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Direct Experience of Low Frequency Noise and Infrasound within a Windfarm Community.

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Summary

The author first became aware of the adverse health problems associated with infrasound many years ago in 1974, when an aero-engine manufacturer approached him to consider the problems that office personnel were experiencing close to engine test facilities. He had been conducting research into the active control of sound, and the question was posed as to whether active sound control could be used to address this problem. At that time, this research was in its infancy, and the scale of the problem clearly lay outside practical implementation. Five years later, however, the author was asked to address a related problem associated with the low-frequency noise of a 15,000SHP ground-based gas-turbine compressor installation, having a 40 foot high, 10 foot diameter exhaust stack. This problem was of a more tractable scale, and the author and his colleagues successfully reduced the low-frequency noise of the installation by over 12dB. He subsequently was requested to address a similar installation of significantly greater size and power, again with accurately predicted results.

As a consequence of this and subsequent work, the author has gained considerable experience of the disturbing effects of low-frequency noise and infrasound. So when he first became aware of the nature of adverse health reports from windfarm residents, they were immediately recognisable as effects with which he had been familiar for as many as 35 years.

Since late 2009, the author has lived part-time within a Michigan community where wind-turbines have been increasingly deployed. Consequently he has had significant interaction with residents whose lives and well-being have been damaged, and moreover has experienced the associated very severe effects directly, at first hand. His resultant perspective is thus based on both detailed theoretical analysis, and extensive personal, practical experience.

1. Introduction

In the latter part of 2009, the intention was announced to install up to 2,800 wind turbines in Huron County, Michigan, together with adjacent regions of the Thumb of Michigan. The agricultural areas of the county are made up of 1 square mile sections, bounded by a grid of roads running north-south and east-west. The proposed wind-turbine density would amount to approximately 2-3 turbines per square mile, but in each square mile there can be typically 4 to 6 residences, usually located around the perimeter. Consequently, the requirement for adequate turbine separation would very substantially restrict the possible setbacks from residences. At that time, there existed two recently commissioned windfarms in Huron county, at Elkton (32 Vestas 80m diameter V80 turbines) and Ubly (46 GE 1.5MW 77m diameter turbines). The Elkton windfarm is in unobstructed open country, but the Ubly windfarm is in an area with significant clusters of trees, which in certain wind directions could obstruct and disrupt the low-level airflow to the turbines.

Following this announcement, the author attended an Open Meeting of the Michigan Public Services Commission, at which a number of residents spoke of the problems that they were already encountering from the windfarms, in particular the windfarm at Ubly. This author immediately recognized these problems as relating to the characteristics of low-frequency noise and infrasound, with which he had been familiar for many years. But on subsequently visiting the windfarms, it became clear that the higher frequency audible noise levels were also unacceptable, at Ubly in particular, with up to 50dBA L10 being permitted by the ordinances. The author was astonished that any professional acoustician could possibly regard the levels as acceptable.

Following the county's early experience the ordinances were reconsidered, so that the existing setbacks of 1000 feet, and levels of 50dBA L10, were changed for non-participating landowners to 1320 feet and 45dBA L10. But problems at Ubly were still apparent even at 1500 feet and 45dBA.

The author obtained data from one such residence, which was immediately downwind of 6 turbines located approximately in a line at distances of 1500 feet to 1.25 miles, and found that there could be significant impulsive infrasound present, even though these turbines were of modern, upwind rotor design. Under some circumstances this infrasound took the form of single pulses per blade passing interval, presumably from the nearest turbine, but sometimes up to 6 separate impulses could be detected from the turbine array.

The commissioning of further wind-turbine developments was initially hampered by the lack of high capacity transmission lines, but more recently a 5GW high voltage transmission line has been routed through the county, permitting more than adequate capacity for any intended number of windfarms and turbines. Several further windfarms, with larger 100m and even 114m diameter turbines up to 500 feet in height have now been constructed, resulting in a total of more than 320 wind-turbines installed to date.

Recently, the county has turned to reconsidering the ordinances, but as of the present date has not finalized any changes. Currently permitted wind turbine sound levels and setbacks appear to be dictated primarily by an over-riding incentive to install the requisite number of turbines per square mile.

The author has attended and commented at many public meetings, but has found that the reluctance to acknowledge adverse effects associated with low frequency and infrasound, has resulted in a situation where little traction can be gained.

Several aspects deriving from his first-hand experience will now be described in the following sections.

2. The Detection of Infrasonic Pulses from Wind-Turbines

In prior presentations e.g. (1), the author has shown the graph of Figure 1, which is a snapshot of the infrasonic pressure distribution at a home downwind of 6 GE 1.5MW wind turbines located near Ubly, Michigan. The wind turbines form a part of a 46-turbine installation which has given rise to significant noise nuisance for nearby residents.

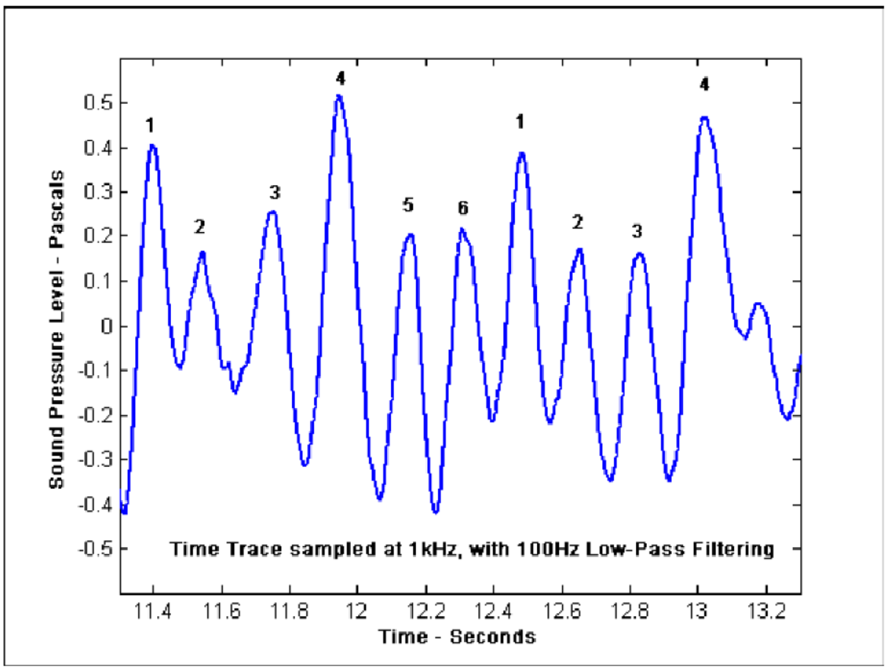

Figure 1 Impulsive periodic wind turbine infrasound in bedroom of house. Six separate turbines can be identified. Peak level 88dB

To make clear that these varying components of sound do indeed represent separate, distinct infrasonic impulses, an alternative presentation of the data will now be given.

The original full bandwidth B&K 4193-L-004 microphone data was down-sampled to 1kHz, then subsequently bandpass filtered using a combination of high-pass and low-pass Butterworth filters at 0.5Hz and 10Hz respectively, to uniformly embrace the frequency range 0.5Hz-10Hz. To emphasise the peak levels at blade passage frequency, it was then further filtered with a 5-point FIR filter consisting of periodically distributed Hanning weighted time-coefficients, separated by the average blade-passage period of 1.089 seconds (1089 ms), corresponding to 0.918Hz BPF. The resultant time-domain filter characteristic is shown in Figure 2.

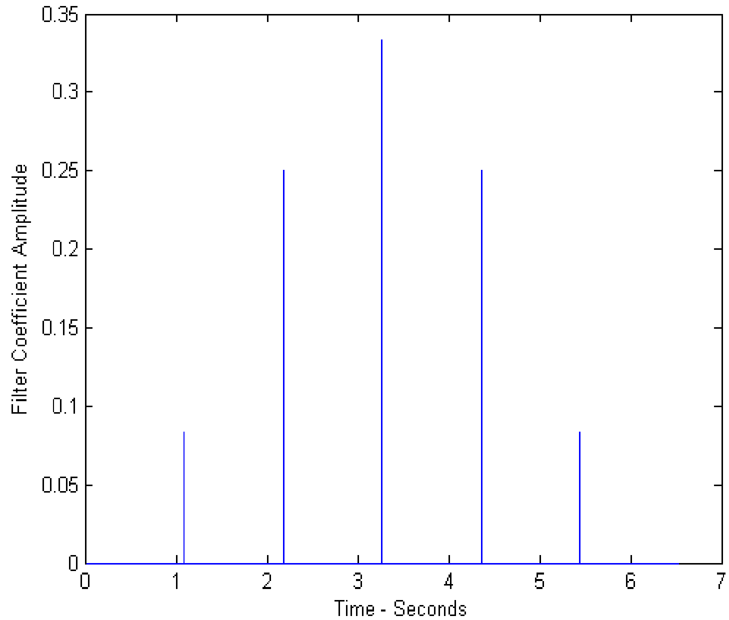

Figure 2 Coefficients of Time Domain FIR Filter

The effect of this filter is to highlight the BPF components of the wind-turbine infrasound, although in the process introducing a finite time-constant amounting to 2 blade passage intervals either side of centre.

The combination of the bandpass filtering and subsequent filtering with this periodic time-domain filter results in the overall frequency response of Figure 3

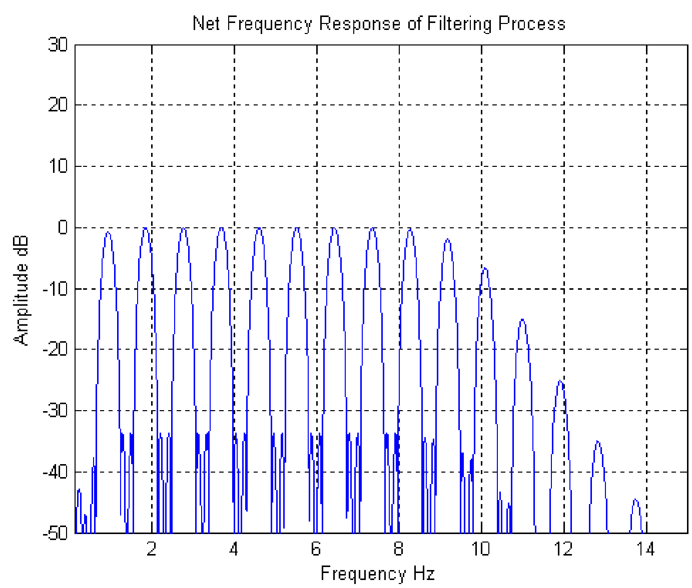

Figure 3 Frequency Response of Complete Filtering Process

The resultant filtered data was then presented as a time-domain representation, shown in Figure 4

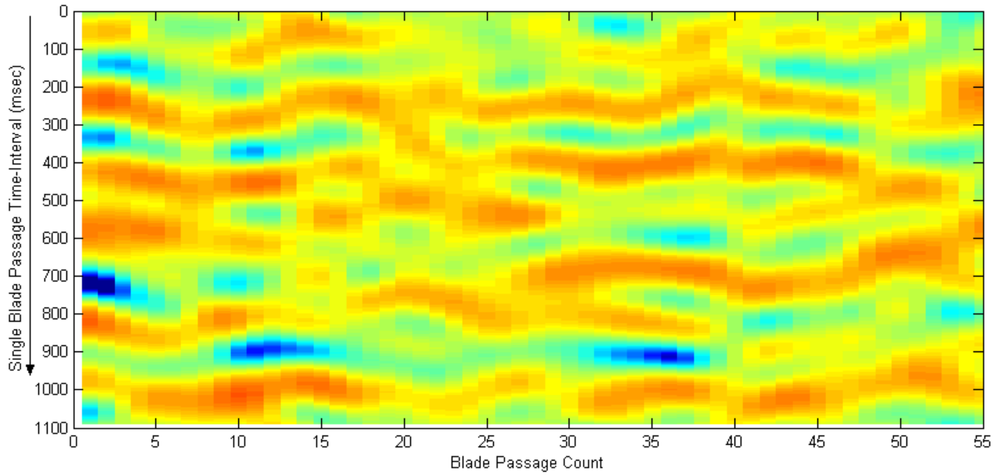

Figure 4 2D Time History Representing SPL during Sequential Blade Passage Intervals

This figure represents a two-dimensional time-history, with (logarithmic) peak amplitude indicated by colour, red being highest and blue being lowest. The overall presentation is synchronized to the nominal, average blade passage rate of 0.918Hz. Moving directly downwards from the upper left of the diagram represents the progression of a single blade passage. Upon reaching the bottom, the trace reverts again to the top of the figure, to trace out the next blade passage. Thus progress along the horizontal axis represents sequential blade passages, and successive descents from top to bottom represents the detail of the time history within each blade passage.

As a result of the finite time-constant of the periodic filter, the signal marking each blade passage descent is not completely independent of its immediate neighbours – there is finite smearing either side, amounting to +/- 2.2 seconds, but this is of short duration compared to the overall 1 minute time trace. The actual maximum and minimum levels of the two dimensional data corresponds to a positive going peak of 87dB, and a less clearly defined negative going peak also of 87dB.

It is clear that there are well-defined horizontal components of signal, each corresponding to peak levels which are occurring at essentially the same instant within each blade passage interval. But these horizontal components do not form completely straight lines, as would be expected for truly synchronous observation of a rotating source. The acoustic signal is being received from turbines at distances varying from 1500 feet to 1.25 miles. Consequently there are variations in arrival time which are the result of changes in the propagation time associated with the rise and fall of the convective windspeed. Moreover, rotation of individual turbines is not completely synchronous with the underlying timebase, although it can be seen that over a period of 1 minute, the general position of the peak levels within each nominal blade passage interval remains relatively consistent, indicating a close correlation with the overall time-base.

One possible feature exacerbating the generation of such impulses may lie in the fact that some of the turbines are located behind significant wooded areas of trees. It is well-known that even in an unobstructed atmosphere, the result of wind-speed decreasing with altitude can result in a low-level change in wind-direction. This effect, namely the Ekman layer, is brought about by the fact that higher level windspeeds coupled with the Coriolis effect result in a balancing pressure gradient at 90^0 which persists at all altitudes, down to ground level. But the progressively reducing windspeed means that this pressure gradient at lower levels exceeds the value necessary to overcome the local Coriolis force, and the wind progressively shears round towards the downstream direction of the pressure gradient.

The effect of groups of trees which can further slow and obstruct the low-level flow into the turbine can significantly enhance this shearing effect, so that at the bottom of their rotation the turbine blades can encounter slower airflow incident from a very different direction from that which is present higher up, with resultant significant transient change in lift over the airfoil.

3. The Effect of Airflow over the Ears

In (2), Bray & James reported the results of using a model of the human head and shoulders (HEAD) to conduct sound measurements within both ears of the model, at a residence adjacent to the Ubly wind farm, Michigan. Measurements were carried out both inside and outside the residence, under low surface wind conditions. The resultant data have been made available to this author, and show effects which highlight the substantial difference in perception of wind-turbine noise when in an outside environment and within a residence.

The model head was positioned with its shoulders at a height of about 5 feet above ground, and was equipped with foam earmuffs. Throughout the measurement period, wind speed and direction was measured by a weather station having the anemometer at a height of ~ 30 feet. This wind speed was projected to 5 feet height, assuming the profile $v_5 = v_{30} \times (5/30)^{0.37}$

The author has analysed this data, and in particular, the coherence between the two ear microphones. It was found that outside the residence, this coherence could be significantly degraded according to windspeed. Despite the presence of the ear muffs, the effect of a recorded wind speed as low as 3 mph was sufficient to degrade the cross-coherence over the frequency range 1-20Hz by a substantial amount.

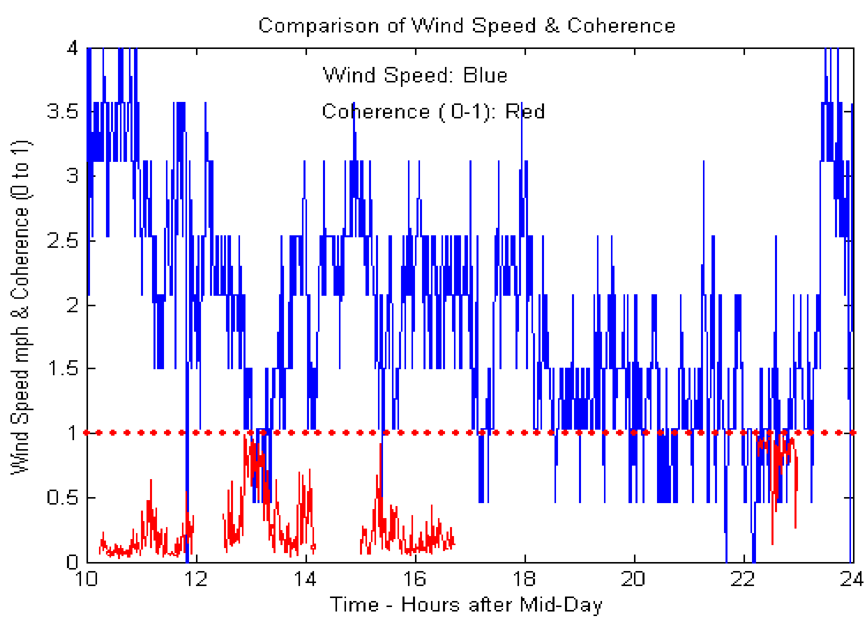

Figure 5

Figure 5 shows the variation of wind-speed during the period of outside measurement, and the corresponding mean level of coherence, measured with an FFT bandwidth of 1Hz for 1 minute averages, and averaged over the infrasound regime 1Hz-20Hz .

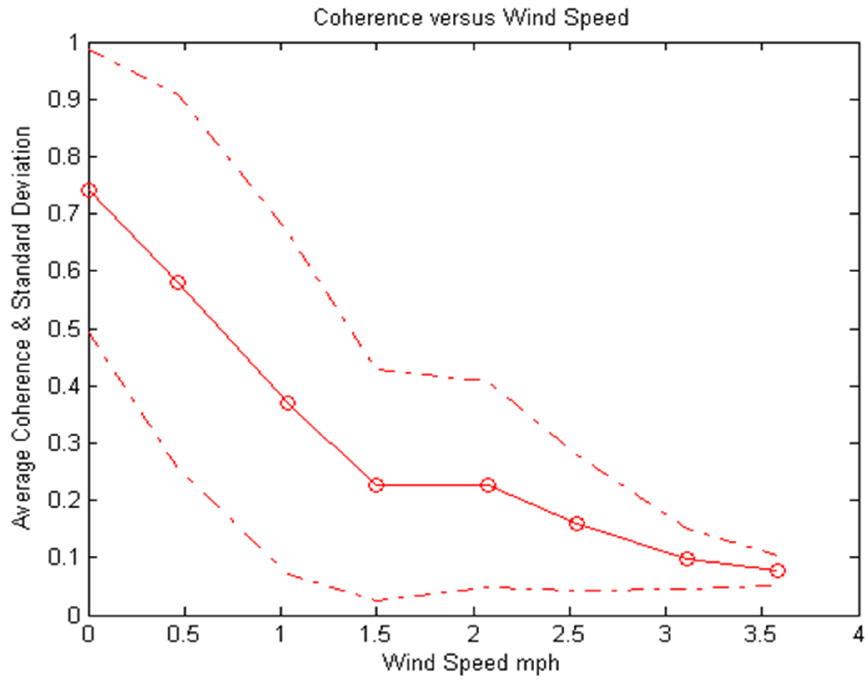

Figure 6

Figure 6 shows the resultant degradation of average coherence versus wind-speed, with upper and lower bounds corresponding to the standard deviation.   In contrast, coherence in the still air within the house was found to be good across the entire spectrum, even at the lowest sound levels.

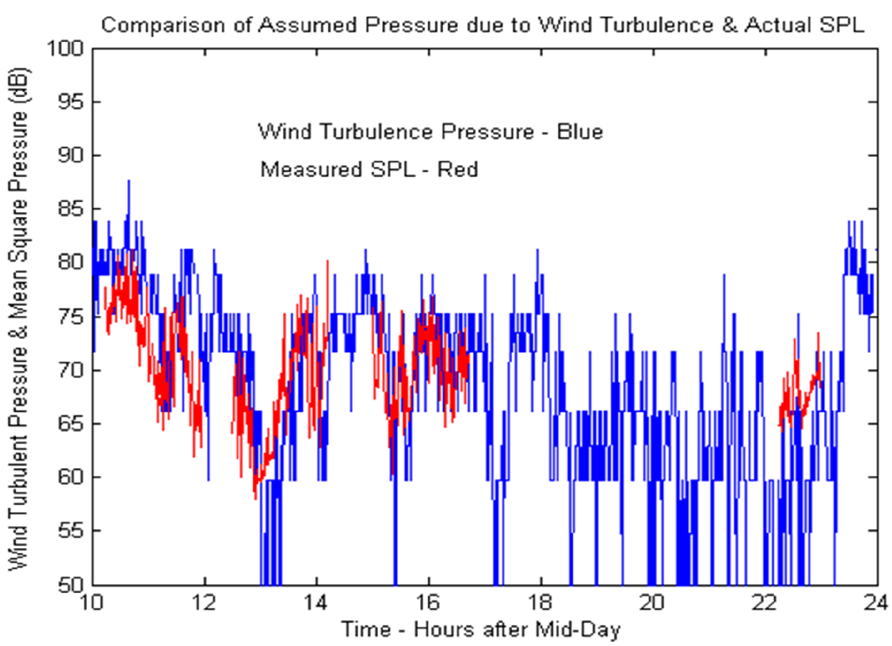

Figure 7

Figure 7 shows the outside rms infrasonic sound pressure level recorded by one of the ear microphones, and superposed is the corresponding level of hydrodynamic pressure fluctuation that would be expected if the turbulent pressure variation over the ears amounted to 15% of the stagnation pressure at each appropriate windspeed. It is clear that the outside sound pressure levels can be quickly dominated by the hydrodynamic pressures resulting from airflow, even at these very low windspeeds

This immediately indicates that in contrast to a conventional microphone which can be carefully shielded against wind-airflow at infrasonic frequencies, the human head and ears are highly susceptible to the effects of airflow, and this in turn can completely compromise the perception of wind-turbine infrasound when in an outside environment.

During the early 1980's while working on an industrial gas turbine compressor, the author became very aware that the very low-frequency sound can quickly become imperceptible when outside in any moderate breeze. More recently, while attempting to sleep in a house 3 miles from the nearest wind-turbine of a new wind farm consisting of 35 GE 1.6 100m diameter wind turbines, the author and his wife have sometimes been kept awake by the low-frequency rumble or infrasonic "silent thump" of the turbines. This situation can occur when the wind has veered from a cold north wind from Canada, to a warm wind from the south blowing over cold ground. Such conditions give rise to a classic temperature inversion, and the resultant wind turbine infrasound can readily propagate for 3 miles or more.

On such occasions, the author has more than once donned outdoor clothes at 1am and gone out onto the road outside the house, clear of trees and obstructions, but in the airflow of an outside wind has been consistently unable to detect any similar subjective disturbance.

It is often argued that infrasound is more readily detectable within a residence simply because the building structure greatly attenuates the higher frequencies, but has little effect on the lower frequencies. There is an additional effect, however, that tends to be overlooked. Outside, individual ears effectively represent unshrouded pointwise microphones, equally sensitive to the full effects of airflow and true infrasound. In contrast, the conditions within a building are very different. Pressure due to wind turbulence tends to be only locally correlated over the outside surface of the building, whereas true infrasound acts coherently over the entire structure. This gives rise to an additional spatial filtering effect, whereby the wind induced pressure distribution tends to cancel itself out, but the fully coherent very low frequency wind-turbine infrasound acts to fully reinforce itself over the entire structure.

This characteristic has been exploited for many years in the design of conformal sonar arrays – distributed pressure sensing surfaces which preferentially detect acoustic signals that are fully coherent over the surface, yet "average-out" the uncorrelated pressures due to hydrodynamic flow, yielding a significant improvement in signal-to-noise ratio.

A direct consequence of this difference between inside and outside observation is that observers visiting windfarms in the open air may quite correctly comment that they cannot hear any significant low-frequency sound. Put simply, they are not observing under the appropriate conditions. Perception within a residence, particularly in a quiet bedroom, can be entirely different.

This difference is significantly enhanced by the fact that the threshold of hearing is not a constant threshold, but is automatically raised or lowered according to the background ambient sound conditions. It is for this reason that people in urban areas, with typical ambient sound levels around 55dBA, have a naturally raised threshold and are able to tolerate additional noise of comparable level, yet this same level of noise would be completely intolerable in rural areas where ambient levels can be very much lower, not infrequently in the region of 25-30dBA. This is one of the most important effects with respect to perception of low-frequency noise and infrasound, yet the widely cited AWEA/CANWEA Expert Health Report of 2009 (3), completely failed to indicate the consequences of this process of automatic threshold adjustment.

4. First Hand Experience of the Severe Adverse Effects of Infrasound.

Approximately 18 months ago, the author was asked by a family living near the Ubly wind-turbines to help set up instrumentation and assess acoustic conditions within their basement, which is partially underground, where they hoped to encounter more tolerable sleeping conditions. In the early evening, the author arrived at the site. It was a beautiful evening, with very little wind at ground level, but the turbines were operating. Within the house, however, it was impossible to hear any noise from the turbines and it became necessary to go outside from time-to-time to confirm that they were indeed running.

The author did not expect to obtain any significant measurements under these conditions, but nevertheless proceeded to help set up instrumentation in the form of a B&K 4193-L-004 infrasonic microphone and several Infiltek microbarometers. Calibration of the microbarometers had previously been confirmed by performing background infrasonic measurements directly side-by-side with the precision B&K microphone. The intention was to define measurement locations, to establish instrumentation gains having appropriate headroom, and to agree and go through practice procedures so that the occupants could conduct further measurements themselves.

After a period of about one hour, which time had been spent setting up instrumentation in the basement and using a laptop computer in the kitchen, the author began to feel a significant sense of lethargy. As further time passed this progressed to difficulty in concentration accompanied by nausea, so that around the 3 hour mark, he was feeling distinctly unwell. He thought back over the day, to remember what food he had eaten and whether he might have undertaken any other action that might bring about this effect. He had light meals of cereal for breakfast and salad for lunch, so it seemed unlikely that either could have been responsible. Meanwhile, the sun was going down leaving a beautiful orange-pink glow in the sky, while ground windspeed levels remained almost zero and the evening conditions could not have been more tranquil and pleasant.

It was only after about 3.5 hours that it suddenly struck home that these symptoms were being brought about by the wind-turbines. Since there was no audible sound, and the infrasound levels appeared to be sufficiently low that the author considered them to be of little consequence, he had not hitherto given any thought to this possibility.

As further time passed, the effects increasingly worsened, so that by 5 hours he felt extremely ill. It was quite uncanny to be trying to concentrate on a computer in a very solid, completely stationary kitchen, surrounded by solid oak cabinets, with granite counter tops and a cast-iron sink, while feeling almost exactly the same symptoms as being seasick in a rough sea.

Finally, after 5 hours it was considered that enough trial runs had been taken and analysed that it was decided to set up for a long overnight run, leaving the instrumentation under the control of the home owners. The author was immensely relieved finally to be leaving the premises and able to make his way home clear of the wind turbines.

But it was by no means over. Upon getting into the car and driving out of the gateway, the author found that his balance and co-ordination were completely compromised, so that he was consistently oversteering, and the front of the car seemed to sway around like a boat at sea. It became very difficult to judge speed and distance, so that it was necessary to drive extremely slowly and with great caution.

Arriving home 40 minutes later, his wife observed immediately that he was unwell – apparently his face was completely ashen. It was a total of 5 hours after leaving the site before the symptoms finally abated.

It is often argued that such effects associated with wind turbines are due to stress or annoyance brought about by the relentless noise, but on this occasion there was no audible noise at all within the house. Moreover, it was a remarkably tranquil evening with a very impressive sunset, so any thought that problems could arise from the turbines was completely absent. It was only once the symptoms became increasingly severe that the author finally made the connection, having first considered and ruled out any other possibilities. So explanations of “nocebo effect” would hardly appear to be appropriate, when such awareness occurred only well into the event.

In the following two figures, the typical measured infrasound levels in the basement are shown, as measured with one of the Infiltek microbarometers . Figure 8 shows

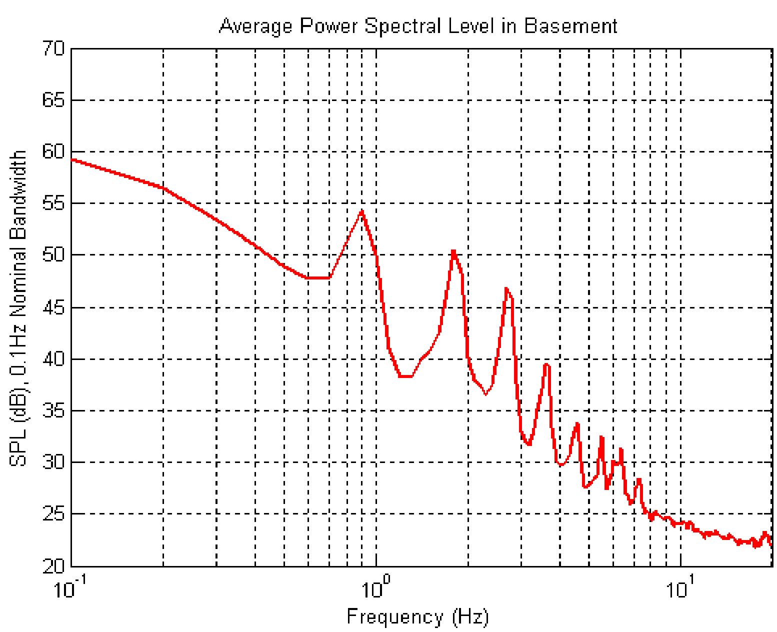

Figure 8 Average Power Spectrum of Infrasound in Basement

the power spectrum, measured with a nominal 0.1Hz FFT bandwidth. As can be seen, the peak of the fundamental blade rate component, at 55dB, might not normally be considered to represent a particularly obtrusive level of infrasound. Several higher harmonics of progressively reducing amplitude are visible, but this characteristic is very much as one would expect for an upwind-rotor turbine operating in comparatively smooth airflow.

The corresponding time-trace is shown in Figure 9. It can be seen that there is a single comparatively sharply defined pulse per blade-passage, so it would appear that only the closest wind-turbine is contributing significantly.

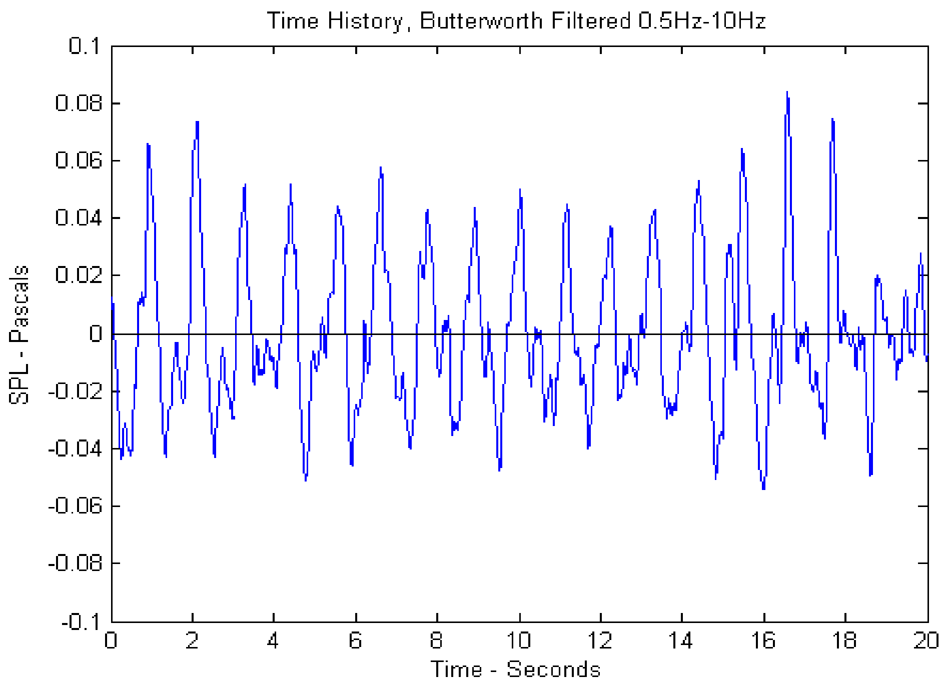

Figure 9 Time History of Infrasound in Basement

Nevertheless, it should be noted that while the fundamental harmonic of blade-passage is at only 55dB, the cumulative effect of the higher harmonics can raise the peak level of the waveform on occasion to 69-72dB. Most of the author's prior work has concentrated on time-history analysis of the waveform, consistent with the 2004 observation by Moller & Pedersen (4) that at the very lowest frequencies it is the time-history of infrasound which is most relevant to perception. Simply observing separate spectral levels at discrete frequencies and regarding these as independent components can lead to considerable underestimate of the true levels of repetitive infrasound.

The fact that balance and coordination were found to be adversely compromised during the night drive home would suggest interference with the vestibular organs, as proposed by Pierpont (5) and subsequently by Schomer (6). An important additional observation, however, is that the effects persisted for 5 hours afterwards, when the immediate excitation was no longer present. In contrast, for sea-sickness, effects tend to dissipate rapidly once sea conditions moderate. It is of interest that a 1984 investigation (7), in which test subjects experienced 30 minutes exposure to 8Hz excitation at very much higher levels of 130dB, reported that some adverse effects could persist for several hours later.

5.Conclusions

It has been shown that upwind-rotor turbines can indeed sometimes give rise to impulsive low-frequency infrasound – a characteristic commonly attributed only to old-fashioned downwind rotor configurations. But perception of wind turbine low frequency noise and infrasound can be quickly suppressed by the effects of wind-induced airflow over the ears, with the result that incorrect conclusions can easily result from observations made when exposed to outside breezy conditions. The effects within a residence are much more readily perceptible, and cannot be ignored. An account has been given of an occurrence of severe direct health effects experienced by the author, and considered to be due entirely to wind-turbine infrasound, yet manifest under superficially benign conditions where no such adverse effects were anticipated.

Acknowledgement

The author wishes to acknowledge and thank W.Bray and R.James for making available the data obtained from the HEAD measurements.

References

(1) Swinbanks M.A.(2012) *Numerical Simulation of Infrasound Perception, with Reference to Prior Reported Laboratory Effects.* Inter-Noise, August 19-22, 2012

(2) Bray W.,James R (2011) *Dynamic Measurements of Wind Turbine Acoustic Signals, Employing Sound Quality Engineering Methods considering the Time & Frequency Sensitivities of Human Perception* NOISE-CON 2011, July 25-27, 2011

(3) ColbyW.D, DobieR, LeventhallG, LiscombM, McCunneyRJ, SeiloMT, Sondergaard.B, (2009) *Wind Turbine Sound and Health Effects.* An Expert Panel Review AWEA/CANWEA, December 2009

(4) Moller H & Pedersen C.S. (2004) *Hearing at Low & Infrasonic Frequencies*, Noise & Health, Volume 6, Issue 23, April-June 2004

(5) Pierpont N. *WindTurbine Syndrome* (2009). K-selected books.

(6) Schomer P, Edreich J, Boyle J, Pamidighantam P (2013) *A proposed theory to explain some adverse physiological effects of the infrasonic emissions at some wind farm sites.* 5th International Conference on Wind Turbine Noise 28-30, August 2013

(7) D.S.Nussbaum, S.Reinis (1985) *Some Individual Differences in Human Response to Infrasound* UTIAS Report No 282, CN ISSN 0082-5255, January 1985