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A Review of Wind Turbine-Generated Infrasound: Source, Measurement and Effect on Health

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Abstract Some people who reside in proximity to wind turbines complain of a range of adverse health impacts. These include tinnitus, raised blood pressure, heart palpitations, tachycardia, stress, anxiety, vertigo, dizziness, nausea, blurred vision, fatigue, cognitive dysfunction, headaches, ear pressure, exacerbated migraine disorders, motion sensitivity, inner ear damage and sleep deprivation. This article begins with a historical review of prognoses such as Vibroacoustic Disease and Wind Turbine Syndrome which were proposed to explain the reported health symptoms and the hypothesised link to the emission of infrasound from wind turbines. A review of noise measurements at wind turbine sites conducted by various investigators shows that the level of infrasound is below the threshold of hearing. Notwithstanding, others postulate that stimulation by infrasound of the otolith organs causes nauseogenic symptoms or that stimulation of the outer hair cells, which are said to be particularly sensitive to infrasound frequencies, explains the symptoms. A review of social surveys is undertaken of self-reported health effects attributable to wind turbine noise, including the effects of sleep disturbance. A description is finally provided of physical exploration studies which subject participants to infrasound and measure their response.

Keywords Wind farm · Wind turbine noise · Infrasound · Health impacts · Nauseogenic symptoms

1 Introduction

In 2015, the Australian Senate Select Committee on Wind Turbines concluded there was credible evidence from a number of people who reside in proximity to wind turbines who have complained of a range of adverse health symptoms. These include tinnitus, raised blood pressure, heart palpitations, tachycardia, stress, anxiety, vertigo, dizziness, nausea, blurred vision, fatigue, cognitive dysfunction, headaches, ear pressure, exacerbated migraine disorders, motion sensitivity, inner ear damage and sleep deprivation [1].

Ms Janet Hetherington, an adjacent landholder to the Macarthur Wind Farm in south-west Victoria, relayed her own experience:

> At my farm, I experience severe adverse health effects such as vibration, heart palpitations, tinnitus, head pressure, headaches, sleep deprivation, anxiety, night sweats, nausea, itchy skin, cramps, and ear, nose and throat pain. Twice now I have experienced horrendous pain in my chest stabbing through to my backbone in between my shoulder blades. I contemplated calling an ambulance both times but could not move to do so because of the severity of the pain. Ten minutes later it had dissipated, leaving me with great stress and anxiety and feeling washed out. All these sensations leave me drained in the morning. I find it very hard to start work that day.[1]

Waubra resident Mr Donald Thomas identified hearing difficulties from the nearby Waubra Wind Farm turbines. He claimed that these difficulties disappeared when he left the area:

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[1] Section 2.9 reference [1].

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> I went to the doctor with what I kept saying was a lot of ear pressure and earaches. I went to see a specialist, and my ears came back as being in good health and functioning pretty well, even though I have lost a lot of hearing. Basically, my left ear does not work too good…
> My ears - especially when I go to my Stud Farm Road property, I have ear pressure that can develop into a headache and rapid heartbeat. If I leave that area and go back to one of my other properties, that can settle back down.[2]

These witness testimonies represent only a small fraction of the stories heard by the Senate Select Committee. The question is why, if these and so many other wind farms are claimed to be compliant with wind farm codes mandated by the various states in Australia under current regulations, are they still creating complaints of this nature?

Are the complaints simply a consequence of the expression of ill-will towards those making money by hosting wind turbines? In 2004 when multiple wind farms were being mooted for Bald Hill and Toora in South Gippsland Victoria, it divided the community:

> Once the dust settled, something else became clear as well. Neighbours had stopped talking to each other. Lifelong friends were at loggerheads. Businesses were being boycotted. On Victoria's south-west coast, an environmental panel noted that the wind farms planned for the Portland region's three headlands had split the community. In South Gippsland, the mayor described the developments as the most divisive issue in a generation. … Local proponents of wind farms say it is all about money - those who are paid are happy, those who aren't are either jealous or fear for their property values. Opponents say it's all about aesthetics - the turbines will pollute both the landscape and lifestyles with their triffid-like forms, industrial noise and giant flickering shadows.[3]

What is the extent of complaints? The Office of the National Wind Farm Commissioner was announced in October 2015 as a key recommendation of the Senate Select Committee.[4] From its inception up to 31 December 2016, the Office of the Wind Farm Commissioner received a total of 90 complaints:

- 46 complaints relating to nine operating wind farms
- 42 complaints relating to 19 proposed wind farms
- two complaints that did not specify a wind farm.

As at 31 December 2016, 67 complaints were closed by the Office. The remaining 23 matters are at various stages of the complaint handling process [2].

In relating the number of complaints to the size of the wind generating industry in Australia, based on figures in the Clean Energy Council's 2015 report, there are 76 wind farms operating in Australia [3]. South Australia has the largest wind generating capacity of any state with 651 wind turbines generating 35.2% of Australia's wind energy. Victoria is the second largest with 596 wind turbines generating 29.4% of Australia's wind energy, and NSW is third with 361 wind turbines generating 16% of Australia's wind energy.[5]

In comparison with the environmental effects of transportation noise, for example, these numbers are relatively small. According to Tonin [4], it is estimated (based on the population reported in the 2014 Australian Bureau of Statistics) that there are almost 12 million people in Australia affected by noise from transportation (road, air and rail), with the vast majority (10 million) affected by road and of those, 2 million seriously affected. The consequence of high transportation noise levels is that people become annoyed, their sleep is disturbed, and they suffer adverse health effects.

There is a proliferation of anti-wind farm organisations in Australia and in other countries. According to one anti-wind farm organisation,[6] there are over 2200 international anti-wind farm groups with 23 groups in Australia, such as the Waubra Foundation and Stop These Things.[7] The existence of such groups is not inconsistent with the presence of community groups opposed to other industries, such as the extraction of coal seam gas (CSG), for example. According to one source,[8] there are six anti-CSG groups in Australia, with one of those groups "Lock The Gate" claiming to have 97,000 members comprising more than 250 local anti-CSG groups.[9]

Conversely, a number of professional and government organisations, whilst supportive of further research, have concluded that wind farms do not impact on human health provided planning guidelines are followed.

The Australian Government's National Health and Medical Research Council (NHMRC) concluded as follows:

> The health effects of many forms of renewable energy generation, such as wind farms, have not been assessed to the same extent as those from traditional sources. However, renewable energy generation is associated with few adverse health effects compared with the well

[2] Section 2.14 *ibid*.

[3] An ill wind blowing. John van Tiggelen. SMH Good Weekend, 4 Sept 2004.

[4] Section 1.12 *ibid*.

[5] Reference [3].

[6] https://quixoteslaststand.com/worldwide-anti-wind-groups/.

[7] http://waubrafoundation.org.au/, https://stopthesethings.com/.

[8] https://www.crikey.com.au/community-groups-opposed-to-csg/.

[9] http://www.lockthegate.org.au/.

documented health burdens of polluting forms of electricity generation (Markandya & Wilkinson, 2007).
This review of the available evidence, including journal articles, surveys, literature reviews and government reports, supports the statement that: *There are no direct pathological effects from wind farms and that any potential impact on humans can be minimised by following existing planning guidelines* [5].

In response to public concern, the Government of Canada, through the Minister of Health, asked the Council of Canadian Academies to determine whether there is evidence to support a causal association between exposure to wind turbine noise and health effects [6]. The Council is an independent, not-for-profit organisation that supports independent, science-based, authoritative expert assessments to inform public policy development in Canada. The Council found sufficient evidence to establish a causal relationship between exposure to wind turbine noise and annoyance and limited evidence to establish a causal relationship between exposure to wind turbine noise and sleep disturbance. The Council found evidence suggesting a lack of causality between exposure to wind turbine noise and hearing loss and that the available evidence was inadequate to draw any conclusion regarding causation for all other health effects considered.

The Association of Australian Acoustical Consultants (AAAC) comprising as members the preponderance of professional acoustic firms in Australia concluded as follows:

> Infrasound … is generated by both natural sources … and mechanical sources …. Investigations have found that infrasound levels around wind farms are no higher than levels measured at other locations where people live, work and sleep. Those investigations conclude that infrasound levels adjacent to wind farms are below the threshold of perception and below currently accepted limits set for infrasound. The AAAC encourages members to continue to contribute to new research and review research in the technical literature.[7]

In this article, infrasound is defined as sound covering the frequency range 0–20 Hz.

The Australian Medical Association (AMA) holds the following position:

> The available Australian and international evidence does not support the view that the infrasound or low frequency sound generated by wind farms, as they are currently regulated in Australia, causes adverse health effects on populations residing in their vicinity. The infrasound and low-frequency sound generated by modern wind farms in Australia is well below the level where known health effects occur, and there is no accepted physiological mechanism where sub-audible infrasound could cause health effects.
> Individuals residing in the vicinity of wind farms who do experience adverse health or well-being, may do so as a consequence of their heightened anxiety or negative perceptions regarding wind farm developments in their area. Individuals who experience heightened anxiety or diminished health and well-being in the context of local wind farms should seek medical advice.
> The reporting of 'health scares' and misinformation regarding wind farm developments may contribute to heightened anxiety and community division, and overrigorous regulation of these developments by state governments.
> The regulation of wind farm developments should be guided entirely by the evidence regarding their impacts and benefits. Such regulation should ensure that structured and extensive local community consultation and engagement is undertaken at the outset of planning, in order to minimise misinformation, anxiety and community division. …[10]

Surprisingly, these position statements appear to have evoked a convocation of strong criticism, in parts tending on the emotive, from members of the profession unlike any response to other industrial or transportation projects. In his submission to the Senate Select Committee, Thorne states:

> … the National Health and Medical Research Council be required to cease wasting taxpayer monies on academic exercise into wind farm health effects. …the current members of the NHMRC Wind Farms and Human Health Reference Group [should] be dismissed and not permitted to have any further involvement in wind farm studies or reports. … the NHMRC gives an appearance of being biased towards dismissal of adverse health effects raised by ordinary people. …[11]

In an editorial, Hansen opines:

> It's time to stop denying that wind farm noise causes adverse health effects in some people. It's insulting to sufferers to be accused of only suffering from a "nocebo" effect. Everyone who is adversely affected by wind farm operations deserves to be heard and deserves adequate compensation, which should include an offer to purchase their property at a fair price [8].

Cooper alleges that there are questions as to whether members of the AAAC and the Australian Acoustical Society (AAS) have acted ethically:

> In attending various rural dwellings to undertake wind farm noise measurements questions have been raised by the occupants as to the conduct of members of

[10] Section 2.37 Reference [1].

[11] Submission 338 by Robert Thorne *ibid*.

> the AAAC and the AAS in relation to monitoring and reporting of the results/impact. … The question now being asked in the community, and invariably will be asked in courts of law, whether the absence of that material in the "noise assessment" is a Breach of Code of Ethics.[9]

Is there not a simple solution to this problem? Perhaps, the answer is not to put wind farms close to people. Under the Victorian Planning Provision 52.32, a written consent of an owner must be obtained if an existing dwelling is located within 1 km of a proposed turbine [10]. In South Australia, the minimum setback distance is 2 km [11]. In New South Wales, there is no minimum setback distance [12].

It will be demonstrated in this paper that wind farm infrasound has a very different characteristic to environmental infrasound in that it is periodic, whereas environmental infrasound is random. As stated by Hansen:

> It is unknown whether the adverse health effects are a result of sleep deprivation resulting from audible noise or whether there is a direct physiological effect of long-term exposure to low-level, periodic infrasound. Not enough research has been done to rule out the latter, so it should not be discarded as a possible mechanism.[12]

This paper addresses the adverse health effects on people of periodic infrasound caused by wind turbines. It begins with a historical perspective, a description of the generation of infrasound by wind turbines and the special techniques used to measure it, the response of humans to infrasound, the various hypotheses to explain the symptoms and the research into health effects.

2 Historical Perspective

In 1979, an investigation was commenced into the cause of noise complaints related to a DOE/NASA 2MW MOD-1 wind turbine operating near Boone, North Carolina, USA [13]. The MOD-1 had two blades with a rotor diameter of 61m and was the largest wind turbine so far constructed. The turbine operated until 1981 when a major mechanical failure resulted in the turbine being decommissioned.

Importantly, there were two distinguishing features which made this wind turbine problematic. Firstly, the rotor was a downwind type which meant that the blades were located so that the wind hit the tower first and then the rotor blades. Secondly, the supporting structure was a lattice tower which disturbed the inflow wind which, on striking the blades, caused noise to be generated.

Whilst there were more than 1000 families living within a 3-km radius of MOD-1, only about a dozen families complained of "thumping sounds and vibrations" similar to the sensation of having someone walk heavily across a wooden porch. Many persons reported they could "feel" more than "hear" the sounds which created a sensation of uneasiness and personal disturbance. The effect was more annoying inside the home than outside. The report concluded this was due to the excitation of resonant acoustic modes within the rooms.

In 1993 in Wales, UK, a local resident of Llangwyryfon who lives 350 m from the 20 turbine Llangwyryfon Windfarm wrote to the Daily Telegraph UK as follows:

> We live about 350 metres from the nearest turbine and about 750 metres from six or seven others. The "thwump" of the blades and grinding gears is driving us to distraction. My kitchen chimney amplifies these noises sickeningly. Earlier this year during wind turbine experimental stages, and since commissioning in July, the house has frequently vibrated with penetrating soundwaves. At night, these disrupt sleep even when all windows are closed. As I write, turbine droning is audible above the computer's hum.[13]

Since about 1999, Branco and Alves-Pereira have published research articles on a pathology which they have given the name "Vibroacoustic disease" (VAD) which is allegedly caused by excessive exposure to low-frequency noise. Initially, VAD was a study about the health effects of low-frequency noise in aircraft and its effects on aviation personnel. VAD was identified by a thickening of the mitral valve (one of the valves in the heart) and the pericardium (a sac containing the heart), in aeronautical workers who were exposed to high sound levels over long periods of time. However, over time, the scope of their study widened to include health effects caused by other low-frequency noise sources such as nightclub music and industrial noise and finally in a claim that infrasound from wind turbines causes VAD. It is therefore instructive to pause at this point in this article to follow the chronology of articles written by Branco and Alves-Pereira as there appears to be a strong connection between those articles and the adoption of infrasound as being the cause of adverse health effects from wind turbines.

In 2004, the authors published a summary article on what is known to date about VAD [14]. That article states that VAD is not an "acknowledged entity" which is presumed to mean that VAD is not a recognised medical illness. VAD is described as follows:

[12] Reference [7] *op cit*.

[13] Wind Farm's noise is worst aspect. Letter to the Editor from Caroline Kerkham, Llangwyryfon, Dyfed, Wales. Daily Telegraph UK, 21 October 1993.

> VAD has been observed in LFN-exposed professionals, such as, aircraft technicians, commercial and military pilots and cabin crewmembers, ship machinists, restaurant workers, and disk-jockeys. VAD has also been observed in several populations exposed to environmental LFN. … In both human and animal models, LFN exposure causes thickening of cardiovascular structures. Indeed, pericardial thickening with no inflammatory process, and in the absence of diastolic dysfunction, is the hallmark of VAD. Depressions, increased irritability and aggressiveness, a tendency for isolation, and decreased cognitive skills are all part of the clinical picture of VAD.

The article concludes in the following terms:

> Given the data collected to date and the worldwide suffering of millions of LFN-exposed citizens, this status quo situation is unethical, unsustainable, and downright obscene.

A follow-up article by Branco and Alves-Pereira includes infrasound as an "agent of disease" and includes an extended history of the authors' work in researching the effects of VAD [15]. The paper concludes that suspicion of VAD should arise if the patient exhibits complaints of noise sensitivity, tiredness, out-of-breath, heart palpitations and coughing.

Two articles written by Branco and Alves-Pereira in 2007 linked VAD to infrasound from wind turbines. In the first [16], a family of four living within 322 m of a wind farm comprised 4 off 2MW turbines received VAD diagnostic tests which did not disclose adverse results. Nevertheless, the authors concluded that the family will develop VAD should they choose to remain in their home. In the second [17], the authors conclude that the family shows the initial signs of Stage-1 VAD and that they will develop severe VAD since they are already exhibiting symptoms consistent with early VAD.

Turning back now to chronological events, in 2005 the Waubra Wind Farm was approved by Planning Panels Victoria for the construction by Acciona of 128 wind turbines up to 121 m in height in three groups at a site approximately 25 km north-west of Ballarat along the Sunraysia Highway (Victoria's second biggest wind farm) [18]. A submission by an objector raised the issue of low-frequency noise, in particular the cyclic beats which Van den Berg had identified as occurring at night at a wind farm on the German-Netherlands border [19] and which came to be discussed at the Bald Hills Panel Hearing. However, as there was no evidence to demonstrate whether the "Van den Berg effect" is specific to the German location or not, the Panel accepted a penalty of 5 dBA should be applied if the sound contained tonal variations and cyclic beats.

In 2006, a study was commissioned by the UK Department of Trade & Industry (DTI) into low-frequency noise (LFN) emissions from wind turbines which had allegedly given rise to health effects to neighbours of three wind farms in Cumbria, North Wales and Cornwall [20]. The study concluded that:

- infrasound associated with modern wind turbines is not a source which will result in noise levels which may be injurious to the health of a wind farm neighbour;
- low-frequency noise was measurable on a few occasions, but below the existing permitted night time noise criterion. Wind turbine noise may result in internal noise levels within a dwelling that is just above the threshold of audibility; however, at all sites it was always lower than that of local road traffic noise; and,
- that the common cause of complaint was not associated with LFN, but the occasional audible modulation of aerodynamic noise especially at night. Data collected showed that the internal noise levels were insufficient to wake up residents at these three sites. However, once awoken, this noise can result in difficulties in returning to sleep.

In 2009, N Pierpont published the book "Wind Turbine Syndrome" [21]. The book documents the symptoms experienced by 38 individuals from 10 families living near large industrial wind turbines (1.5–3 MW). Symptoms include sleep disturbance, headache, tinnitus, ear pressure, dizziness, vertigo, nausea, visual blurring, tachycardia, irritability, problems with concentration and memory, and panic episodes associated with sensations of internal pulsation or quivering that arise whilst awake or asleep. The proposed hypothesis is that low-frequency noise or vibration affects the body's balance system and brain functions including spatial awareness, spatial memory, spatial problem-solving, fear, anxiety, autonomic functions and aversive learning which it claims explains the foregoing symptoms.

In October 2009, The Ballarat Courier newspaper reported that the Victorian Government was to examine claims that Waubra's 128-turbine wind farm was harming the health of nearby residents. The article stated:

> Finance, WorkCover and Transport Accident Commission Minister, Tim Holding, wrote to Western Victoria MLC Peter Kavanagh earlier this week to confirm that three government departments would examine "potential hazards" caused by sub-audible noise emitted by the turbines. Mr Kavanagh raised the issue in parliament on September 2, after meeting with several Waubra residents who claim the towers have caused headaches, nausea and sleep deprivation since they began operating in June. 'I did a tour of Waubra in late August and people there are very upset about the wind farm,' Mr

Kavanagh said. ‘Most of them were fairly happy to go along with the turbines before they were installed, but now I know of one family who won’t live in their house. It certainly isn’t an isolated incident.’[14]

3 Sources and Measurement of Infrasound

The combination of noise sources from a wind turbine can generally be described as a mechanical noise (such as a car running or a train in continuous motion) combined with an aerodynamic swishing sound (described as like a stick being swung through the air quickly).

Aerodynamic noise associated with the passage of air over the blades is typically the most important component of modern wind turbine acoustic emissions [22]. A large number of complex flow phenomena occur, each of which generate sound in particular frequency bands. Aerodynamic sound level generally increases with rotor speed.

In principle, there are two mechanisms which are likely to be responsible for the aerodynamic noise from the blades. The first is inflow-turbulence noise, which is radiated from the leading edge of the blade and which is caused by upstream atmospheric turbulence. The second mechanism is trailing edge noise caused by an interaction of boundary layer turbulence with the blade trailing edge. Oerlemans concludes that trailing edge noise is the major source of noise in modern wind turbines [23].

According to Doolan [24], trailing edge noise has a cardioid directivity characteristic associated with dipole aerodynamic sources with its predominant lobe oriented towards the leading edge of the blade. As shown in Fig. 1, on the downward movement of the blades, the change in orientation of the asymmetric directivity pattern associated with the trailing edge noise source results in a frequency modulation which is colloquially described as a “swish” [25].

Associated with the “swish” is an amplitude modulation of the sound at the blade passing frequency. The swish amplitude is defined as the difference between the minimum and maximum dB(A) sound level during one revolution of the blades [26].

Amplitude modulation may also occur from the flow over a section of the blade momentarily entering stall. Stall over an airfoil occurs when the angle of attack of the inflow relative to the airfoil chord becomes larger than a critical value. In this case, the flow over the airfoil no longer smoothly follows the contour of the airfoil (referred to as “attached flow”) and flow separation occurs on the suction side of the airfoil. This typically yields a turbulent flow region above the suction side that further convects downstream into the wake. This phenomenon is associated with a significant increase in noise level [27].

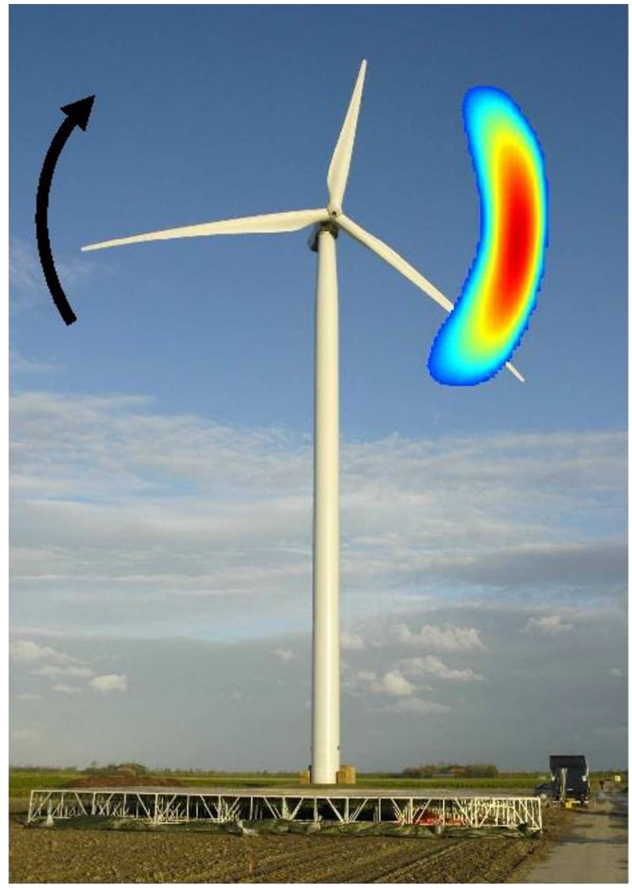

Fig. 1 Test set-up with GE 2.3 MW turbine with 94 m diameter rotor and microphone array platform. The noise sources in the rotor plane (averaged over several rotations) are projected on the picture [28]

In the case of upwind rotors (turbines with the rotor on the upwind side of the tower), it is reasonable to infer that the infrasound energy is also generated on the downward movement of the blades; however, the true source of infrasound is yet to be proven.

In the case of downwind rotors (turbines with the rotor on the downwind side of the tower which are no longer common), there is also an impulsive sound caused by the interaction of the blades with the perturbed upstream flow caused by the tower. The flow of air around the tower is disturbed (or separated) upstream of the tower causing the blades to experience a change in lift force and a corresponding production of noise. The frequencies associated with this source are generally infrasonic. Turbines with downwind rotors produce 10–30 dB higher infrasound levels compared with upwind rotors [29].

Turning now to the method of infrasound measurement, the half-inch microphones typically used to measure infrasound are the GRAS type 40AZ with 26CG preamplifier (or

[14] Health check for Waubra Wind Farm. The Ballarat Courier. 15 October 2009.

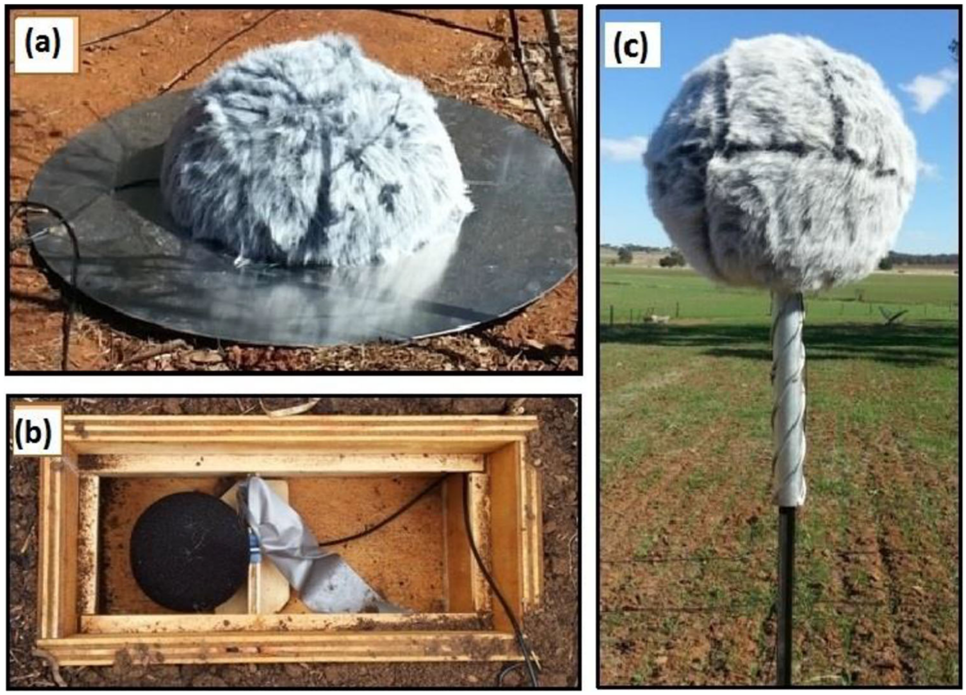

Fig. 2 **a** Hemispherical windshield, **b** submerged box windshield and **c** spherical windshield [30]

type 46AZ microphone preamplifier set) which has a noise floor of 17 dB(A) and a low-frequency limit of 0.5 Hz (–2 dB) and the Bruel and Kjaer type 4193 and preamplifier type 2669 which has a noise floor of 29 dB(A) when fitted with adapter UC-0211 to attain a low-frequency limit of 0.07 Hz (–2 dB).

In order to accurately characterise the noise measured in the vicinity of wind farms, it is necessary to ensure that outdoor microphones are adequately protected from the wind. A standard 90 mm windshield is inappropriate for measurement of infrasound, even in light winds, as wind-induced pressure fluctuations erroneously contribute to the measured sound pressure level. Three commonly used secondary windshields are shown in Fig. 2. These include a hemispherical windscreen on a flat board, a microphone placed in a box with an acoustically transparent cover and a large spherical windscreen [30]. If measuring infrasound only (<20 Hz) then it matters not whether the microphone is located on the ground or above ground as the quarter-wavelength of sound exceeds 4 metres and so the pressure field at the microphone will be influenced by the ground plane up to at least a height of 4 metres.

The measurement of infrasound indoors is just as important as it is outdoors, particularly since the attenuation of typical dwellings is quite small, being in the range 0–5 dB at infrasound frequencies [31]. If internal noise levels are measured, the microphone should be placed in a corner of the room close to the intersection of two walls and the floor or ceiling.

A typical measured power spectral density (PSD) spectrum measured inside the bedroom of a house located 1.6 km from the nearest wind turbine at Cape Bridgewater Wind Farm is shown in Fig. 3 [32]. In this figure, the fundamental blade passing frequency is 0.85 Hz (corresponding to a wind turbine rotational speed of 17 rpm) with five harmonics evident at frequencies 1.7, 2.55, 3.4, 4.25 and 5.1 Hz. Note that, being a PSD spectrum, a conversion factor is required to convert those levels to an equivalent sound pressure level re 20 uPa.[15]

It is these spectral peaks that are being referred to in the literature to date as periodic infrasound associated with wind farms and allegedly causing the symptoms described in the previous section. However, there is a suggestion by Zajamsek et al. [33] that perhaps the focus of concern should instead be at higher frequencies around 50 Hz.

4 Human Response to Infrasound

It is generally recognised that the audibility of sound by humans extends from frequencies 20 Hz to 20 kHz. The loudness of sounds in this frequency range is frequency

[15] The actual value of the conversion factor depends upon the distribution of the PSD spectrum levels in the individual bands clustered around the tone. Theoretically, if all the energy were located in one spectral band, then the conversion factor would be 18 dB and therefore a PSD level of 90 dB represents a sound pressure level of (90–18=) 72 dB re 20 uPa. On the other hand, by way of example, if the energy were equally distributed across three contiguous bands, then the conversion factor would be 13 dB. There is insufficient information provided in the original reference to enable an accurate determination of the conversion factor to be made.

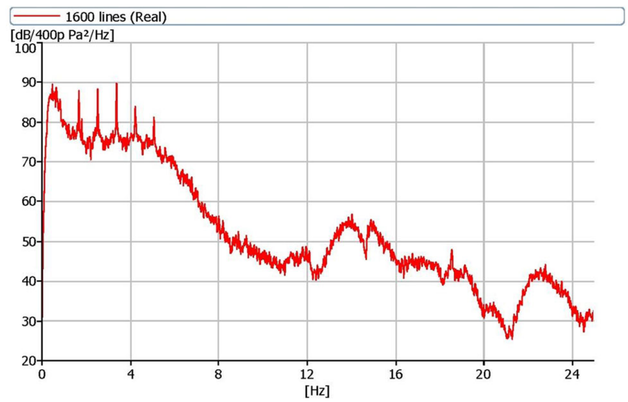

Fig. 3 Measured infrasound power spectral density spectrum (1600 lines 0–25 Hz) showing a fundamental blade pass frequency of 0.85 Hz and harmonics recorded inside the bedroom of a residence located 1.6 km from Cape Bridgewater Wind Farm, Victoria [32]

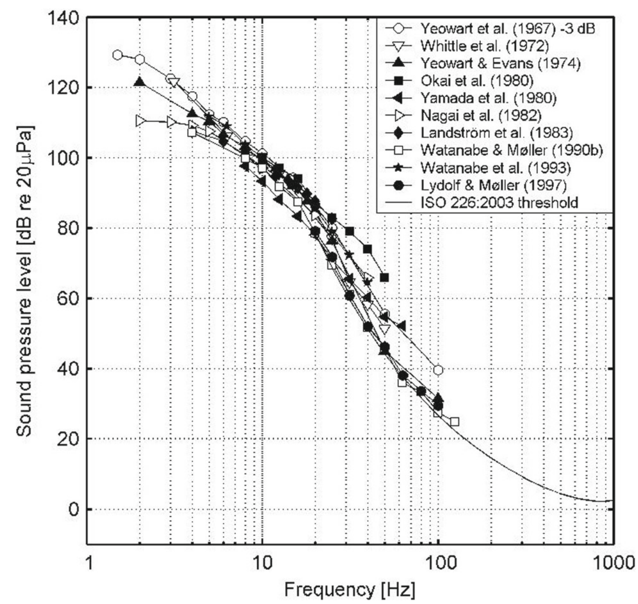

Fig. 4 Mean low-frequency hearing thresholds measured in the period from 1967 to 1997 and ISO226:2003 [35,37]

dependent, low-frequency sounds not being heard as loud as high-frequency sounds when presented at the same sound pressure level. However, what is not generally appreciated is that the human ear can hear sounds below 20 Hz, even down to 1 Hz, if the sound pressure level is high enough. However, a sound with a frequency of 1 Hz is not "heard" as much as "sensed" as a change in pressure not unlike one feels in the cabin of an aircraft when taking off or landing or when going up and down a passenger lift. At frequencies around 6 Hz, the sensation can feel quite uncomfortable and sickening if the sound pressure is high enough.

There are many sources in our everyday environment capable of producing infrasound including man-made sources such as engines, compressors, ventilation systems, traffic and musical instruments as well as natural sources such as thunder, ocean waves and earthquakes. Driving a car at speed with a partly open window is a common situation practically everyone has experienced which exposes the passengers to high levels of infrasound [34].

An important issue is whether or not in the infrasound range, we sense the sound with our ears in the same way as we sense sound in the audible range. Human sensitivity to sound is measured in two ways a) by comparing the loudness of sound of one frequency to that of another frequency at a given intensity level and b) by measuring the onset of hearing at a specific frequency (called the threshold of hearing). These tests can be done either using an audiometer with earmuffs containing loudspeakers or in a very quiet room fitted with loudspeakers. Moller et al. conclude that either method produces the same result and that the same thresholds are obtained if the whole body or only the ears are exposed [35,36]. A compilation by Moller and Pedersen of measured hearing thresholds from 2 to 100 Hz by various investigators together with the current ISO226:2003 thresholds from 20 Hz to 1 kHz is shown in Fig. 4 [35,37].

The data in Fig. 4 represent the mean hearing threshold values for 50% of the population, with about 2% of people expected to have a threshold of between 10 and 12 dB lower than the mean value [36]. Also, as the perceived loudness of noise at low frequencies changes much more rapidly with sound pressure level than it does in the mid to high-frequency range, the difference between perception and annoyance level is much smaller in the infrasound range.

The significance of the low-frequency hearing thresholds is that a central thesis of some investigators, to be discussed later in this article, is that a measured infrasound level below the threshold of hearing cannot be problematic.

Another method of measuring infrasound is by use of the G-weighting function which is defined in ISO 7196 [38]. The G-weighting function is valid in the frequency range 0.25 to 315 Hz and has a zero weighting value at 10 Hz and a negative slope of approximately 12 dB per octave from 10 to 1 Hz to reflect the reduced sensitivity of human perception at those lower frequencies as shown in Fig. 4. The G-weighting is similar in concept to the A-weighting function but for the frequency range and slope. The recommended limit for environmental infrasound in dwellings in Denmark is 85 dB(G) which by reference to the sound level value of 85 dB at 10 Hz in Fig. 4 above is about 10 dB below the average hearing threshold.

5 Measured Wind Turbine Infrasound Noise Levels

As referred to in Sect. 2 of this article, one of the earliest investigations into wind turbine infrasound was in 1979 relat-

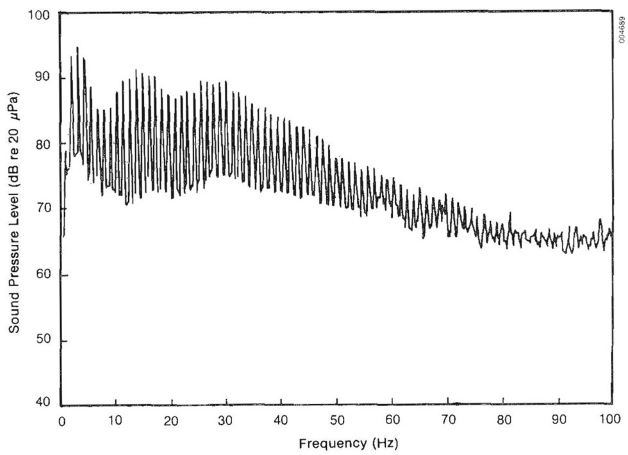

Fig. 5 Average sound pressure level spectrum of MOD-1 measured at 107 m from the wind turbine (Figs. 3, 4; reference [13])

ing to a DOE/NASA 2MW MOD-1 wind turbine operating near Boone, North Carolina, USA. As previously stated, this turbine was a downwind type supported by a lattice tower. At 107 m from the turbine, the measured sound level spectrum is shown in Fig. 5.

The figure shows spectral peaks of about 95 dB below 10 Hz, 90 dB at 10–30 Hz, 80 dB at 50 Hz and about 70–75 dB at 50–100 Hz. Comparing these with Fig. 4, the sound levels at 10–20 Hz are on the cusp of threshold; at 30–50 Hz, they are 10 dB above threshold; and at 50–100 Hz they are 10–20 dB above threshold. Therefore, the low-frequency sound would be audible above the threshold at the measuring location, but, however, would reduce in level with distance from the source.

Jakobsen conducted a compilation of infrasound emission surveys from wind turbines up to the year 2005 [29]. The results are presented in terms of dB(G). In respect of the MOD-1 wind turbine, Jakobsen reports a value of 107 dB(G) at 105 m and 73–75 dB(G) at 1 km. In respect of nine other wind turbines ranging in power from 50kW to 4.2MW, the infrasound level does not exceed 85 dB(G) at distances typically as close as 100–200 m.

In the 2006, study commissioned by the UK Department of Trade and Industry (DTI) into low-frequency noise (LFN) emissions from wind turbines (referred to in Sect. 2 above), infrasound noise levels were measured at residential homes located in three wind farms in Cumbria, North Wales are Cornwall [20]. The internal measurements extended down to 1 Hz; however, the external measurements used a 10 Hz high-pass filter to avoid overloading the instruments due to wind and other problems and therefore should be ignored. Measurements were taken in one-third octave bands. Figure 6 shows a typical result of an internal noise measurement.

In Fig. 6, the measured infrasound noise level is compared with the various thresholds discussed in the preceding section of this article. The DTI report concluded that infrasound noise emissions from wind turbines are significantly below the recognised threshold of perception for acoustic energy within the frequency range 0–20 Hz. The report found that at the higher frequencies above 20 Hz, noise will be audible; however, the noise levels comply with acceptable UK environmental standards. The report concludes that infrasound associated with the wind turbines is not a source which will result in noise levels which may be injurious to the health of a wind farm neighbour.

In 2011, a study was published by Turnbull and Turner [39] describing the results of infrasound noise measurements at Clements Gap Wind Farm and Cape Bridgewater Wind Farm in Victoria. The microphone was located in a submerged box similar to that shown in Fig. 2b at varying distances from the turbine ranging from 85 to 200 m in a downwind direction and with a hub height wind speed of 6–8 m/s. Noise levels were measured in one-third octave bands with a typical result shown in Fig. 7.

The figure shows the one-third octave band spectra at the various distances from the wind turbine together with the 85 dB(G) curve. The investigation concluded that the turbine-generated infrasound was well below the threshold of 85 dB(G).

A collaborative investigation occurred in 2012 at the Shirley Wind Farm in Wisconsin, USA [40]. The Shirley Wind Farm comprises eight Nordex100 2.5MW wind turbines with 85 meter hub height and 100 meter rotor diameter. Residents in close proximity to the wind farm reported that they and their children have suffered severe adverse health effects to the point that they have abandoned their homes at Shirley. They attribute their problems to arrival of the wind turbines.

Figure 8 shows a typical sound level spectrum that measured inside and outside residence R2 which is located 1280 m from the nearest turbine. The figure shows the higher-order blade pass harmonics (the second harmonic being 1.4 Hz, the third 2.1 Hz, the fourth 2.8 Hz and so on). The fundamental blade pass frequency is 0.7 Hz and is obscured by broadband noise.

The study acknowledged that the critical question is what physical effects do these low frequencies have on residents and what limits, if any, should be imposed on wind turbine projects. It noted that the wife and child suffered ill effects and the family moved far away for a solution. The four investigating firms concluded that there was sufficient evidence and hypotheses to classify low-frequency noise and infrasound as a serious issue, "possibly affecting the future of the industry", and that investigations should go beyond the present practice of showing that wind turbine levels are magnitudes below the threshold of hearing at low frequencies.

A noise monitoring program was conducted by the South Australian Environment Protection Authority in 2013 at the

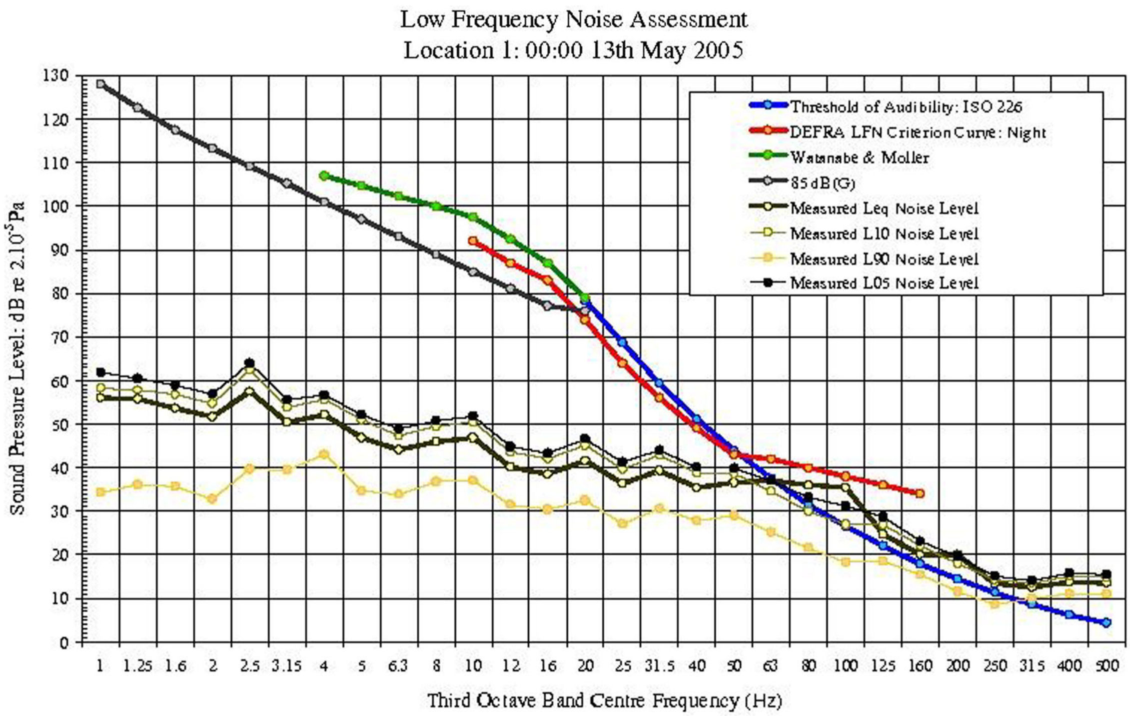

Fig. 6 Typical wind farm-generated infrasound noise measurement inside of a dwelling [20]

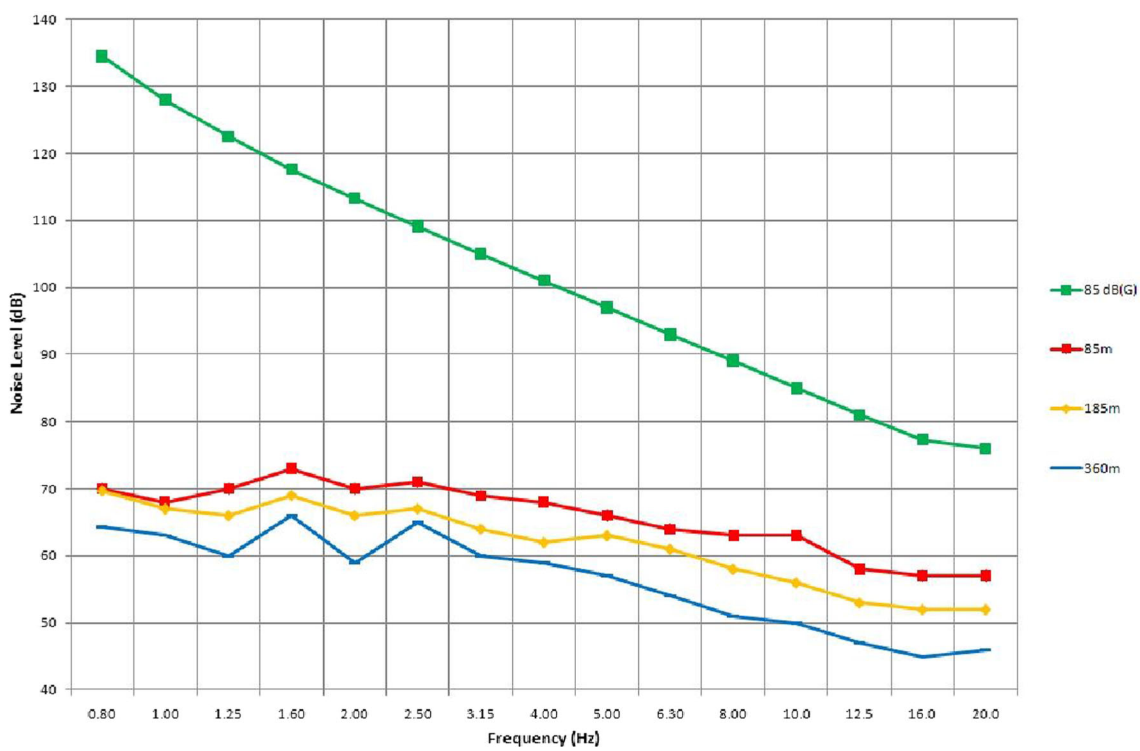

Fig. 7 Measured levels of infrasound at Clements Gap Wind farm with a hub height wind speed of 6–8 m/s [39]

Waterloo Wind Farm which is located approximately 100 km north of Adelaide in South Australia [41]. Situated atop a north–south ridge, and stretching for 18 km, the wind farm comprises 37 Vestas V90 3MW wind turbine generators, each having a hub height of 80 m, with a rated total generation capacity of 111 MW.

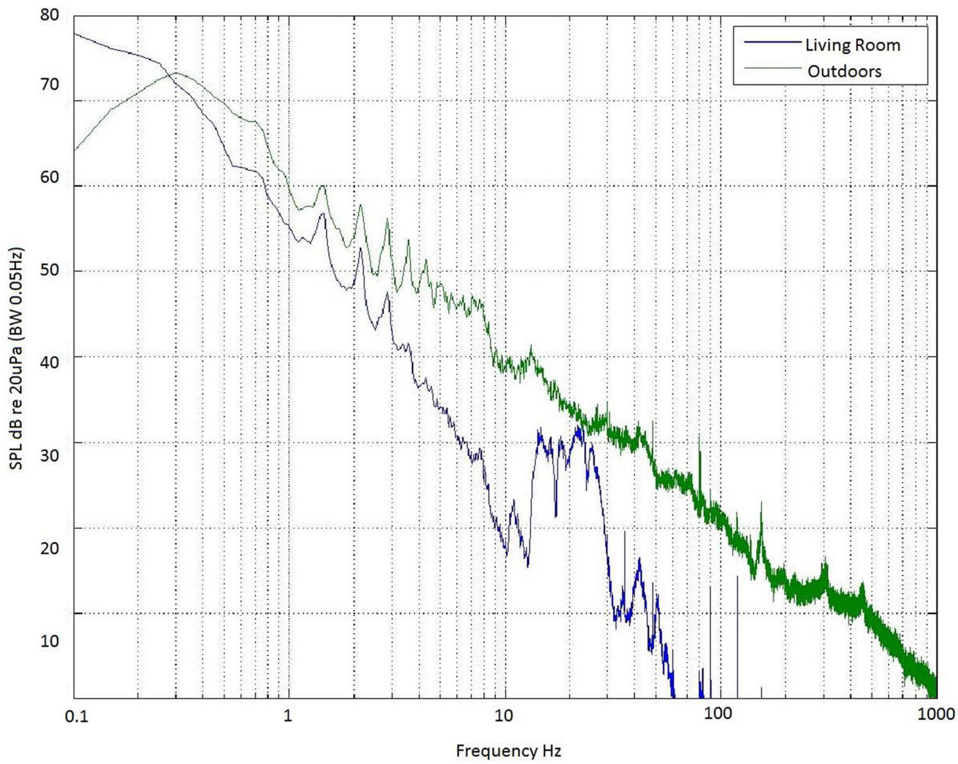

Fig. 8 Narrow band spectrum level in the living room and outdoors at Shirley residence R2 [40]

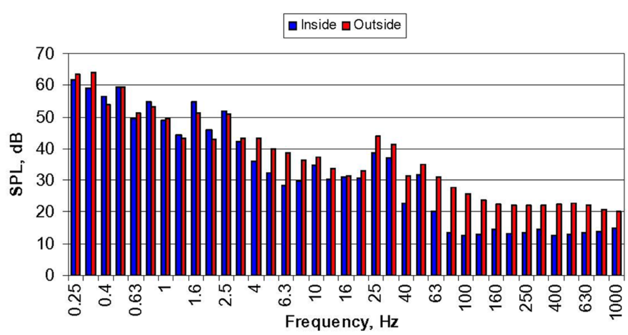

Fig. 9 Waterloo Wind Farm one-third octave unweighted spectrum, downwind/crosswind wind speed 9.7 m/s, 16 rpm (blade pass frequency 0.8 Hz) [41]

Measurements were taken of noise inside and outside of five dwellings located a distance of between 1.3 and 7.6 km from the nearest turbine including the measurement of infrasound frequency inside and outside at two of those dwellings. Figure 9 shows the results for the North Site which is the closest location to the wind farm at about 1.3 km from the nearest wind turbine. Measurements were taken in one-third octave bands.

The investigation concluded that no evidence was found of excessive infrasound. The blade pass frequency component, which falls within the infrasound frequency range, was found to be below the perception threshold by a significant margin, and typical levels were consistent with results of other relevant studies. G-weighted levels were also found to be below the perception threshold.

A comprehensive noise measurement program was reported by Tachibana et al. [42] involving the measurement of infrasound outdoors at 34 wind farms across Japan including laboratory experiments on the psycho-acoustical effects of wind turbine noise. A compilation of measured one-third octave band spectra for 29 of the wind farms is shown in Fig. 10.

In Fig. 10, the measured results are compared with an audibility criterion proposed by Moorhouse et al. [43] for low-frequency noise and ISO 389-7:2005 (which is the applicable standard for calibrating audiometers but is identical to ISO 226:2003 at infrasound frequencies). The investigation concludes that almost all wind turbines produce similar spectral characteristics with a −4 dB/octave spectrum slope on average. Tonal components are seen in some wind turbines. By comparing the measurement results with the criterion curve proposed by Moorhouse et al., it concludes that the frequency components below 20 Hz of almost all wind turbines measured in the study are much lower than the hearing/sensation thresholds.

However, Bell [44] suggests that the assessment of noise from wind turbines is more complicated than simply comparing the average measured levels with the threshold of audibility. Bell's hypothesis is that wind turbine infrasound can be narrow band, have multiple sources and occur intermittently as the sources drift in and out of phase and therefore

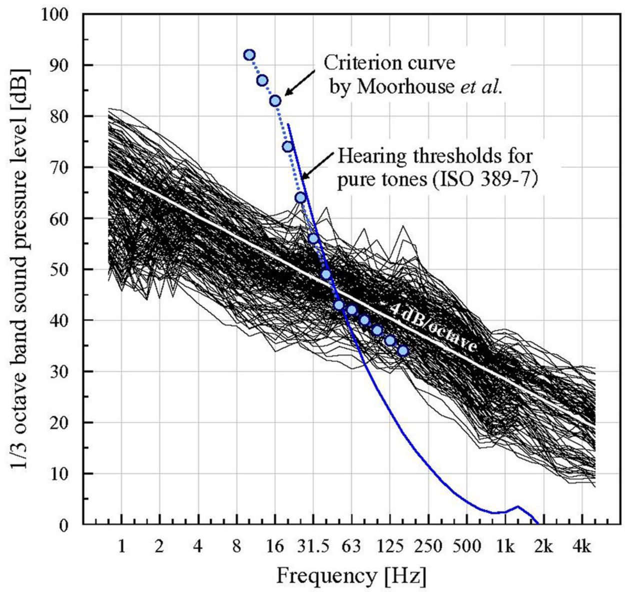

Fig. 10 Measurement result of wind turbine noise levels at 164 points around 29 wind farms in Japan [42]

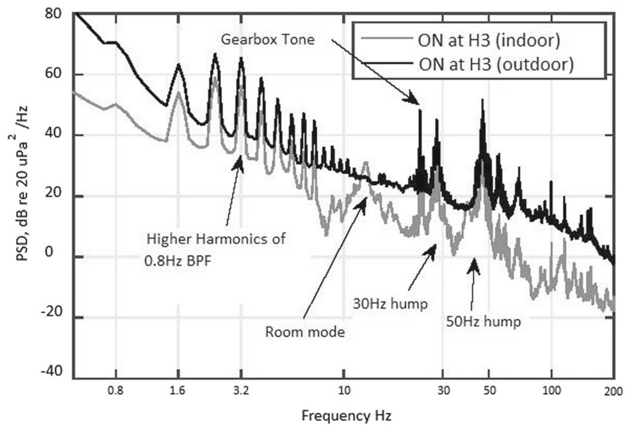

Fig. 11 Comparison between the indoor/outdoor power spectral density (dwelling H3) [33]

the intensity of the fundamental and some of its harmonics could, at nodes, be at least 6 dB higher, but the levels will revert to baseline when the sources fall out of synchronicity. The paper suggests that the apparent paradox between what is heard and what is measured might be resolved by recognising the tonal nature of infrasound at the blade passing frequency (0.8 Hz) and of its harmonics, which may extend to 20–30 Hz.

In 2014, The Acoustic Group published a report of an investigation into infrasound at the Cape Bridgewater Wind Farm in Victoria [32]. Cape Bridgewater Wind Farm was completed in 2008 comprised 29 Senvion (RePower) MM82 2MW wind turbines with an 82 m diameter rotor. The investigation involved noise measurements at three residential properties located between 650 and 1600 m from the nearest turbine and a correlation of noise levels with the residents' perception of "sensation" using a daily diary to ascertain any identifiable noise impacts from the wind turbines operating at various wind conditions. A typical measured sound level spectrum is presented in Fig. 3.

Hansen et al. [33] have published a number of studies relating to wind farms, with reference [33] being selected for review in this article. Noise measurements were taken in 2013 at Waterloo Wind Farm which, as previously stated, is located approximately 100 km north of Adelaide in South Australia and comprises 37 Vestas V90 3 MW wind turbines with a hub height of 80 m. A typical result is shown in Fig. 11.

The figure shows the blade pass frequency (BPF) spectral components at 0.8 Hz and multiples there-off. The level of the highest infrasound component is about 68 dB at about 3 Hz which is well below the audibility threshold of Fig. 4.

The paper concludes that wind turbine noise is characterised by periodic infrasound with significantly higher levels than the ambient when the wind farm is operational. The infrasound levels are, however, below the normal hearing threshold. On the other hand, low-frequency noise (i.e. above 20 Hz) was shown, on average, to exceed the normal hearing threshold curve in the 50 Hz one-third octave band and above for the worst-case conditions. As previously stated, many people will have hearing sensitivities well above and well below the 50th percentile threshold provided by ISO 226. Further, the 50 Hz one-third octave band centre frequency showed significant variation in magnitude with time that could be perceived as annoying.

This is probably a fair summary of the investigations presented in this section.

6 Pro and Con Hypotheses to Explain the Symptoms

As described in the introduction to this article, some people living near wind turbines exhibit real symptoms of adverse health which they say are attributable to infrasound emitted from the turbines. If, as concluded in the previous section, the level of infrasound measured by investigators is below the normal hearing threshold then how can this explain the symptoms?

Leventhall [45] states that it is commonly accepted that sub-audible sounds in the audible frequency range have never been considered to be harmful, so why should infrasound be any different? Hartman [46] responds, by way of analogy, that for some technologies, such as the use of asbestos as a fire retardant and insulation material in residential and commercial construction or the use of newly designed insecticides or herbicides (say DDT) to improve crop productivity, it may take decades to fully document and understand their unanticipated side effect profiles. This is simply the nature of the diffusion of information about new products and technologies—there may be subtle side effects, the consequences of which are unclear for years.

Is infrasound unique to wind farms? Evans et al. [47] and Sonus [48] conclude on the basis of their measurements in South Australia that there is nothing unique about wind turbine noise as infrasound and low-frequency noise are common in nature. The measured G-weighted infrasound levels within 100 m of a wind turbine are of the same order as that measured in rural, urban and seaside locations. However, as noted in the previous section, infrasound contains blade pass components which are not a feature of infrasound found in nature.

Stead et al. [49] measured the frequency and level of infrasound at the ear from the simple act of walking and conclude that levels are higher than that measured at wind farms. Leventhall [50] concludes that infrasound and low-frequency noise are commonly produced by the body in the inner ear from heartbeat and other processes with the same frequency range and level as wind turbines.

However, Salt [51] disputes this and says that pressure fluctuations generated by the body, such as by heartbeat and respiration, enter the ear via the cochlear aqueduct and not through the stapes and therefore the fluid flows are localised in this tiny region of the ear. On the other hand, low frequency and infrasound enters the ear via the stapes and causes fluid movements throughout the entire ear between the stapes in the vestibule to the compliant round window. It is these fluid movements that drive sensory tissue movements and cause stimulation.

Schomer [52] proposes a motion sickness hypothesis in explaining the symptoms. This is motivated by Schomer's experience with Navy pilots in the US airforce becoming ill from using flight simulators. Schomer observed that the problems encountered by Navy pilots appear to be similar to those reported by about five of the residents he interviewed at the Shirley Wind Farm investigation mentioned in the previous section [40]. The motion sickness or nausea observed in Navy pilots occurred from exposure to acceleration primarily below 1 Hz. Schomer postulates that exposure to infrasound produces similar acceleration levels on the vestibular components of the inner ear (in particular the otolith organs which are responsible for transmitting information to the brain about gravity, balance, movement and direction), thereby resulting in the nauseogenic symptoms.

Salt [53] disagrees with the proposition that "what you can't hear can't affect you". In his proposal, it is the outer hair cells (OHC) in the cochlear that are stimulated by infrasound as opposed to the inner hair cells (IHC) which are responsible for audible hearing. Figure 12 is a cross section through the cochlear in the inner ear and the location of the Organ of Corti containing the OHC and the IHC. Figure 13 is a more detailed view of the Organ of Corti.

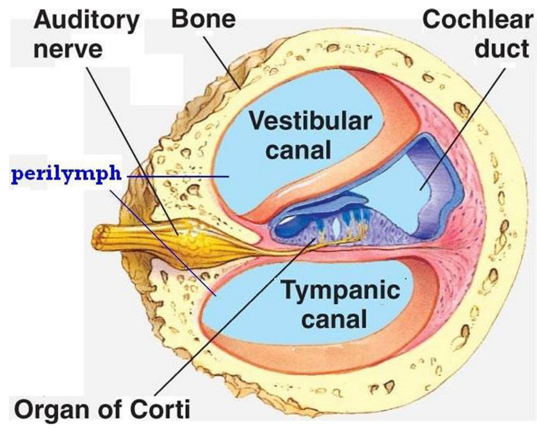

Fig. 12 A cross section of the cochlear showing the location of the Organ of Corti. Adapted from http://flipper.diff.org/app/items/info/6238

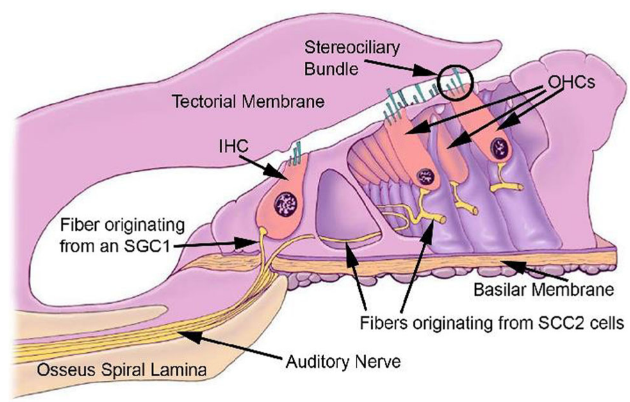

Fig. 13 A detailed cross section of the Organ of Corti showing inner hair cells (IHC) and outer hair cells (OHC) with their stereociliary bundles. An OHC stereociliary bundle is circled [54]

According to Salt, the ear responds to infrasound through the OHC and whilst the sensation is not "heard", there is nevertheless a stimulation of the cochlea. The question is whether the stimulation by infrasound remains confined to the ear and has no other influence on the person or whether there are on-flowing effects which would explain the symptoms allegedly attributable to wind turbine infrasound.

The proposition advanced by Alves-Pereira et al. [17] as discussed in Sect. 2 of this article is that wind turbine infrasound causes VAD in both humans and animals. Bolin et al. [55] is sceptical of the VAD hypothesis because discussion of VAD remains at a hypothetical stage and evidence of problems related to noise from wind turbines is lacking.

Van den Berg [56] has similar reservations. He says that Alves-Pereira and Branco [16] stated that it was not clear at what sound level VAD can occur and that dose response relations for infrasound and low-frequency noise for developing VAD did not exist and thus the risk for developing VAD cannot be assessed. Nevertheless, in their investigation of the family in reference [17], they concluded that VAD occurred and was caused by low-frequency sound. Other possible causes were not considered. The reported infrasound noise levels were below the normal hearing threshold for a considerable range of frequencies. If the same sound energy were to be presented at audible frequencies, it would not cause hearing damage although the ear is the most sensitive organ. For these reasons, according to Van den Berg, it is therefore highly unlikely that wind turbine-generated infrasound could have effected physiological damage.

As described in Sect. 2 of this article, Pierpont coined the term "Wind Turbine Syndrome" to explain the symptoms of persons exposed to infrasound from wind turbines including "a feeling of internal pulsation, quivering or jitteriness, and it is accompanied by nervousness, anxiety, fear, a compulsion to flee or check the environment for safety, nausea, chest tightness, and tachycardia". According to Van den Berg [56], these symptoms are well known when persons are put under stress and thus might not be specific to the impact of wind turbines. People with a generalised anxiety disorder also have symptoms which include trembling, restlessness or a feeling of being "edgy", excessive worry and tension, an unrealistic view of problems, nausea and muscle tension and these conditions might become worse during periods of stress.

Van den Berg is critical of the fact that Pierpont did not eliminate the possibility that these symptoms might have been attributable to an existing condition in which case there is no need to invent a new prognosis. If Pierpont's selection procedure were to be applied to other sources of noise, one might probably find similar results: there are also people that suffer from, for example, the sound of aircraft, neighbours, barking dogs or untraceable hums. The selection procedure utilised by Pierpont is bound to find people who suffer the most, for whatever reason. It is possible that the selected people are by their nature above-average anxious and are thus most sensitive to what they feel is an intrusion of their home.

7 Research into the Health Effects of Infrasound

It should come as no surprise to the reader that in view of the intensity of the debate relating to the health effects of infrasound, that there might be a paucity of research articles which go to the heart of the question seeking to uncover a direct cause and effect link. However, this situation is likely to improve as institutions and interested parties commit to funds to undertake meaningful research. For example, in March 2016 the NHMRC granted two awards totalling $3.3 million to conduct evidence-based research into the effects of wind farms on human health.[16]

[16] https://www.nhmrc.gov.au/media/releases/2016/nhmrc-awards-funding-wind-farms-and-human-health.

The available research studies published to date fall into two categories: social survey study and physical exploration study. A social survey involves the elicitation of information from participants and a statistical comparison with measured or predicted variables such as noise level. An example includes sending a questionnaire to participants and correlating the responses with physical attributes such as noise level, age, gender, health, sleep. However, whilst the social studies reported here-in address health, infrasound is not reported as an independent variable. This will need to change in the future.

A physical exploration study involves the direct exposure of participants to a stimulus and the measurement of a response. An example includes the exposure of participants to infrasound and a correlation with physical attributes (such as blood pressure and heart rate) or psychological or psychosomatic attributes (such as do you feel "tired" or "nauseous" expressed on an appropriate intensity scale). Valid experiments usually involve a careful selection of methodology and subjects to avoid bias. For example, an experiment should involve the use of a control group and/or the use of "sham" exposure (where a participant is told they are being exposed to infrasound but in fact they are not).

The outcome of experiments should always be expressed in statistical terms involving an outcome which is said to be "statistically significant" with a confidence level of at least 95%. This means that the chance of a reported outcome being due to random factors only is less than 1 in 20.

Turning first to social surveys, Pedersen [57] presents the results of three social surveys conducted in 2007 of subjectively measured responses from 1755 people, to explore the relationships between sound levels and aspects of health and well-being. All three studies were cross-sectional studies in which the dB(A) sound levels of wind turbine noise were compared to self-reported health status among people living in wind farm areas at two locations in Sweden and one location in the Netherlands. The use of A-weighted sound levels of course cannot infer the presence or otherwise of infrasound and the results of this, and other like social surveys should therefore be interpreted with that limitation in mind. All three studies showed a statistical correlation between annoyance outdoors and indoors with wind turbine noise level.

The proportion of respondents who reported being interrupted in their sleep by a noise source was stable at all levels of wind turbine sound, except at the strongest levels above approximately 40–45 dB(A) above which respondents reported sleep interruption. No other variable measuring health or well-being (including high blood pressure, headache, undue tiredness, tense/stressed and irritable) was significantly related to sound pressure levels throughout the three studies.

A social survey was conducted by Shepherd et al. [58] in New Zealand in 2010 of residents near the West Winds wind farm located in the Makara Valley 10 km west of Wellington. The survey group included 39 respondents in the exposed group that is those residents who live near the wind turbines, and 158 in a control group located at least 8 km away. In the exposed group, wind turbine noise levels ranged from between 20 and 50 dB(A). A health assessment was undertaken by questionnaire of health-related quality of life variables including sensitivity, annoyance, sleep, health, physical and psychological status. There was no correlation made between noise level and self-rated health score. The study found the self-rated health score of the exposed group was lower than the control group; however, the result for the exposed group was not statistically significant. Surprisingly there was a negative correlation between annoyance and self-rated health for both groups (meaning that those more highly annoyed considered they had better health); however, again the result for the exposed group was not statistically significant. The exposed group reported less sleep satisfaction than the control group. Overall, the study concluded that living close to wind turbines is associated with degraded amenity.

A similar social survey was conducted by Nissenbaum et al. [59] in 2010 of 38 residents (the exposed group) located near two wind farms, one at Mars Hill with 28 GE 1.5 MW turbines and another at Vinalhaven in Maine, USA, with 3 similar turbines. A control group of 41 residents living away from the wind farms was used. The LAeq wind turbine noise levels at full power were measured and predicted at various distances at both sites. The results showed that there was not a statistical significant result in sleep quality measured using two different methods. However, participants in the exposed group were significantly more likely to report an improvement in sleep quality when sleeping away from home. The authors conclude that there was a significant effect of better health reported with increasing distance away from wind turbines.

Kuwano et al. [60] conducted a social survey at 34 wind farm sites across Japan beginning in 2010 and extending from Hokkaido to Okinawa Prefecture. The respondents included 744 persons in the exposed group living near wind farms and 332 persons in the control group living away from the wind farms. Sound levels were measured in LAeq at various distances from the wind farm sites which enabled sound levels at the participants homes to be estimated. The outside noise levels ranged from 26 to 50 dB(A). The study found that wind turbine noise was more annoying than road traffic at the same LAeq level, that there was an effect on sleep disturbance when the wind turbine noise was audible, particularly when the LAeq was 40 dB(A) or greater and that there was no evidence of self-reported somatic/mental health symptoms other than disturbance to sleep associated with wind turbine noise. Self-reported sensitivity to noise and perceived visual disturbance due to wind turbine generators were significantly associated with insomnia and somatic/mental health, suggesting that these variables present features of individuals who are prone to complaining of sleep or health problems.

Health Canada launched a multi-year research study in July 2012 to explore the relationship between exposure to sound levels produced from wind turbines and the extent of health effects reported by, and objectively measured in, those living near wind turbines. Original articles can be found in Schomer et al. [61] and a summary of results on the Health Canada Web site.[17] The study was conducted in Ontario and Prince Edward Island involving a total of 18 wind farms and 1238 dwellings located between 600 m and 10 km from those wind farms. Questionnaires were distributed to participants and the results correlated with measured and calculated noise levels in metrics of dB(A), dB(C) and infrasound (method unreported). Sleep quality was measured using a wrist-worn activity monitor that resembles a watch. The study found there was no association between wind turbine exposure and self-reported sleep, self-reported illnesses or self-reported perceived stress and quality of life.

Annoyance was shown to increase with an increase in wind turbine noise levels. A statistically significant increase in annoyance was found when wind turbine levels exceeded 35 dB(A). Objectively measured health outcomes were found to be consistent and statistically related to corresponding self-reported results. Wind turbine noise was not observed to be related to hair cortisol concentrations, blood pressure, resting heart rate or measured sleep (e.g., sleep latency, awakenings, sleep efficiency).

Infrasound was measureable at distances of up to 10 km from the wind turbines, but was in many cases below background infrasound levels. The levels were found to decrease with increasing distance from the wind turbine at a rate of 3 dB per doubling of distance beyond 1 km, downwind from a wind turbine. The levels of infrasound measured near the base of the turbine were around the threshold of audibility that has been reported for about 1% of people that have the most sensitive hearing.

We now proceed to a review of the physical exploration studies.

Crichton et al. [62,63] were the first to conduct a physical exploration study directly related to the effect of infrasound from wind turbines. The investigators subjected a group of 54 participants to either real or sham infrasound after half the participants had watched a video on the health effects of wind turbine noise designed to increase their expectations of harm, whilst the other half watched a video designed to play down their expectations of harm. The study found that participants exposed to material designed to increase their concern about the effects of wind turbine infrasound were statisti-

[17] http://www.hc-sc.gc.ca/ewh-semt/noise-bruit/turbine-eoliennes/summary-resume-eng.php.

cally more likely to report symptoms, even when in the sham group. These results are consistent with a nocebo hypothesis. The nocebo effect is a negative reaction from exposure to an innocuous substance due to expectations of harm. It is the converse to a placebo which is an inert substance that creates either a beneficial response or no response in a patient. The nocebo effect is psychogenic in nature and is a reaction to a patient's expectations and perceptions of how an exposure to a substance will affect them.

However, Tonin et al. [64] pointed out that the level of infrasound produced in the Crichton study was too low (40–50 dB, unreported as to whether this is rms or peak and whether the sound was sinusoidal or not). In addition, the duration of exposure to infrasound was only 10 min. Whilst it is understandable that it is difficult in a laboratory situation to entertain long periods of exposure, it is nevertheless desirable to increase it as much as possible in any repeat experiment. In adopting a stimulus with such a low level of infrasound, the conclusions in the Crichton study should therefore be interpreted as if the participants had been exposed to sham infrasound in both parts of the experiment. The Tonin study replicated the Crichton study but with a modified design to avoid those deficiencies.

In the Tonin study, an infrasound waveform modelled on the Shirley Wind Farm investigation [40] was used played at a sound level of 91 dB peak for 23 min. This level was slightly higher than that recorded at Shirley Wind Farm. The apparatus used for generating infrasound was a specially constructed pneumatic driver incorporated into earmuffs with a GRAS 40AZ low-frequency microphone as shown in Fig. 14.

A total of 72 volunteers was tested aged from 17 to 82 years with a median age of 29 years. The experiment was a double blind study which subjects the participants to either infrasound or no noise (sham noise) after manipulating their expectations into either high expectancy (HE) or low expectancy (LE) by using appropriate videos. Responses were recorded on identical questionnaires filled out by participants before and after the experiment. Participants were assigned randomly to each of the four groups.

The Tonin study found that the presence of infrasound in the experiment did not increase the number or intensity of typical symptoms in any statistically significant manner. This is supportive of the hypothesis that the infrasound has no direct physiological effect on human health, at least for the time of exposure used in this experiment.

Whilst the expectancy manipulation was found to have shown a loose trend in influencing the typical symptoms associated with wind turbine infrasound health complaints indicating that the manipulation was working to a degree, it was the level of concern that a volunteer felt prior to the beginning of the experiment instead that had a statistically significant effect on the reported typical symptoms associated with wind turbine infrasound.

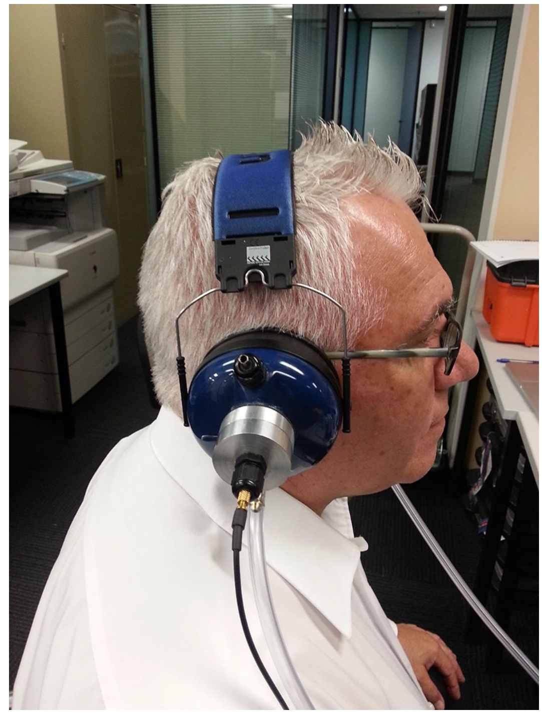

Fig. 14 Pneumatic driver constructed using earmuffs with attached tubing and low-frequency microphone [64]

The Tonin study concluded that volunteers who came into the experiment with preconceived notions of infrasound being harmful generally reported more symptoms than volunteers who began the experiment more sceptical about the potential health impacts of infrasound. These results support the hypothesis that a nocebo effect and not a direct physiological effect may be the cause of reported symptoms, at least for the time of exposure used in the experiment.

8 Conclusion

In 2015, the Australian Senate Select Committee on Wind Turbines concluded there was credible evidence from a number of people who reside in proximity to wind turbines who have complained of a range of adverse health impacts. These include tinnitus, raised blood pressure, heart palpitations, tachycardia, stress, anxiety, vertigo, dizziness, nausea, blurred vision, fatigue, cognitive dysfunction, headaches, ear pressure, exacerbated migraine disorders, motion sensitivity, inner ear damage and sleep deprivation.

As a consequence of that hearing, the Office of the National Wind Farm Commissioner was established. The Office reported that as at 31 December 2016, 67 complaints were closed by the Office and there were 23 remaining matters at various stages of the complaint handling process.

A historical review shows that whilst initially the audible sounds of wind turbines disturbed people in their sleep, more complex prognoses such as Vibroacoustic Disease and Wind Turbine Syndrome were proposed to explain the reported health symptoms. These diseases were hypothesised to be linked to the emission of infrasound from wind turbines, particularly tonal infrasound at the blade pass frequency of the turbine blades and associated harmonics.

Extensive measurements have shown that the level of tonal infrasound emitted by wind farms is below the threshold of hearing. Some observers have noted that the level of infrasound generated internally within the human body can exceed that generated by wind turbines. Others disagree with the proposition that "what you can't hear can't affect you". They postulate mechanisms involving the stimulation by infrasound of the otolith organs causing nauseogenic symptoms or stimulation of the outer hair cells which are said to be particularly sensitive to infrasound frequencies.

There are a number of social surveys in which self-reported health effects resulting from wind turbine noise, including the effects of sleep disturbance, are inconsistent. The most recent Health Canada survey found there was no association between wind turbine exposure and self-reported sleep, self-reported illnesses or self-reported perceived stress and quality of life. It found that annoyance was shown to increase with an increase in audible wind turbine noise levels especially when wind turbine levels exceeded 35 dB(A).

There is a paucity of physical exploration studies in which participants are intentionally subjected to infrasound and a response measured. Of the two studies described in this report, they both conclude (within the limits of the exposure times used) that the presence of infrasound in the experiment did not increase the number or intensity of typical symptoms in any statistically significant manner but that it was the level of concern that a volunteer felt prior to the beginning of the experiment instead that had a statistically significant effect on the reported typical symptoms associated with wind turbine infrasound.

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