The Australian Senate

Select Committee on Wind Turbines

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Infrasound Generation, Perception and Health Effects Associated with Wind Turbines

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CONTENTS

Executive Summary

This submission provides an account of the generation, perception and health consequences of low-frequency sound and infrasound emanating from wind-turbine installations, followed by a description of the author's first-hand experience of such effects. It is set out in four main sections, dealing with each of these specific aspects. Sections are intended to be largely self-contained, so that they can be read separately and independently.

Shortened overviews of all four sections are given first. Lengthier, more detailed accounts including appropriate references are presented subsequently as separate Appendices, for those wishing to consider the issues more fully.

1. The Generation of Infrasound by Modern Upwind-Rotor Wind Turbines

Initial investigation into the characteristics of large 2.5MW, 90m diameter upwind-rotor wind turbines was first undertaken by NASA and Boeing in 1979. Three 2-bladed MOD-2 turbines forming a triangular array were commissioned in 1981, so that the characteristics of power production, sound generation and wake interactions could be studied. The results validated prior theoretical and numerical studies, confirming the fundamental mechanisms by which such upwind turbines generate low-frequency noise and infrasound. In the intervening years, the improved blade profiles associated with composite blade construction together with more precise control of pitch have yielded quieter noise characteristics at higher frequencies. The primary mechanisms defining infrasound generation, namely the underlying lift forces which are the necessary requirement for generating torque and power, cannot be similarly reduced, so the corresponding infrasound associated with modern turbines is still inevitably present.

As windfarms become consistently larger, sometimes with 140 wind turbines or more, a number of factors can lead to increased infrasound levels. Specifically, wakes from upstream turbines incident on turbines further downstream lead to additional unsteady lift forces and corresponding additional infrasound generation, particularly if the turbines are too closely spaced.

Sound propagation characteristics under conditions of stable atmospheric temperature inversion can result in the infrasound propagating over significantly greater distances, while the basic acoustics of large arrays mean that problems first encountered only at short ranges from small windfarms can be manifest at much greater distances from the periphery of larger installations. So it becomes increasingly important to identify correctly the influence of infrasound and low frequency sound on neighbouring communities.

2. The Perception of Low Frequency Sound & Infrasound

The conventional method of assessing whether low-frequency and infrasound is perceptible has usually involved visually comparing power spectral levels or 3rd octave levels with the threshold of hearing. This approximate process, however, is unlikely to be accurate in the low-frequency wind-turbine context, because it assesses only the mean level of sound, and fails to take account either the character of the sound or the relationship between adjacent frequency bands. Under circumstances where the sound is impulsive, peak levels can exceed the average levels by a significant amount, and this information is not present within the conventional power spectrum or 1/3rd octave measurement. Moreover, there are a number of reported cases in the literature where low-frequency and infrasound was clearly being perceived at significantly lower levels than would be assessed by such basic comparisons with the hearing threshold.

This author has pursued specific research in this context, and has identified mechanisms whereby the conventional, known perception mechanisms may be more sensitive than is presently acknowledged. Moreover, other researchers have now proposed two further processes which may account for increased sensitivity to very low frequency infrasound. Conventional hearing perception is considered to take place via response of the inner hair cells of the cochlea (the sensing structure of the inner ear), but it has been shown that the cochlea outer hair cells respond with greater sensitivity at very low frequency, and induce additional neurological signals. Hitherto, these outer hair cells have been considered to perform only the task of controlling the overall sensitivity of the hearing process, but it is possible that they can also contribute directly to very low frequency perception.

A further mechanism has been proposed, whereby sound pressures acting through the lymphatic fluid directly on the otolith components of the vestibular (balance) organs have been calculated to exert comparable forces to those induced by motion and acceleration. Any non-uniformity in the compliance of the structures supporting these otolith sensors may then result in a response which simulates that of physical motion. Indeed, it has been argued that the correlation between persons who suffer from motion sickness, and those who report adverse effects from wind turbines is sufficient to be more than a result of mere chance.

To summarise, there could be more than one process responsible for the perception of infrasound at very low frequencies, so that adoption of one single overall criterion to define whether or not perception takes place may not be at all appropriate.

3. Health Effects associated with Wind Turbine Infrasound

3.1 AWEA/CANWEA Report into Wind Turbine Sound & Health, December 2009

This AWEA/CANWEA report represented the first study to bring together experts from the acoustics community and the medical profession, to examine the nature of adverse health effects associated with wind turbines. As such, it has been widely quoted and has very much defined a perspective which continues to prevail in subsequent, similar studies.

From the present author's perspective, however, it completely failed to take account of two of the most important aspects of low-frequency and infrasound perception. Specifically, there is no mention of the fact that the threshold of hearing automatically adjusts to the background ambient sound level, with the result that infrasound levels in cities and suburban areas are well below the threshold and completely imperceptible, whereas in quiet rural areas, the much lower hearing threshold enables adverse effects from wind-tubines to be perceived. Consequently, dismissive arguments which directly equate infrasound levels in these two very different environments without taking into account these significant differences in perception, are fundamentally flawed.

Secondly, the report also fails to mention that continued exposure to low-frequency noise and infrasound can result in progressively more acute physical sensitivity to the sensations and effects.

The present author became very familiar with both of these aspects while working on the Active Sound Control of industrial gas turbine compressors in the early 1980's, in a rural environment. As a consequence, it is all the more striking that some expert reports fail even to mention these two important effects.

3.2 The High Permitted Wind Turbine Sound Levels in the USA

One of the reasons for confusion in the reporting of adverse health effects from wind-turbines lies in the fact that permitted wind-turbine sound levels in the USA are generally significantly higher than those in other countries. Whereas many countries now seek setbacks of typically 2km, in the USA setbacks of 300m to 400m are not uncommon, with corresponding permitted sound levels of 45-50dBA or higher. Consequently there are considerably more complaints from affected residents, compared to other countries with more cautious standards. World-wide discussion and assessment of such problems often does not make this distinction clear, with the result that there can be significant confusion as to which problems arise from these very close setbacks, and those which can still prevail at larger setbacks.

3.3 Nocebo Effects, Annoyance, Personality, & Activists

It has become a common practice to lay the blame for the adverse reactions to wind-turbines on residents on the receiving end, rather than acknowledging the significant intrusion that such installations can represent. The argument that adverse health reactions are the result of nocebo effects, ie a directly anticipated adverse reaction, completely fails to consider the many cases where communities have initially welcomed the introduction of wind turbines, believing them to represent a clean, benign form of low-cost energy generation. It is only after the wind-turbines are commissioned, that residents start to experience directly the adverse nature of the health problems that they can induce.

Similarly it is often argued that many of the problems arise because residents are “annoyed” by the noise, rather than making the more accurate statement that residents “suffer annoyance”. It is very important to distinguish between an effect that has been externally imposed, rather than self-induced. Moreover, the suggestion that blame lies with specific types of personality, implies that people are at fault who have sought a rural lifestyle because they value quiet and tranquility in preference to an urban environment. It is unlikely that many of those living in rural areas will have preselected personalities enabling them to be tolerant of unwelcome, external adverse intrusion.

Recently the argument has been advanced that problems are created by activists raising alarm in advance of windfarm consent and installation, and that the subsequent number of complaints can be directly correlated with the prior presence of such activists. This argument is meaningless if it fails to take account of the actual sound levels, setbacks and geography of individual windfarms, or the fact that there are reportedly many more complaints in the USA than in Europe, given that the permitted sound levels in the USA are clearly significantly higher than elsewhere.

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

The present author has lived part time in Huron County, Michigan, where in late 2009 the intention was announced to install up to 2,800 wind turbines over 800 square miles. It had been assessed that the area, namely the Thumb of Michigan, was the most appropriate area of Michigan for wind-power development. At that time, two preliminary windfarms had been constructed, at Elkton (32 V80 Vestas 2MW turbines) and Ubly (46 GE 1.5 SLE turbines). To date, over 320 wind-turbines have now been erected, and the County is considering appropriate Ordinances for future installations, given that a 5 GW transmission line has been installed thus permitting a significantly greater complement of wind turbines to be erected.

The windfarm at Ubly was constructed by the same wind-developer as that whom Dr Nina Pierpont had opposed elsewhere in 2005, when she argued that wind-turbines could cause adverse health effects. The Ubly installation was also specified in 2005, with some setbacks as close as 305m, and has manifested all of the adverse effects originally flagged-up by Dr Pierpont. A number of residents have subsequently pursued a lawsuit against the wind-developers, which was ultimately settled out of court, while the exact nature of the settlement remains confidential.

More recently, this author was asked to assist in performing measurements of the infrasound present in the basement of one Ubly residence, 460m from the nearest turbine, but in the process he experienced severe directly unpleasant effects of lassitude and nausea. These effects were completely unexpected, given that it was a very tranquil and quiet evening with negligible low-level wind and an impressive sunset, yet there was clearly wind at higher altitude since all wind- turbines were running and generating power.

After 5 hours assisting in performing measurements and analysis, the author felt extremely unwell, and was only too relieved to leave the premises. He then found that when attempting to drive home, his coordination and judgement were thoroughly compromised, so that it was enormous relief to have finally completed the journey.

This incident was sufficient to bring home to the author just how severe can be the adverse health effects of wind turbines. Indeed, the levels of infrasound that were measured correspond closely to those that have subsequently been measured at significantly greater setbacks at a number of windfarms in Australia, and which have reportedly caused distress to residents.

Consequently, this author does not underestimate the extent to which wind turbines can impact a rural community.

Appendices

A1. The Generation of Infrasound by Modern Upwind-Rotor Wind Turbines

In this section, discussion is focused initially on the early investigations of wind turbines carried out by NASA and Boeing over the 15-year period up to 1989. The reason for doing so is that many of the fundamentals of wind-turbine infrasound characteristics were correctly identified during this time, but appear to have been subsequently overlooked or ignored by more recent windfarm developers.

During the earliest development of very large multi-MW wind turbines in the late 1970's, the configuration initially chosen was the downwind-rotor turbine, with the rotor positioned behind the supporting tower. This enabled natural "weathercock" alignment of the rotor with wind-direction, but possessed the disadvantage that when the blades were rotating, they passed through the wind-generated wake from the tower structure. This led to sharp impulsive changes in lift on the rotor and the resultant generation of very significant levels of infrasound and audible low-frequency sound. NASA, who led this research, quickly realized (1979-80) that mounting and controlling the alignment of the rotor on the upwind side would avoid this effect and should give rise to much quieter operation. In 1981 NASA and Boeing commissioned into service a trio of 3 upwind-rotor 2.5MW 'MOD-2' turbines, at a site in Washington State, USA. [1] These turbines were of 2-bladed, rather than more modern 3-bladed configurations. Nevertheless, this installation became the first example of a multi-MW wind-farm, and essentially confirmed numerical predictions [2] of the expected reduction in low-frequency and infrasound generation associated with upwind-rotor design, proving to yield a significant improvement over the earlier downwind-rotor configurations.

In 1989, however, NASA [3] identified that some later design upwind-rotor turbines, namely the Westinghouse WWG-0600's installed in Hawaii were generating unexpectedly large levels of impulsive infrasound, almost comparable to the earlier downwind-rotor configurations. NASA reported *"The presence of relatively strong rotational noise harmonics for all test conditions and measurement locations was an unexpected result for an upwind configuration of a horizontal axis machine."* These wind-turbines were mounted along ridge-lines perpendicular to the prevailing wind, with undulating, sloping ground in front of the turbines. Analysis of the wind-gradients arising from these contours indicated the likely cause of the increased levels of rotational harmonics, and enabled numerical simulation of the observed sound characteristics. The effect of the turbine blades passing through the reduced windspeeds towards the bottom of their plane of rotation resulted in transient changes in lift force, resulting in increased levels of impulsive infrasound, not unrelated to the wake-crossing effects of the original downwind turbines.

These early NASA investigations, although carried out more than 25-35 years ago identified the two primary characteristics of infrasound generation by upwind-rotor wind-turbines, which still very much apply to modern designs. Namely, that under near-uniform wind conditions, the infrasound generation is confined only to the very lowest blade-rate harmonics, but that under adverse conditions, the infrasound can become of a more impulsive nature. This refutes arguments which this author has experienced first-hand from wind-developers and their colleagues, namely that the early NASA research related only to old-fashioned downwind-rotor designs.

Indeed, in a "peer-reviewed" 2006 paper [4], Dr H.G.Leventhall sought to discredit Dr Nina Pierpont (subsequently author of [5]) for suggesting that modern turbines could generate impulsive infrasound, arguing that she had misrepresented Van den Berg's 2004 first publication [6]. But he chose to overlook that Van den Berg's second 2004 publication directly implied the generation of impulsive infrasound harmonics [7]. Moreover, in later Kent Breeze written testimony [8], Leventhall also dismissed the present author's preliminary analyses relating to the perception of impulsive infrasound, arguing that he (ie this author) had misunderstood, and that such characteristics related only to old-fashioned wind-turbines. So there has clearly been reluctance within the wind-turbine community to acknowledge these characteristics of modern upwind-rotor turbines.

A1.2 The Infrasound Generating Mechanisms

The overall mechanisms by which jet engines, aerodynamic structures and wind-turbines generate sound was first placed on a rigorous mathematical foundation by M.J.Lighthill in 1952 [9]. His analysis has since stood the test of time, and indeed has directly resulted in the enormous reductions in the noise of jet engines since the early 1960's. He identified three distinct types of aerodynamic noise source, namely monopole sources of volume outflow, dipole sources associated with aerodynamic forces, and quadrupole sources associated with turbulent airflows.

It is sometimes mistakenly considered that the very low frequency sound generation associated with wind-turbines results from the process of the blade "parting the air" and giving rise to a transient increase in displaced volume (a monopole source). But if a turbine is declutched from its generator so that it does not generate any power, yet is still allowed to rotate freely, there is comparatively little noise despite the fact that this "parting of the air" is still taking place.

The principal process which generates very low frequency infrasound is the effect of the aerodynamic lift force of the blade acting upon the air – ie the second of Lighthill's three source generating mechanisms. Even if a steady, unchanging lift force rotates in a circle, the periodic changes in its position give rise to sound generation. For an ideal wind-turbine blade generating power in a completely uniform, steady oncoming airflow, the resultant sound consists primarily of the lowest blade-rate harmonic, plus to a lesser extent the immediate second and third harmonics.

This infrasound-generating process is unavoidable. If a wind turbine is to provide useful power, it must satisfy two requirements. First, it must slow down the oncoming wind in order to extract its energy. Secondly, it must convert this energy into a rotational torque to drive its generator. Thus the blades of the turbine must exert a forward-acting force on the oncoming wind to slow it down, while exerting additional tangential forces in the circumferential direction to give the required torque. These simultaneous objectives are achieved by the twist and alignment of the blades relative to the oncoming wind, so that both components of force can be generated by the aerodynamic “lift” from the blades.

For any wind-turbine that is generating power, these two rotating force components have to be present. In turn a specific amount of infrasound is inevitably generated, regardless of how precisely and accurately the blades are profiled, polished and streamlined.

These basic underlying effects were accurately modelled by NASA in their investigation of upstream-rotor turbines. However, real circumstances introduce additional effects. The existence of the support tower downstream of the blades still requires the airflow to separate around the tower, which gives rise to some degree of upstream modification of the flow directly in front of the tower. NASA initially modeled these effects using the assumptions of a comparatively smooth flow change, but in practice trailing vortices from the tips of the turbine blades can also impact the tower and lead to an increase in infrasonic noise generation. At the same time, as already discussed, slower moving air closer to the ground at the bottom of the blade rotation can give rise to additional recurring transient variations in lift force on the turbine blades. This effect becomes more significant as the diameters of wind-turbine rotors increase in size, since the blades then rotate through a much greater vertical distance and the change in wind-speed from the top to bottom of the rotation arc can then be much greater. Finally, any large-scale turbulence present in the incident airflow results in additional fluctuating lift forces which can also interact with and modify the infrasound that is generated.

This latter aspect is particularly true of wind-turbines which are positioned too closely together in a wind-farm. The wakes from turbines positioned upstream are convected downstream by the wind and may compromise the lift forces generated by turbines located further downstream, with resultant adverse consequences for both the fatigue life of the blades and the generation of excess infrasound. Moreover the “wake deficit” brought about by the extraction of energy upstream also reduces the amount of power that the downstream turbine can generate in a given wind-strength. This effect was first intentionally investigated in the design of the 1981 MOD-2 array of 3 upwind-rotor turbines. [10]. The 3 turbines were positioned in a non-uniform triangular array, each side of this triangle having a different length, representing turbine separations of 5 diameters, 7 diameters, and 10 diameters respectively. According to the direction of the wind, one leg of this unequal triangle would be pointing closest into the wind, and the two turbines at each end of it would then be separated by one of the downwind spacings 5, 7 or 10 diameters. NASA subsequently reported that any adverse effects were within acceptable limits at 7 and 10 diameters spacing, although even at 10 diameters there were some instances of reduced power output (15%-25%) from the downstream turbine [11].

Yet despite this early research, more recent examples of wind-farms have been constructed with separations in the downwind direction as little as 3 turbine blade-diameters, which not surprisingly have resulted in complaints from nearby residents of excessive noise and infrasound. The equal-sided triangular array of three modern 1.5MW GE1.5sle turbines installed on Vinalhaven, Maine at this close separation would appear to represent one example, likely to yield adverse effects in almost any wind direction. Moreover, the Macarthur windfarm in Australia of Vestas 3MW V112 turbines, with some turbines having minimum separations of 3 blade-diameters, would also be expected to give rise to increased low-frequency noise and infrasound, and corresponding loss of overall power generating efficiency.

The overall conclusions from this section can be summarized in two figures, namely figure (1) & figure (2). Figure (1) shows a near-typical infrasound spectrum for a wind-turbine operating in relatively smooth, clean airflow while figure (2) shows the change in character associated with much more impulsive infrasound measured downwind from an array of wind turbines, resulting in multiple periodic transient effects. The difference is immediately apparent, and readily recognizable in practice.

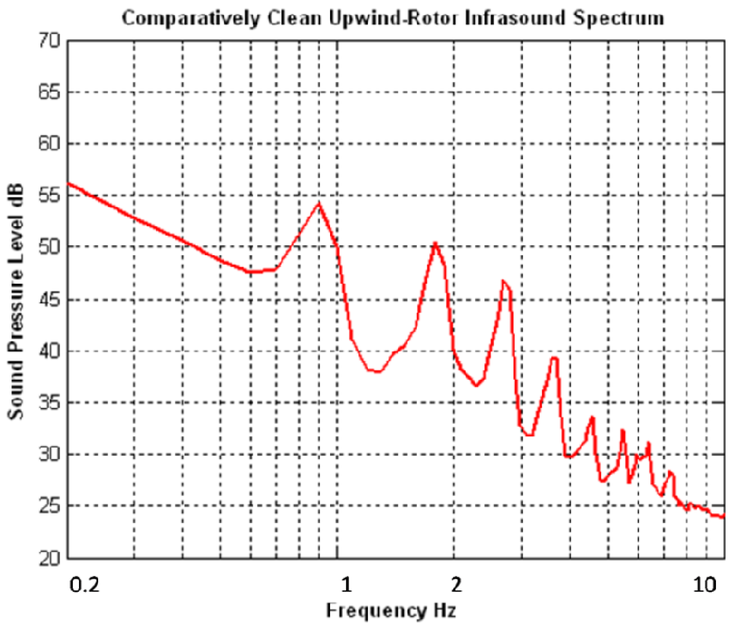

Figure 1

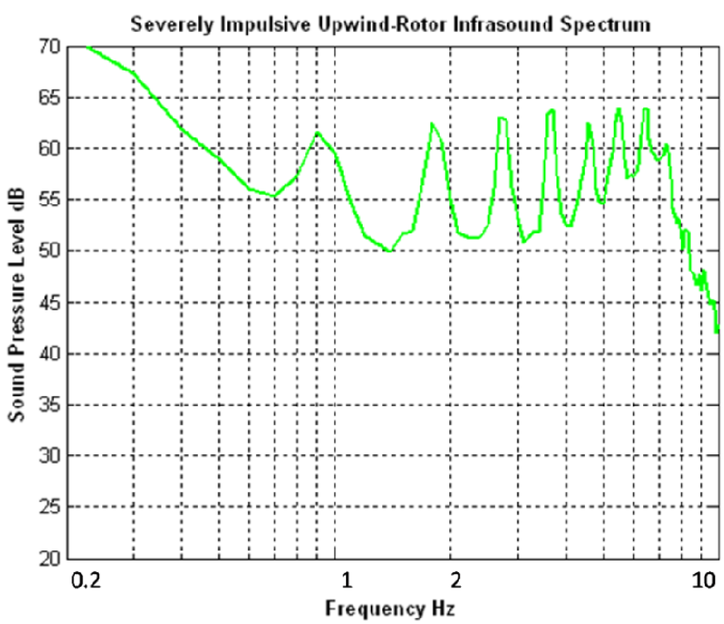

Figure 2

A1.3 Long Range Propagation of Infrasound

An additional effect must be taken into consideration when considering how low frequency and infrasound, once generated by wind-turbines, can subsequently propagate. Under normal atmospheric conditions, the temperature of the air progressively reduces as altitude increases, and under such circumstances the propagation of both audible sound and infrasound spreads out and attenuates at a similar rate of -6dB per doubling of distance. There is also progressively greater attenuation of the higher audible frequencies, as a result of atmospheric sound absorption.

Under certain atmospheric conditions, however, there may be a temperature “inversion”. This can occur particularly at night or the early morning, when the ground and the air immediately above it lose heat faster than the air at higher altitude. Consequently, for several hundred feet or more, the air may actually get warmer with increasing altitude, before ultimately reverting at higher altitude to its more usual cooling profile.

A similar situation can occur when the wind changes from a cold wind blowing over cold ground, to a warmer wind from a different direction blowing over the same initially colder ground.

A well-known consequence of this inversion temperature profile is that low frequency sound can be trapped and reflected by the inversion layer, so that it spreads out more slowly. Its rate of attenuation then reduces to more typically -3dB per doubling of distance, so that at large distances, although the higher frequencies may be imperceptible, the low-frequency and infrasound can still be clearly detected. This author and his wife have on occasion been kept awake by the readily perceptible low frequency noise and infrasonic “silent thump” of a windfarm at a distance of 3 miles.

A1.4 Effect of Increasing Wind Farm Size & Numbers of Turbines

An additional effect which does not seem to be widely acknowledged is that as windfarm sizes increase, the distance beyond the windfarm boundary that the audible sound can propagate before significantly attenuating also tends to increase. Thus, for example, for a small windfarm of 8 – 10 turbines, it may be sufficient to go no more than 1km for the sound to reduce to an acceptable level. As the size of the windfarm increases to (say) 40 turbines, the distance required to reduce to a similar level may be increased to 1.5-2km. For an even larger windfarm of 160 turbines, this requirement may not be met until 3-4km.

In contrast, the sound within the windfarm tends to be dominated by the “nearest turbine”, with the result that as the overall size of the windfarm increases, the effect of any change in size is much less noticeable. This in turn can cause developers to believe that if a small windfarm has proven to be satisfactory, making it larger but of similar layout will also be satisfactory. While this may be true within or immediately outside the bounds of the windfarm, the effect for distant residents can become increasingly noticeable as the size increases, so that the appropriate setbacks from the outer boundaries have to be increased.

This dual structure for the sound level effects associated with large wind turbine arrays is certainly not widely recognized. Within the windfarm, and close to the immediate boundaries of the windfarm, the sound level is very largely dominated by the nearest turbines, and overall numbers are comparatively unimportant. For more remote residences, particularly in respect of low frequencies and infrasound, the total number of turbines making up the windfarm becomes increasingly the dominant factor so that the overall size of the windfarm is then directly relevant.

A1.5 Concluding Remarks

As stated in the introduction, the early research of NASA identified a number of characteristics which are associated with upwind rotor turbines. Specifically, these are (i) infrasound emissions at the very lowest frequencies resulting from the rotation of the steady blade-lift forces necessary for power generation, (ii) the effect of wind-gradients and undulating ground contours upwind which lead to repetitive impulsive infrasound emissions, (iii) enhanced wind shear effects that can result from mounting wind-turbines on ridges, and (iv) the problems of wake interaction associated with too close a separation between wind turbines.

Aerodynamic design alone cannot easily overcome these basic characteristics, but must be integrated with more accurate control of the blade operating conditions. Techniques such as automatic pitch control of individual blades can offer dynamic load alleviation to reduce the periodic impulsive effects, but the underlying need to generate power will always require the presence of steady, rotating lift forces which give rise to an inevitable component of infrasound.

The reason for referring back to the original NASA research of the 1980’s may now become clearer. The very earliest designs of downwind-rotor wind-turbines were undoubtedly extremely noisy, giving rise to a wide spectrum of impulsive infrasound and low-frequency sound. Setbacks associated with such wind-turbines were necessarily large, and the need for such setbacks was clearly apparent. The improvements brought about by changing to upwind-rotor configurations, and subsequently using composite blade construction to give more precisely defined aerodynamic surfaces led to immediate reductions in the overall audible component of noise. This, coupled with improved control technology resulted in apparently very much more acceptable audible wind-turbine noise characteristics. As a consequence, wind-developers began to locate wind-turbines very much closer to residences, so that setbacks originally measured in kilometers were now reduced to distances of 300 – 400m.

The basic physics associated with the generation and propagation of very low infrasonic blade-rate frequencies, however, has not changed, with the result that residents might be experiencing comparable or greater levels of infrasound from these close-in turbines compared to that associated with the more distant, older generation turbines. In this respect, the situation can be misleading, because the need for significant setbacks has no longer been so obvious. The question reduces to one of whether or not the inevitable existence of this low frequency infrasound represents a real problem for health and well-being. That aspect is addressed in the following sections.

A2. The Perception of Low Frequency Sound & Infrasound

Having described the principal mechanisms by which wind-turbines can generate very low-frequency sound and infrasound, in this section the author will consider the means by which these effects may be perceived.

In a series of conference papers [12], [13] he has described a sequence of investigations, with the objective that these represent a coherent progression relating to aspects of the hearing and perception process.

The motivation for this resulted from reading endless acoustic assessments of wind turbine sound pressure level (SPL) spectra, in which the commentator would compare the level of individual spectral discrete frequencies with a curve representing the threshold of hearing, and pronounce that the sound was well below the threshold of audibility and of no consequence. This approach completely fails to consider the likely relationship between different frequency components, and the fact that their cumulative effect can result in considerably enhanced sound pressure levels compared to the levels assessed by considering them separately and independently.

As a first step, he showed how these separate components, regardless of frequency resolution, might be normalized and combined in cumulative mean-square amplitude, yielding a first assessment of audibility which corresponded to an existing “rule-of-thumb”. According to this, the comparison of average third octave levels with the threshold of hearing is taken to indicate the transition from inaudible to audible sound. But the author considered that this averaged criterion does not adequately take into account the “crest factor” of the sound, ie the extent to which the sound is sharply peaked in relation to its mean-square amplitude as a result of the coherent relationship between the separate components. Specifically, early NASA research had shown that the impulsive noise of the early wind-turbines could be detected when individual discrete frequencies were as much as 20dB below the threshold of hearing, and the corresponding mean-square levels were 13dB lower [14]. So comparison of individual spectral components with the threshold of hearing was obviously incorrect in this context.

Indeed, a feature of the 1980’s research conducted by NASA and associated research organizations was that they performed rigorous laboratory assessments to determine thresholds of perception for wind-turbine low-frequency noise. In addition to the work described in [14], Kelley [15] set out to establish criteria for audibility, considering both the downwind-rotor MOD-1 turbine and the upwind-rotor MOD-2. His commentary described very accurately the sensations that many residents are now consistently reporting in the context of large windfarms of modern upwind-rotor turbines. Yet, thirty years later, his rigorous approach contrasts with more recent assessments of audibility and perception based merely on visually comparing power spectral measurements with the threshold of hearing, the latter having been defined by testing only with ideal, pure sinusoidal single-tone components.

An important reservation relating to the testing performed in the 1980's is that the exposure to noise of the test subjects was only for a comparatively limited duration. This does not adequately take account of a situation where residents may be exposed to the low-frequency and infrasound from wind-turbines for hours or days at a time, particularly impacting their nighttime ability to relax and sleep.

Noting that the widely cited paper [16] by Moller and Pedersen argues that as frequency reduces it is the time-evolution of the waveform that ultimately defines audibility, the author then set out to simulate numerically the hearing process, as a time-domain instead of a conventional frequency domain analysis. Simulation of the NASA downwind-rotor impulsive sound immediately indicated how enhanced perception could arise, and similarly showed that examples of gas-turbine compressor low-frequency "rumble" (with which the author had worked in the 1980's) could also be audible even when the average third octave criterion placed it below the nominal threshold of hearing.

Lastly, the author set out to examine the effects of the threshold-induced interaction between slightly audible higher frequency noise within the first critical band (ie less than 100Hz) and simultaneous very low-frequency infrasound [17]. In this respect, the author drew upon an effect which had been clearly identified in the mid-1970's, when commercial digital frequency sound-analysers first became available. These analysers generally used a finite-range 12-bit analogue-to-digital converter, which in principle would permit sound to be analysed over a 72dB dynamic range. If the maximum peak-to-peak amplitude of a sound signal was lower than -72dB below the maximum range of the 12-bit converter, it would not trigger the digital transition threshold and so would not register any response. But if such a signal were mixed with background random noise of a sufficient level that the overall combination easily crossed the threshold, then it was found that the hitherto unobservable low-level signal was "carried over the threshold" and could then be detected. In this way, it became common experience that sinusoidal tones as much as -20dB below the response threshold of the A-to-D converter could be detected and accurately analysed, so long as an appropriate level of background sound was present.

A similar principle is routinely exploited in modern GPS receivers. The GPS signal present at the earth's surface is of an extremely low level, well below the electromagnetic background noise, having the specific objective of avoiding interference with other communication systems. GPS receivers then implement threshold detection, whereby the presence of random background noise "lifts" and enables detection of this very low level signal, performing the same function as the background acoustic sound in the process described above

Given the proven robustness of such techniques, the author decided to investigate whether similar effects might enable the perception of very low-level infrasound which at first sight was clearly below the threshold of hearing   So he set out to simulate numerically a process having the following characteristics.   (i) A frequency response corresponding to the frequency-dependent threshold of hearing, extending into the infrasound regime. (ii) A well-defined amplitude threshold below which no signal would be transmitted (iii) Simulated sound signals confined to the lowest critical band of hearing (i.e. less than 100Hz).

By simulating the mixing of a very low-level infrasound signal with additional slightly audible sound, it was shown that the low-level infrasound signal could indeed be detected with a significant level of accuracy. Moreover, by taking an actual example of recorded wind-turbine infrasound which was notionally imperceptible, the author showed that, in principle, such infrasound could be detected at much lower levels and frequencies than was previously considered possible.

This process has also proven to be entirely consistent with hitherto unexplained, peer-reviewed laboratory tests [18], [19] where infrasound below the notional threshold of hearing had nevertheless induced a sensed response.   Earlier NASA assessment had also reported the awareness of infrasonic effects at levels that would not have been generally considered perceptible [14].

It should be emphasized that all of the present author's analyses have focused on examining the dynamic effects which would be expected of a system possessing the well-defined macro-scale characteristics of hearing.   These characteristics have been repeatedly established by conventional audiology testing, and have been reported consistently over many years.

More recently, however, substantial research has been carried out to examine the micro-scale behaviour of the hair cells of the inner ear (cochlea) and their associated neurological response characteristics [20].   Such research probes and investigates aspects which are well outside the everyday experience and capability of many acousticians. Nevertheless, there is one important respect in which the results immediately overlap with known experience.   This aspect will be described towards the end of the following section.

A2.2 Existence of Several Infrasound Perception Mechanisms

As commented, the analyses which have been described so far relate to the conventionally accepted characteristics of hearing.   These correspond to the known mechanical transmission which results from airborne vibration of the eardrum, via the stapes of the middle-ear to the entrance of the cochlea, and the subsequent response of lymphatic fluids of the inner-ear leading to displacement of the basilar membrane, and excitation of the inner hair-cells (IHC).

The well-established -12dB per octave reduction in low-frequency hearing response as the frequency of sound reduces is a direct consequence of the basic hydromechanical properties of this system. In the infrasound regime, this can be characterized by the internationally defined G-weighting dBG scale, which in many respects represents an extension of the A-weighting characteristic into these extremely low frequencies. But unlike the A-weighting scale which is normalized to 0dB at 1kHz, the G-weighting scale is normalized to 0dB at 10Hz, so there is no direct equivalence between G-weighted sound values and A-weighted sound values. Indeed if one applies the G-weighting process to the nominal median hearing threshold, one finds that the dBG hearing threshold varies in level between 98dBG at the mid-infrasonic frequencies, falling to 89dBG around 20Hz.

The infrasonic G -weighting frequency range is deliberately restricted by bandpass filtering so as to reject frequencies above 20Hz and below 1Hz, so it ceases to be a relevant criterion outside this frequency range. Within its intended frequency range of 1Hz-20Hz, however, the dBG-scale can provide a useful initial measure of infrasound perception, reflecting the likely response of the inner hair cells (IHC) of the cochlea via the defined transmission process described in the preceding paragraph.

Recently, however, Alec Salt [20] has reported how the cochlea outer hair cells (OHC) behave very differently from the inner hair cells. Unlike inner hair cells which can flex freely like waving reeds in response to the velocity of the endolymphatic fluid, the outer hair cells are attached at their ends to the tectorial membrane. So they respond primarily to direct displacement of the surrounding structures, rather than to the velocity of the associated fluid. The kinematic relationship between velocity and displacement is such that for any given value of velocity, the corresponding displacement becomes proportionately larger as frequency reduces. Consequently, the response of the outer hair cells becomes larger and more dominant than that of the inner hair cells at very low frequencies. As a result, the G-weighting scale is no longer appropriate for describing the response of these particular elements, which nevertheless can give rise to a neurological stimulus.

Moreover in very recent analysis, P. Schomer has hypothesized [21] that at extremely low frequencies, ie less than1Hz, the supporting structures within the vestibular (balance) organs, in particular the saccule, may be distorted by infrasonic pressure variations transmitted by the same lymphatic fluids that are present in the cochlea. This theory is based on comparison of the relative magnitude of inertial and pressure forces on the otolith elements, together with recent identification of the cantilevered nature of their support structures which appear to possess non-isotropic mechanical compliance. Previously A. Salt had argued that the vestibular organs, which have evolved to sense physical acceleration, should be comparatively insensitive to infrasonic pressure variations. Salt's argument was undoubtedly correct if one assumes regular, isotropic structural characteristics. But if there are non-uniform compliances associated with the cantilever elements, then the effect of pulsating sub-1Hz pressure changes may lead to corresponding distortion and a subsequently induced neurological response. In addition, Schomer has shown that for several residents known to suffer from motion sickness and who simultaneously have reported adverse effects from wind-turbine infrasound, the correlation far exceeds the probability that would normally be associated with mere chance.

If these components are indeed sensitive to pressure, this indicates a further mechanism which could become comparable to the response of the outer hair cells at frequencies below 1Hz. The effect would be to compromise the sense of balance of an individual, thus giving the mistaken impression that he is being subject to motion and acceleration.

Thus, rather than one simple process characterized by the G-weighting response, there could be as many as three additional processes which may relate to infrasound perception as the frequency is reduced, summarized as follows. First,the process of enhanced conventional threshold detection investigated by the present author. Secondly the increasingly more sensitive response of the outer hair cells to membrane displacements. Thirdly the hypothesized cantilever distortion within the saccule, leading to motion-like sensing at sub-1Hz frequencies.

There is, however, one very important feature that has already been demonstrated and confirmed by A.Salt. The outer hair cells are conventionally regarded as controlling the overall <u>sensitivity</u> of the hearing process, not unlike Automatic Gain Control in radio receivers. He has shown that by exciting these outer hair cells with a mid-frequency tone at 500Hz, the response to infrasound of the inner hair cells becomes very significantly suppressed. This explains the established observation that the hearing threshold is automatically raised by the presence of increased ambient background noise. Thus an individual becomes progressively less sensitive to the presence of low-frequency noise and infrasound in ambient backgrounds of typically 55dBA and upwards. On the other hand, in a very quiet rural environment, this process of suppression does not take place, and sensitivity to wind-turbine infrasound is correspondingly enhanced. So infrasound perception in quiet rural environments should never be equated to the comparative insensitivity to infrasound which is a feature of the higher ambient levels of urban or suburban environments.

A3. Health Effects Associated with Low Frequency Sound & Infrasound from Wind Turbines.

A3.1 AWEA/CANWEA Report into Wind Turbine Sound & Health, December 2009

This 2009 report [22] continues to be frequently cited and has undoubtedly influenced many subsequent Wind Turbine Health studies, yet it has never been peer–reviewed. Although portrayed as providing guidance for decision-makers, it yields a very misleading overall perspective.

Specifically, it cites the 1974 US EPA guidelines [23] for community noise, but states only one specific criterion – a level of 45dBA Ldn (ie 45dBA Leq day, 35dBA Leq night) **inside** a dwelling to avoid sleep disturbance. Yet the full context of the 1974 EPA guidelines (Appendix D) [24] proposes a Normalized Outdoor Day-Night Sound Level of 55dBA Ldn. "Normalized Level" entails including an extra 10dBA correction for rural environments. The resultant Normalized Ldn formula yields **outside** 45dBA Leq in daytime/35dBA Leq at night, or a continuous **outside** day-and-night level of 38.6dBA Leq. Moreover, it recommends an additional 5dBA correction under circumstances where the sound being introduced is unusual to the neighbourhood. Such rural outside nighttime levels, competently defined over 40 years ago, would now be regarded as being widely consistent with recent wind-turbine experience and recommendation. Yet the AWEA report does not convey any of this more detailed information, effectively dismissing these aspects as having been intended only for guidance. It gives the impression that because the EPA guidelines sought to provide an "adequate margin of safety", its guidelines are over-cautious. This present author has never before seen a commentary, particularly regarding potential health issues, where it is appropriate to dispense so casually with an "adequate margin of safety".

It should be noted, moreover, that this EPA recommendation of Normalized Ldn = 55dBA has been substantially misused, with damaging results to some communities. A document summarizing the Michigan Land Use Guidelines (2007) [25] citing the EPA guidelines as its primary source, recommended an unmodified 55dBA as being acceptable for wind-turbine installations. There was complete failure to incorporate any of the modifications associated with the Day-Night or Rural Corrections. This raw 55dBA figure has subsequently become embedded into some Michigan wind-turbine ordinances, yet the AWEA/CANWEA report never acknowledged such obvious examples of misuse.

In December 2009, several days before this AWEA report was announced, the author had submitted a 5-page document to the Michigan Public Services Commission [26]. His report was written in a matter of days in order to meet a prescribed deadline, and drew very largely on direct experience over many years. In particular, he emphasized the importance of the automatic raising and lowering of the threshold of hearing according to the ambient environment. Moreover (again from direct experience), frequent exposure to low-frequency noise on a prolonged basis can result in a person's perception of it becoming very much more pronounced, with the consequence that it can become increasingly readily sensed.

The author regards these two specific features as being amongst the most fundamentally important in any assessment of low-frequency wind-turbine noise perception, yet no mention is made of either in the AWEA/CANWEA report. Indeed, the converse is portrayed. It is argued that wind-turbine noise cannot be harmful because people live without difficulty in urban environments of 55dBA, and many people acclimatize to persistent low level noise.

"If sound levels from wind turbines were harmful, it would be impossible to live in a city, given the sound levels normally present in urban environments."

"On the other hand, many people become accustomed to regular exposure to noise or other potential stressors, and are no longer annoyed."

The first statement is totally misleading. It is the automatic raising of the hearing threshold with increased ambient sound that makes living in cities readily tolerable. In quiet rural areas, with low ambient sound levels at night, the ear is "wide-open" so wind-turbine noise becomes very obtrusive. This variable hearing threshold, which protects the sensing processes of the cochlea, operates just like the variable iris of the eye which responds to ambient light and protects the retina.

The result is directly analogous to the fact that a car approaching with full beam headlights in broad daylight is innocuous, yet will completely dazzle at night, when the iris of the eye is "wide-open". No-one would get away with the erroneous statement "Headlights at night cannot possibly dazzle, otherwise it would be impossible to venture outside in broad daylight !"

A3.2 The High Permitted Wind Turbine Sound Levels in the USA

In early 2010 Huron County, Michigan was considering modifying its Ordinances from 50dBA, L10 levels for all landowners, to a reduced 45dBA L10 level just for non-participating landowners. This author attended numerous public meetings at which he argued the requirement for still lower sound levels and greater setbacks, but the AWEA/CANWEA report and its extensive list of authors was cited against him, apparently justifying the County's perspective.

This situation became all the more galling given that one of its authors, Dr Leventhall, had given a presentation at the University of the South Bank, London in November, 2009, one month before publication of the AWEA/CANWEA document. It was reported [27] that he had stated at this presentation

"I think US legislators accept that in many cases the turbines are too close to homes, but publically they deny there is a problem," said Professor Leventhall. "There isn't a health problem, but noise is increasing opposition to wind energy."

Yet nothing in the AWEA/CANWEA document indicates that the permitted USA setbacks and wind-turbine sound levels could be unsatisfactory.

Subsequently, in telephone communication with the Vermont Senate in April 2013 [28], Dr Leventhall emphasized the fact that there are considerably more complaints about wind turbines in North America compared to Europe. He attributed this to "hysterical reaction", but completely failed to indicate the explanation that permitted wind turbine levels could be significantly higher in North America than in Europe.

This difference in permitted levels is confirmed by the following statement in a more recent peer-reviewed publication of November 2014 funded by CANWEA, again relating to Wind Turbines and Health, of which three authors are the same as the original AWEA/CANWEA document [29].

"With respect to noise standards, Hessler and Hessler[13] found an arithmetic average of 45dBA daytime and 40dBA nighttime for governments outside the United States, and a nighttime average of 47.7 dBA for US state noise regulation and siting standards."

This indicates an average 7.7dBA higher night-time levels in the United States. The caution was given that the use of different metrics (eg L90,L50, Leq etc.) change the implicit value of these levels. (see p25*)

This recent CANWEA-funded paper also concludes at one stage:

"Complaints such as sleep disturbance have been associated with A-weighted wind turbine sound pressures of higher than 40 to 45dB but not any other measure of health or well-being."

Thus one might immediately conclude that given the average permitted levels of 47.7dBA in the United States, there would very likely be a greater number of complaints of sleep disturbance. Once again this does not appear as an explicit conclusion. The failure to emphasize such an obvious shortcoming in the USA, in documents which are intended to provide overall guidance, undoubtedly serves to "muddy the waters" when seeking to identify why homeowner complaints proliferate.

Finally, even in this very recent report, there is still no mention of the fundamental consequence of automatic adjustment of hearing threshold to the ambient background level, nor does there appear to be any mention that continuing exposure to low-frequency noise can give rise to enhanced sensitivity. As stated earlier, from direct experience the present author considers that these are two very important aspects of low frequency noise perception, yet they still do not appear to have been widely recognized by health experts.

*(Different metrics do indeed represent differences in actual permitted levels, although it is commonly considered that for slow response (ie 1-second) dBA measurements and extensive observation times, differences when applied to dominant wind turbine noise do not generally account for more than 4-5dBA between the lowest measure (L90) and the highest level (L10), and do not account for as large a difference as 7.7dBA. The US company Epsilon, which performed field assessments of Ordinance compliance in Huron County, MI, explicitly applied the criterion “L10-L90 less than 3.5dBA” for identification of dominant wind-turbine noise.)

A3.3 Nocebo Effects, Annoyance, Personality, & Activists

Claims that wind turbine infrasound cannot represent a health hazard have increasingly sought to lay blame for increasing numbers of complaint on four processes, namely nocebo effects, annoyance, individual personality, and the alarm raised by activists.

The argument that nocebo effects, ie fear of a specific outcome can give rise to symptoms relating to that outcome, does not account for the fact that some communities have welcomed the introduction of wind turbines, only to subsequently discover unexpected adverse effects once the turbines are up-and-running. The present author is personally aware of two families, one in England and one in Michigan, who initially had neutral or favourable prior attitudes towards wind turbines, but who then discovered for themselves that the reality could be quite intolerable. Neither family had heard of the other, yet their circumstances 4000 miles apart became almost identical, and led to them making exactly the same decisions, namely to rent alternative sleeping accommodation, and ultimately to undertake protracted lawsuits against the wind-developers. In both cases, these were settled out of court subject to confidentiality constraints. At the time of onset of these issues, the numbers of activists were few, so the mirror-image first-hand learning sequence of the two families was all the more remarkable.

It should be noted that many of the adverse effects of wind-turbine infrasound are closely related to the symptoms of sea-sickness, which suggests that there may be an interaction with the vestibular (balance) organs. The present author used to sail offshore, extensively, during the 1970’s. At that time, there would be some participants who claimed that sea-sickness was merely psychological, and given sufficiently strong-mindedness, did not affect them. Fellow crew-members often felt a grim sense of satisfaction when such self-styled experts ultimately came face-to-face with physical reality and succumbed to sickness. In this respect, they often prove to be less effective at coping than those with a more realistic outlook. Moreover, while sometimes the effects of seasickness can be manifest quickly, it is not uncommon for the onset to be delayed until after as long as 10 to 12 hours of exposure.

A recent New Zealand study [30] has aimed to reinforce the nocebo argument relating to infrasound from wind-turbines. A group of participants was split into two separate groups, and videos describing the effects of wind-turbine infrasound shown to each group. For one group, these videos showed people describing the adverse health effects that they had experienced from wind-turbine infrasound, while the other group were shown scientists and experts giving assurances that there could be no real effects.

The two sets of participants were then subjected to 10 minute exposures to blind tests of either simulated wind-turbine infrasound, or no (ie "sham") infrasound, at an extremely low-level of 40dB at 5Hz. There was subsequently a minor, but identifiable increase in anxiety- related responses from the group which had been pre-conditioned by the adverse reports, regardless of whether they were exposed to simulated or "sham" infrasound.

One only has to consider the analogy of seasickness, however, to gain a perspective of this experiment. It is directly comparable to taking two groups of people unfamiliar with being afloat, briefing these separate groups with opposing perspectives of the causes and effects of sea-sickness, and then sending the participants out in two separate boats on an inland lake in almost flat calm conditions for 10 minutes. Any conclusions resulting from one group becoming initially slightly anxious in this process would hardly have any relevance to the reality of full-scale exposure to real sea conditions for protracted periods of time !

With regard to the arguments that annoyance and personality play a major part in the response to wind-turbine sound and infrasound, it should be noted that many people who choose to adopt a rural lifestyle do so specifically to enjoy a more tranquil and less stressful environment than suburban or city life. So they are quite likely to have a personality which values these rural characteristics. For such people, this personality may well be one which reacts strongly to an externally imposed, adverse intrusion on their lifestyle. Wind turbine installations should not be such that "failure to have the right personality" undermines the make-up of the community.

The use of the term "annoyance" has two separate common interpretations. It is often said " It's his own fault that he got annoyed ! " which immediately implies a self-imposed condition. In the context of wind-turbines, however, it is more accurate to state that "turbines can cause people to <u>suffer</u> annoyance". This introduces a completely different perspective – it makes clear that the adverse situation has been <u>imposed</u> on the individual, and any reaction is a direct consequence of this imposition. This author considers that the use of the terminology "suffers annoyance" is a much more appropriate and significantly less misleading description, which correctly places responsibility directly with the cause, rather than with the individual's response.

Finally, a recent well-publicized paper (S.Chapman [31]) has argued that the most compelling correlation relating to wind-turbine complaints arises from the presence of "activists" opposing the construction of a wind-farm. Yet this study made no attempt to consider such issues as immediate setbacks, noise, the local geography and configuration of the wind-farm, and the separation and density of the turbines. All of these factors have direct bearing on the conditions experienced in the neighbourhood of wind-turbines. Once again, referring to this author's own experience, in Huron County, Michigan there were initially two windfarms constructed at similar times, in similar sections of the community. Of these, one led immediately to significant numbers of complaints, while hardly any complaints were registered at the other. On paper, this latter windfarm appeared to be the more closely concentrated, so the lack of complaint was all the more surprising. But one only had to visit the two windfarms on a few occasions to immediately realize that there was a very significant difference in noise levels between the two, and not surprisingly the windfarm giving rise to the most noise was the windfarm resulting in the most complaints.

So in this case, there was an obvious correlation between the noise and adverse nature of the windfarm environment and the number of complaints. This situation subsequently gave rise to greater awareness in the overall community, and a greater degree of expressed opposition to windfarms. Thus the process of cause and effect was the completely inverse of that proposed in [31].

A4. 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, 460m downwind of the nearest turbine. 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. 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 a long overnight run could be set up, leaving the instrumentation under the control of the home owners. The author was immensely relieved 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 (3) shows

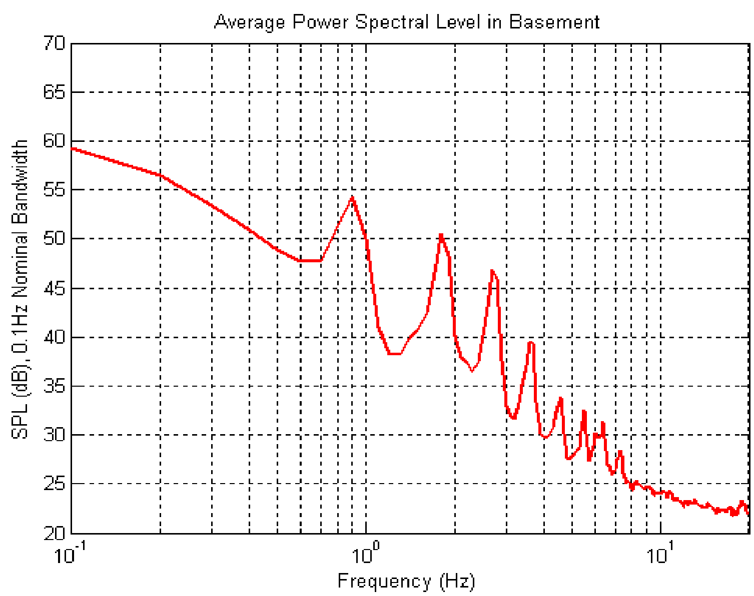

Figure 3 Average Power Spectrum of Infrasound in Basement

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 (4). 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.

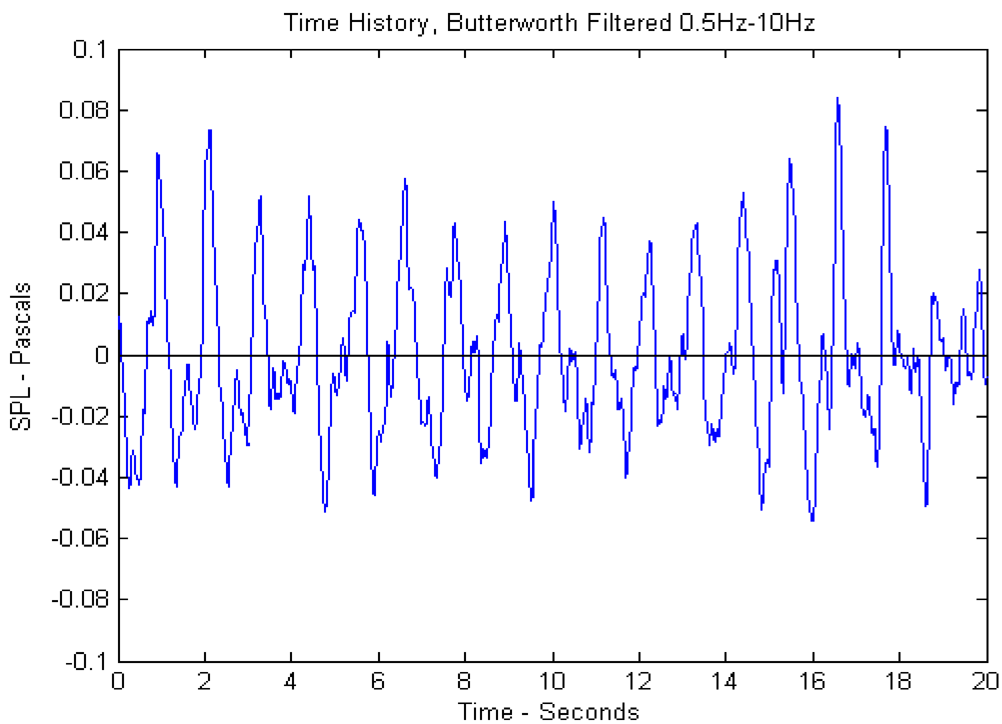

Figure 4 Time History of Infrasound in Basement

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 0.06-0.08 Pascals, representing 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 [16] 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 [20]. 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 [32], 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.

At this point, it is appropriate to conjecture whether a suggestion by Dr A.Salt may be relevant [20]. He has described a process known as “Temporary Endolymphatic Hydrops”, a defect of the inner ear, whereby the pressure-relief opening at the apex of the cochlea (the helicotrema) can become temporarily obstructed by local membranous displacement. This blockage significantly increases the pressure imbalance across the basilar membrane, and consequently a very large increase in sensitivity to infrasound.

If exposure to repetitive wind-turbine infrasound can sometimes induce such an effect, it would then require a finite time after exposure for the condition to subside. So removal of the source of excitation would not result in an immediate return to normal perception, but could cause the symptoms to persist for a further interval of time.

A further observation is that the levels of infrasound shown in Figure (3) are directly comparable to those which have been reported independently by Professor Hansen and colleagues of Adelaide University [33], and L.Huson [34], at significant distances from the Australian windfarms at Waterloo and Macarthur respectively. This appears to provide cogent, independent corroboration given the reports of adverse effects associated with these latter installations. Moreover S.Cooper [35] in his Cape Bridgewater Windfarm Study has now shown direct correlation between the documented sensations of residents and the specific infrasonic operating characteristics of wind-turbines.

Consequently, the present author’s experience is entirely consistent with this more recent reporting in Australia, relating to work carried out by experienced acousticians. There is undoubtedly a progressive accumulation of evidence to support the argument that infrasound from wind turbines can be responsible for adverse health effects in rural environments.

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Appendix B1: Author's Biography

Dr Malcolm Swinbanks studied for his doctorate under Sir James Lighthill, Lucasian Professor of Mathematics at Cambridge University. Two of Lighthill's accomplishments – Aeroacoustics, the mathematical procedures for jet-engine noise reduction, together with study of the dynamics of the cochlea (inner ear) –now relate directly to the recent understanding and perception of wind-turbine noise.

Although awarded a Trinity College Title A Fellowship to continue mathematics research, Swinbanks chose to defer this to gain experience in more practical applications, working first with the research department of Yarrows Shipyard in Glasgow, relating to noise and vibration in ships and submarines. He successfully pursued the Active Control of Low Frequency Noise, in the process becoming familiar with issues relating to community perception of Low-Frequency Noise and Infrasound. Further experience was gained working with several divisions of Rolls-Royce on Aero-Engine dynamics and Industrial Gas Turbine noise.

In 1994, the US Congress requested him to transfer to the United States his research in underwater low-frequency sound and vibration, becoming Principal Scientist to a US company under contract to the US Office of Naval Research. Research areas included extremely high precision vibration isolation and shock mitigation. Most recently, he was approached by people who are encountering very real problems from wind-turbine noise, in some cases being driven from their homes. He has spent considerable time at several windfarms where noise is a significant problem, thus gaining first-hand experience and practical data relating to the extremely adverse conditions to which some people are now being subjected.