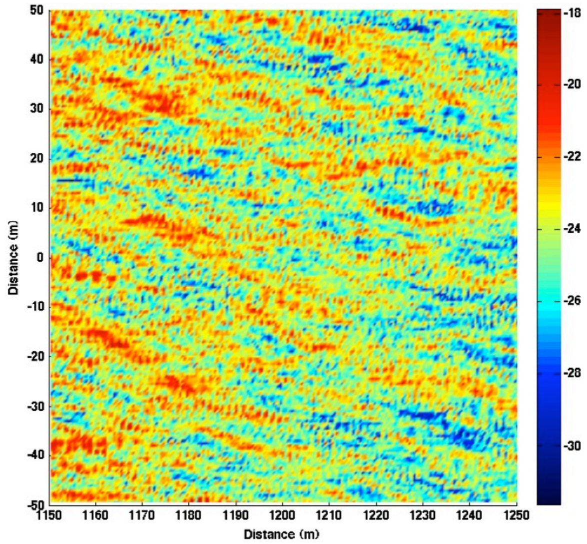

Figure 5. Propagation sound pattern from 14 turbines at Makara.

To measure the change of sound level with position, an experiment was carried out near the Makara wind farm with an array of 8 microphones simultaneously recording sounds within the same region of interest as used for the simulation experiments. This means that the five closest turbines are visible from the location and form a roughly semicircular arc about 1200m from the location of the array.

Three experiments were run approximately 10 metres in front of the home. At the time of observation, 7 pm to 11 pm, the turbines were operating and noise from the turbines was clearly audible.

Figures 6, 7 and 8 show the results of the experiments for 1m, 2m and 3m grid spacings respectively.

The microphones were placed in a 4-by-2 array with the short axis in line with the nearer turbines, i.e. the turbines would be 'up the page' from the arrays. Each microphone was located as marked M1 to M8 in the individual figures and was calibrated to 94 dB, 1000 Hz tone directly prior to the experiments by adjusting the gains of the individual microphone channels. For each of the three runs the microphones were moved to give the correct grid spacing. The recordings were taken over 10- and 15-minute intervals and the time-averaged sound levels calculated. The figures show these unweighted sound pressure levels in decibels at the different microphones, with the colour bar to the right providing the scale. The sound levels of these plots were not calibrated as the relative sound levels only were of interest.

The following figures, 6–8, were generated using MATLAB where the values from each individual microphone were linearly interpolated to produce the continuous plots. This simply makes the soundscape easier to visualise.

The weather conditions at the time of the recordings (evening) were fine and mild in the valley with no wind whatsoever. The wind at the top of the ridge was sufficient to turn the turbines.

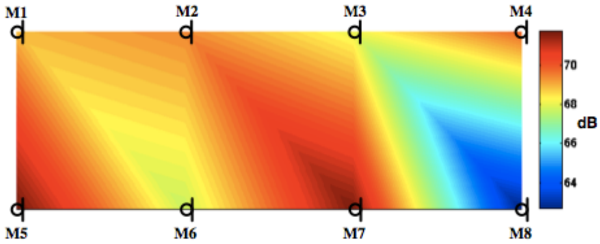

Figure 6. Sound Levels averaged over 10 minutes at Makara with eight microphones in a 4-by-2 grid at 1 m spacing, approximately 1.2 km from the nearest turbine.

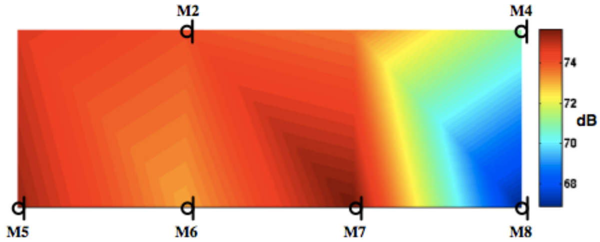

Figure 7. Sound Levels averaged over 10 minutes at Makara with six microphones in a 4-by-2 grid at 2 m spacing, approximately 1.2 km from the nearest turbine. (Signals from microphones 1 and 3 could not be recorded and have been added here as the average of the surrounding microphones to allow plotting.)

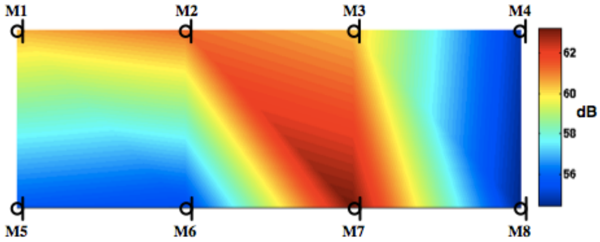

Figure 8. Sound Levels averaged over 15 minutes at Makara with eight microphones in a 4-by-2 grid at 3 m spacing, approximately 1.2km from the nearest turbine.

DISCUSSION

Simulation

By the nature of the simulations, it was assumed that the blade-passing frequency of all the turbines was the same throughout the simulation. This is not an unreasonable assumption since the turbines do not change speed very quickly and the turbines would be experiencing similar wind speeds. Some substance is given to this assumption by the fact that the recordings used to provide the frequencies were averaged over a minute. Furthermore the microphone array experiments were averaged over 10 or 15 minutes and still showed similar differences, indicating that the sound patterns were stable over the 10-minute or 15-minute period.

Sound levels are taken from the immission spectrum of the turbines in the region of interest, thus they will not match the amplitudes of the turbine emission spectra, particularly at the higher frequencies since these are attenuated most. However, this means that, since attenuation is not included in the simulation, they will, in fact, be a closer approximation than using the true turbine emission spectra. This does not ameliorate the fact that the immission spectrum is that of all the turbines, not any individual turbine.

The effect of multiple turbines was tested using runs with only one turbine (trial 7, see Table 2) and with all 14 turbines (trial 1). The sound level difference for one turbine was 8 dB lower than that from the multiple turbines, as could be expected from superposition theory.

Trial 1 was considered the base case. Further trials were carried out to explore the sensitivity of the simulation to different parameters. If the results changed in a reasonable manner to these parameter changes, more confidence could be placed upon the simulation.

Lengthening the integration time of the simulation runs from 30 s to 60 s and 90 s (1, 2 and 3) showed a decrease in sound level difference of about 2 dB or 15%. This suggests that the effects of the interference will be smoothed out to some degree over longer time intervals and that the trials would overestimate the sound level difference for longer intervals, such as the 10-15 minutes of the array microphone trials.

The space between samples was decreased from 1 m to 0.5 m for some trials (5 & 6) and showed no significant change, suggesting that the 1 m spacing was adequate to capture the interference effects.

To test the effect of changing the phase of the sounds from the turbines, simulation runs (10 & 11) were carried out where the initial phase of each frequency at each turbine was randomly assigned. The resulting sound level differences were somewhat lower than the standard run (1) but this was not much more than the variation between the runs. Apparently the simulation was not sensitive to the phase difference between the individual turbine immissions.

Another simulation (4) was carried out to check that the fixed sampling period did not hide effects through aliasing. This was done by running a simulation with a random offset from the base sampling period at each sample and showed a decrease in the sound level difference of about 20%. This suggests there was some overestimation of the SPL differences through a fixed sampling period and the a smaller sampling might also show this effect.

A further simulation (12) was carried out which included sound modulation below 20 Hz, i.e. modulations of the audio frequencies with modulation frequencies less than 20 Hz. These modulations are one of the unique characteristics of wind turbines and the feature most remarked upon by residents. This showed a decrease in sound level difference from the standard run of slightly more than 10% indicating that the modulations do not appear to affect the differences in SPL with position.

Conversely, adding in higher frequencies to the standard mix (6 & 13) did not significantly change the result either. This is an important observation since it supports the decision to use only the lower frequencies in the simulation.

Only the centre frequencies of the 1/3 octave bands were used in the simulation, so how would a more continuous spectrum affect the results? A trial (14) with 1/12 octave emission spectra based on the same sound file shows a halving of the sound level difference. This is in agreement with another run (8) with only one turbine, which also shows a halving of the sound level difference when compared to its 1/3 octave run (7). Clearly when the additional frequencies are included in the simulation they are seen to smooth the effects of the superposition. This is a reasonable result, in line with a priori knowledge of the situation and indicating that the simulation results may be expected to overestimate the differences in SPL.

Taken altogether it seems apparent that the real differences in sound level with position should be less, because of these effects, than the value of 13 dB derived from the standard simulation, maybe to a figure as low as 6 dB. However the effects of geography, ground cover, atmospheric conditions, wind speed and wind direction have not been considered in this simulation and these may have significantly increased or decreased the sound level differences.

Validation from microphone array experiment

The microphone-array validation trials show good agreement with those of the simulation, the previous paragraph notwithstanding. The simulation suggests something in the region of 6–12 dB of sound level difference and the microphone-array experiments also show somewhere between 6 and 11 dB. This represents exceptionally good agreement given the large uncertainties inherent in such a simple simulation, that ignores the complexities of geography, ground cover, weather conditions, etc. For instance, if the wind was taken into account then these plots would change with the average wind direction and speed.

Consequences for sound monitoring of wind farms

The significant differences in sound levels between closely separated locations has consequences for the prediction and monitoring of sounds near wind farms. The assumption that measuring sound levels at four, widely-scattered locations near the Makara wind farm, for example, can be shown, from these results, to be ineffective in producing an accurate record of low-frequency sound levels near residents' homes. The possibility of the sound measurement being 12 dB lower than that of a nearby dwelling dispels any assurance that might be given that the sound levels at homes will be below a 40 dB threshold.

Only by installing microphones at the homes themselves can any accurate measure be taken and only then by experimenting with the positioning of the microphones to find a representative location. Even so, this representative position may change with weather conditions and wind farm operating conditions.

Note also that these results do not answer the question of how the sound levels may change within the home. This is a further area that must be studied to gain an understanding of how residents are affected by nearby wind farms.

CONCLUSIONS

The conclusions of this study into variations in the sound levels from wind farms are:

- Simple simulations of sound levels close to multiple-turbine wind farms have shown significant variations in sound level with position.
- Simulations with one turbine only have suggested changes in sound level with position of between 3 and 5 dB.
- With multiple turbines this range of sound levels increases to 6–12 dB; the full change can occur over distances as small as 2–4 m.
- Various simulation trials, to judge the sensitivity of the results to changes in the simulation parameters, resulted in changes of about 10-20% to the simulation outputs. The one exception to this was increasing the number of representative frequencies from 1/3 octave to 1/12 octave, which halved the range.
- Measurement studies with microphone arrays in 2-by-4 grids, and at 1 m, 2 m and 3 m intervals, gave good agreement with the simulations, showing sound level ranges between 6 and 11 dB.
- These measurements were taken over 10-minutes intervals, indicating that the sound patterns were fairly stable at this timescale.
- These conclusions support the idea of Heightened Noise Zones (HNZs) and their importance to wind farms immissions.
- When measuring sound levels near wind farms, for the purposes of compliance testing, these results suggest that a small number of measurement locations can not be used as locums for much larger areas and that microphones should be placed next to all affected dwellings.

ACKNOWLEDGMENTS

The authors gratefully acknowledge work done by Rachel Summers, research assistant for this paper.

APPENDIX

Table 1. Simulation parameters

Parameter	Value
Sampling time	0.1 s
Run length	30 s
Frequency range	25–315 Hz
Bandwidth	1/3 octave
Spatial Resolution	1 m
Frequency Weighting	Unweighted

Table 2. Description of sensitivity tests carried out for the simulations.

Run	Description	SPL range (dB)
1	Standard trial: As in Table 1	13.54
2	Standard trial + 60 sec run time	12.16
3	Standard trial + 90 sec run time	11.63
4	Standard trial + stochastic sampling time (0 to +0.05s)	10.94
5	Standard trial + 0.5m spacing	13.21
6	Standard trial + 0.5m spacing + 20-800 Hz	13.93
7	Standard trial + 1 turbine only	5.23
8	Standard trial + 1 turbine only + 1/12 octave	2.83
9	Standard trial + 0.05 s sampling	11.83
10	Standard trial + random initial phases	12.71
11	Standard trial + random initial phases	11.89
12	Standard trial + infrasound	11.91
13	Standard trial + 25-800 Hz	13.11
14	Standard trial + 1/12 octave	6.65

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