Wind turbine sound: past, present, and future

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ABSTRACT

In the 1980s, research in the United States led by NASA and the National Renewable Energy Laboratory focused on the experience of people living near the first megawatt-scale turbines. In 2005, Dr Geoff Leventhall established the first biannual conference focusing solely on wind turbine noise. Since that time, wind turbine-specific sessions are increasingly common at acoustical conferences. Several large studies recently investigated individual and community response to wind developments. Notably, Health Canada concluded its multi-year epidemiological study, and similarly extensive efforts funded by the Japanese Ministry of Environment have been published. The Crichton team from New Zealand published numerous papers about the role of the nocebo effect and infrasound, and a small study in the United Kingdom measured the psychophysiological response to the visual impact of turbines on the landscape. In Australia, the Senate's Select Committee on Wind Turbines published a 350-page final report. Australia's (and likely the world's) first national Wind Farm Commissioner was appointed in late 2015, and the National Health and Medical Research Council-targeted grant for Research into Wind Farms and Human Health was recently awarded. This paper summarizes highlights of past, present, and future research.

1. OVERVIEW OF 1980s RESEARCH

In the United States, the late 1970s and early 1980s were characterized by political tensions in the Middle East, an oil embargo, and an energy crisis. The focus was on energy security, and President Carter installed solar panels at the White House. During this period, the United States Department of Energy (DOE) worked with the commercial aerospace industry (Westinghouse, General Electric, Hamilton Standard and Boeing) to scale up wind turbine technology with the goal of developing megawatt (MW) scale turbines. The downwind turbine design, in which blades pass behind the support tower, offered several engineering benefits, not the least of which was the natural tendency of the downwind turbine to self-orient into the wind, thus reducing yawing system requirements (the system that rotates turbine blades into the wind). These two-bladed machines had airfoils that were derived from aircraft wings, and only the outer portion of the blades pitched. The Hamilton Standard machine (WTS-4) had full blade pitch and the airfoil shape was derived from experience with propellers. It too was a downwind design.

Scaling up from 100-kilowatts (kW) to 2 MW presented operational and acoustical challenges. In the mid-1970s, the 100 kW MOD-0 unit research turbine was constructed and operated in Sandusky, Ohio. Four 200-kW MOD-0A demonstration wind turbines were constructed and installed in Puerto Rico, New Mexico, Hawaii, and Rhode Island between 1977 and 1980. A 2-MW MOD-1 turbine (refer Figure 1) installed in Boone, North Carolina, was scaled up 10 times in power output over the MOD-0A turbine. Operation of the MOD-1 turbine produced a low-frequency thump that was audible for several kilometres; this prompted a series of research efforts in the 1980 that launched the field of wind turbine acoustics. A comprehensive multi-disciplinary and multi-agency team of public and private research was funded, and included NASA, DOE (Solar Energy Research Institute), several universities, utilities, and private industry. The impulsive character of the large downwind turbine was investigated and attributed to the rotor blade/tower wake interaction. Listening tests were conducted to assist in establishing the detection threshold, and Shepherd et al. (1982:650) noted that "frequencies below 20 Hz [hertz] were considered to be unimportant".

Figure 1: MOD-1 Wind Turbine, Source: NASA

In the early 1980s, the MOD-2 turbines (refer Figure 2), an upwind design where rotor blades pass in front of the support tower, were installed in

Washington and Wyoming. These 2.5-MW two-bladed turbines with a tubular rather than a lattice tower were developed to address the impulsive, low-frequency noise associated with the MOD-1 downwind rotor. These early installations were the subject of numerous acoustics studies throughout the 1980s.

To support these early studies, source characterization methods were developed to minimize the signal to noise challenges posed by windy environments. Many of these techniques are still relevant today and include measuring at a reference distance close to the turbine (on the order of 200 metres at the time), developing windscreens (including a secondary horsehair windshield by Willshire [1985]), locating microphones on or near the ground to minimize the wind speed to which it is exposed, and developing acoustic ranging techniques for low-frequency noise by Hemphill (1983). Challenges persisted, and Stephens et al. (1982:6) noted that:

> *…components below 3 Hz* [hertz] *may be difficult to measure … it is believed that these very low frequency blade passage harmonics will not be significant in most cases.*

Penn State and the Solar Energy Research Institute conducted detailed sound propagation studies of MOD-1 turbines that included extensive meteorological measurement and modelling campaigns (Thomson, 1982:iii). The importance of wind shear, the change in wind speed from ground level to the top of the rotor disc, was identified.

> *The results indicate that atmospheric refractions caused by vertical wind shears is the primary mechanism responsible for enhanced noise levels in the valleys below the turbine installation. Also, surface and ground propagation are negligible.*

Stephens et al. (1982) suggested a propagation model noting that:

> *…decay of sound pressure level with distance in the downwind direction is simply the summation of losses due to atmospheric absorption…and spherical spreading….*

and that:

> *..refractive focusing can produce greatly enhanced sound pressure levels, but such effects are unstable in terms of both time and location.*

Measurements by Willshire (1985) were conducted of the WTS-4 turbine, a 4-MW downwind turbine in Wyoming. Measurements at frequencies above 63 Hz indicate that sound levels at in the downwind direction are controlled by absorption and spherical spreading. At lower frequencies (6, 8, 11 Hz), where absorption is negligible, sound levels in the downwind direction at large distances exhibit cylindrical spreading (3dB per doubling of distance) due to atmospheric refraction.

The sound characteristics of the MOD-2 upwind turbine were noted to be influenced by the generator and gear box tones but lacked strong peaks when compared to MOD-1. The sound was summarized as "amplitude modulation of the overall pressure time history, which is characterized by a periodic swishing noise". The broadband swishing was highlighted by Shepherd (1983) noting that:

> *Experience to date indicates that for large wind turbines, broadband noise is of most importance in the frequency range of 500 to 2000 Hz.*

The report *Acoustic Noise Associated with the MOD-1 Wind Turbine: Its Source, Impact and Control* (Kelley et al., 1985) describes the investigation of the downwind MOD-1. The low-frequency pulses were found to be the primary sources of annoyance, and the source of these pulses was related to downwind blade/tower interaction. The problems occurred at a few lightweight wooden houses. The dominant audible annoyance was related to "secondary emissions" as lightweight structural elements (such as windows, pictures, and knickknacks) rattled. It was also noted that dust movement was visible. Lowering the rotational speed from 35 to 23 rotations per minute provided some benefit but was not 100 percent effective. Ultimately, DOE and NASA identified and addressed these unexpected challenges and moved the MW scale ambitions to the upwind design, such as MOD-2.

Figure 2: MOD-2 Wind Turbines, Source: U.S. Government

The report *The MOD-2 Wind Turbine: Aeroacoustical Noise Sources, Emissions, and Potential Impact* (Kelley et al., 1988) presents a similarly detailed summary of the upwind MOD-2 turbine. While the propagation effects were found to be substantial at MOD-1, similar effects do not appear to be documented during the MOD-2 operation. Vortex generators and improved blade pitch control logic were developed to minimize the instabilities that at times resulted in MOD-1 behaviour if the "turbine is allowed to run severely off-design".

To summarize, the experience of the large MW-scale 1980s wind turbine program shows that unanticipated problems were assessed in more than 1,000 pages of published and publicly available research. Source mechanisms, propagation considerations, and human and structural responses were investigated. It was clear that neighbours do not want their pictures rattling on the walls, have dust shaken from the rafters, or have their television reception compromised. The program to rapidly increase the 100-kW to 2-MW scale was not without its critics, however. Obermeier is quoted in Gipe (1995:115) as noting "The Wright brothers didn't start with a [Boeing] 747, they [DOE] leap-frogged too far, too fast".

This early work identified the importance of implementing proper control logic and mitigating tonal noise sources. Modern wind turbine designs place a much greater emphasis on acoustics than did these early prototypes. Many of the acoustical methods developed during this period are still in use and relevant today, including locating microphones near the ground or on ground boards, using oversize or secondary windshields, and using a reference distance closer to the source to increase the signal-to-noise ratio, all of which are incorporated into the International Electrotechnical Commission 61400-11 standard for determining the sound power level of a wind turbine. Today, some of the same challenges persist; for example, at more distant locations, signal-to-noise concerns are routinely encountered, and windscreen designs and measurement procedures continue to evolve, although a universal methodology for measurements at more distant locations is evasive.

One truism that these early researchers realized, and which will likely continue for future generations, is that wind does not always cooperate with testing schedules.

1.1.1 Low-frequency sound level metric

Kelley's 1988 work developed a metric to assess the potential for interior annoyance. A listening test was developed for a simulated small household room for four scenarios:

1. A single, large upwind turbine (a random periodic source);
2. The same source as 1, except with a 40-dB pink noise masking;
3. A single, downwind turbine operating at 30 rotations per minute (a periodic impulsive source);
4. Multiple downwind turbines (a random impulsive source).

Volunteers were asked to rank the sound in terms of loudness, annoyance/displeasure, feelings of vibrations or pressure, and pulsations. The results identified the low-frequency sound level (LSL) metric as "an efficient measure of the annoyance potential to persons exposed to low-frequency wind turbine noise in their homes". The spectral weightings of those considered are shown on Figure 3.

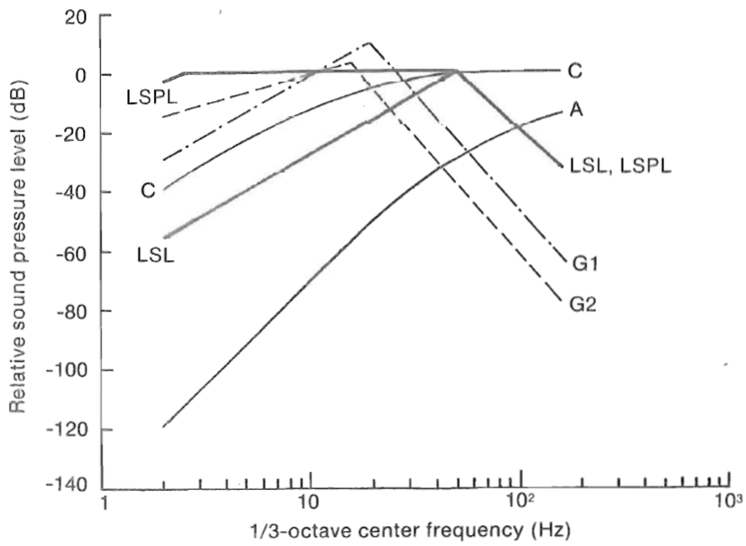

Figure 3: Low-Frequency Noise Metrics Spectral Weightings (Kelley 1988)

The interior perception threshold for upwind turbines was identified as 58 to 59 dB LSL, and the interior annoyance threshold was 65 to 68 dB LSL. The relative weightings shown on Figure 1 indicate that the LSL metric's weightings result in an LSL-weighed value always being less than a C-weighted value; for example, at 50 Hz, both weightings are 0 dB, but at 100 Hz, the LSL is 20 dB less than dBC, and at 10 Hz, the LSL is approximately 15 dB less than dBC. Assuming only a 10 dB differential between LSL and dBC, the interior perception threshold of 58 dB LSL is approximately 68 dBC, and the interior annoyance threshold of 65 dB LSL is 75 dBC. While exterior dBC measurements may be reported in this range, they are often adversely influenced by wind-induced pseudo noise, and the technical literature appears to be lacking documentation of interior levels of this magnitude.

1.2 Lasting influence of the 1980s era research

While current utility scale turbines have advanced substantially since the 1980s, some of these early studies have been a source of confusion. One of the few government reports to revisit this work in the context of current upwind utility scale turbines is the 2012 *Wind Turbine Health Impact Study: Report of Independent Expert Panel* sponsored by the Massachusetts Department of Environmental Protection and Massachusetts Department of Public Health. Below is an excerpt of the summary with minor formatting changes and figures from the referenced documents included for ease of reading (Ellenbogen et al., 2012:46).

> *A NASA report from 1982 gives a figure that estimates the necessary sound pressure level at various frequencies to force vibrations in windows, walls, and floors of typical buildings (Stephens et al., 1982). The figure on page 14 of that report shows infrasound levels of 70–80 dB can induce wall and floor vibrations [Figure 4].*
>
> *On page 39, the report also shows some floor vibration levels that were associated with a wind turbine. On the graph these were the lowest levels of vibration when compared to vibrations from aircraft noise and sonic booms [Figure 5]. Another figure on page 43 shows vibrations and perception across the infrasonic frequency range. Again, wind turbine data are shown, and they are below the perception line* [Figure 6].

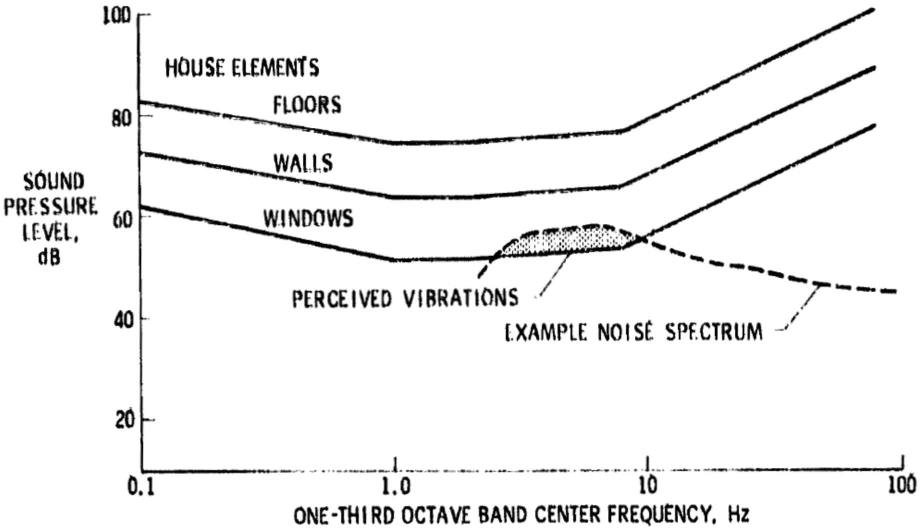

Figure 4: Sound pressure levels sufficient to cause perceptible vibrations of house structure elements over a range of frequencies (Stephens et al., 1982)

A second technical report (Kelley et al., 1985) describes disturbances from the MOD-1 wind turbine, which was a downwind turbine mounted on a truss tower. Of 1,000 homes within about 2 kilometres, 10 homes experienced room vibrations under certain wind conditions. A careful measurement campaign showed that these few homes had room vibrations related to the impulsive noise unique to downwind turbines. The report contains several findings, including the following:

1. *The disturbances inside the homes were linked to the impulsive sound generated by the turbine (due to tower wake/blade interaction) and not seismic waves.*

2. *The impulsive signal was feeding energy into the vibrational modes of the rooms, floors, and walls where the floor/wall modes were the only modes in the infrasonic range.*
3. *People felt the disturbance more than they heard it.*
4. *Peak vibration values were measured in the frequency range 10 to 20 Hz (floor/wall resonances) and it was deduced that the wall facing the turbine was being excited.*
5. *The fact that only 10 homes out of 1,000 (scattered in various directions around the turbine) were affected was shown to be related to complicated sound propagation paths.*
6. *While the shape of the impulse itself was given much attention and was shown to be a driving force in the coupling to the structural vibrations, comments were made in the report to the effect that non-impulsive signals with energy at the right frequency could couple into the structure.*

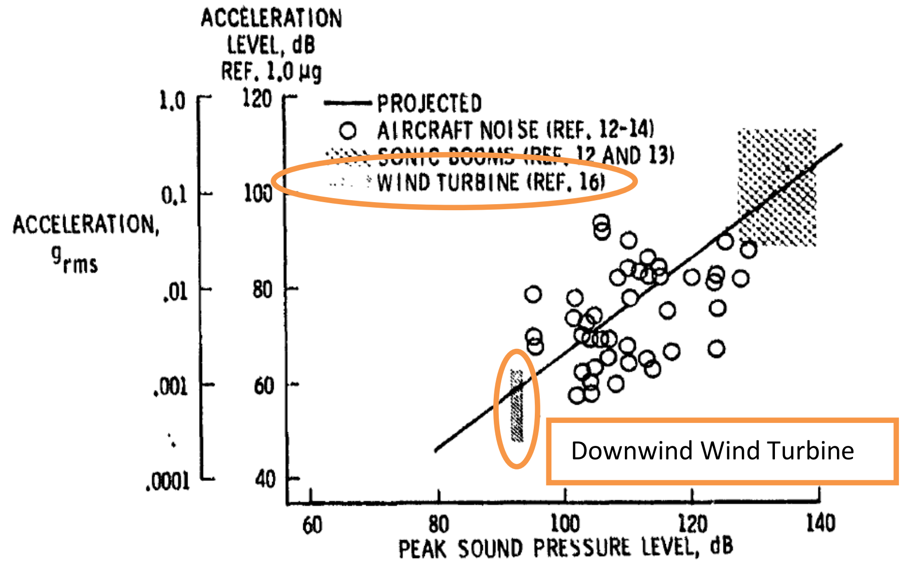

Figure 4: Measured house floor vertical acceleration responses due to noise excitation [of downwind MOD-1 Wind Turbine] (Stephens et al., 1982)

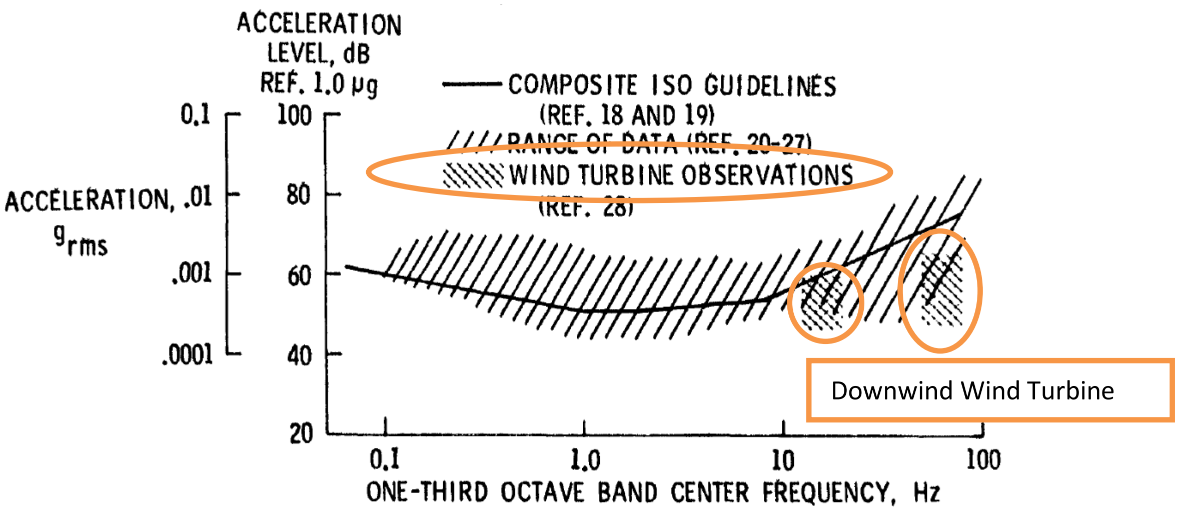

Figure 5: Most sensitive threshold perception of vibratory motion by humans [of downwind MOD-1 Wind Turbine] (Stephens et al., 1982)

The Massachusetts review comments on more recent studies of modern upwind turbines notes that (Ellenbogen et al., 2012:46):

> *…[T]wo sets of measurements that were taken near wind farms to assess the potential impact of seismic activity on extremely sensitive seismic measurement stations (Styles, 2005; Schofield, 2010). One study considered both waves traveling in the ground and the coupling of airborne infrasound to the ground, showing that the dominant source of seismic motion is the Rayleigh waves in the ground transmitted directly*

> *by the tower, and that the airborne infrasound is not playing a role in creating measurable seismic motion. The two reports indicate that at 100 m from a wind turbine farm (>6 turbines) the maximum motion that is induced is 120 nanometers (1.2 *10^{-7} m) at about 1 Hz…. To put the motion in perspective, the diameter of a human hair is on the order of 10^{-6}m. These findings indicate that seismic motion induced from one or two turbines is so small that it would be difficult to induce any physical or structural response.*

The Massachusetts review concludes (Ellenbogen et al., 2012:55):

> *The measured levels of infrasound produced by modern upwind wind turbines at distances as close as 68 meters (m) are well below that required for non-auditory perception (feeling of vibration in parts of the body, pressure in the chest, etc.).*
>
> *If infrasound couples into structures, then people inside the structure could feel a vibration. Such structural vibrations have been shown in other applications to lead to feelings of uneasiness and general annoyance. The measurements have shown no evidence of such coupling from modern upwind turbines.*

2. The 21st century

By the 1990s, the energy crisis was neither a recent memory nor a pressing risk in the United States. The fundamental research by DOE/NASA on source mechanisms was complete and American funding priorities changed. These researchers continued on with successful careers, but with different technical focuses. The European Union continued funding acoustic research through programs such as the Joint Opportunities for Unconventional and Long-term Energy Options (JOULE) and other projects, which are summarized by Wagner et al. (1996). The commercial wind turbine market was defined primarily by sub-MW (upwind) turbines, and in 1995 California's 13,000 turbines located in the state's three primary wind resource areas (Altamont Pass, Tehachapi, and San Gorgonio) produced 30 percent of the world's wind-generated electricity. In Oregon, the first round of larger-scale multiple turbine projects was planned and constructed in 1998 (Vanscycle Wind Farm, 25-MW, Vestas 660-kW turbines) and followed by the Klondike 1 Wind Farm in 2001 (25-MW, 1.5-MW Enron turbine) and the Stateline Wind Farm in 2001 (300-MW, 660-kW Vestas turbines). At the time, Stateline was the largest wind facility in the world. These upwind installations did not result in adverse responses similar to the MOD-1/MOD-2 experience.

In the early to mid-2000s, broader studies on community reaction to wind projects were conducted in Sweden and the Netherlands. These resulted in a series of studies led primarily by Pedersen , Persson-Way and van den Berg. The researchers developed dose-response relationship estimates for annoyance based on dBA and discussed social factors such as economic benefit, visibility, predictability, and control as well as attitude and perceived fairness. These studies and datasets were the basis for multiple publications and numerous reviews and ultimately the basis of a new wind turbine sound regulation in the Netherlands. Similar studies were not conducted elsewhere in the European Union or North America until recently.

In 2005, the first International Wind Turbine Noise Conference was held in Berlin, Germany, and in 2006 Canadian Acoustics published a special issue on Wind Turbine Noise. In this special issue, Dr Geoff Leventhall provided an overview of infrasound in a paper titled "Infrasound from Wind Turbines: Fact, Fiction or Deception".

2.1 The first North American expert panel

Health concerns were raised by some experts who alleged that wind turbines emit potentially dangerous levels of infrasound and low-frequency sound that may result in vibroacoustic disease or "wind turbine syndrome". Together, the American and Canadian Wind Energy Associations (AWEA and CanWEA) proposed to a number of independent groups that they examine the scientific validity of reports on the adverse health effects of wind turbines. Because no independent group or agency committed to conducting a review, AWEA and CanWEA commissioned a report in 2009. They asked a panel of independent experts in acoustics, audiology, medicine, and public health to examine published scientific literature on possible adverse health effects resulting from exposure to wind turbines. The following experts were asked to investigate and analyse existing literature and publish their findings:

- W David Colby, MD: Chatham-Kent Medical Officer of Health (Acting); Associate Professor, Schulich School of Medicine & Dentistry, University of Western Ontario
- Robert Dobie, MD: Clinical Professor, University of Texas, San Antonio; Clinical Professor, University of California, Davis
- Geoff Leventhall, PhD: Consultant in Noise Vibration and Acoustics, United Kingdom
- David M. Lipscomb, PhD: President, Correct Service, Inc.

- Robert J. McCunney, MD: Research Scientist, Massachusetts Institute of Technology Department of Biological Engineering; Staff Physician, Massachusetts General Hospital Pulmonary Division; Harvard Medical School
- Michael T. Seilo, PhD: Professor of Audiology, Western Washington University
- Bo Søndergaard, MSc (Physics): Senior Consultant, Danish Electronics Light and Acoustics (DELTA)

The author of this paper served as a technical advisor to the panel. The study, "Wind Turbine Sound and Health Effects: An Expert Panel Review", was published in 2009 (Colby et al. 2009).

The expert panel concluded that infrasound from wind turbines is not perceptible and does not exceed levels produced by natural sources. Low-frequency sounds from wind turbines are not distinguishable from background sounds for frequencies less than 40 Hz; however, perceptible levels of low-frequency sound may be produced under certain conditions. The audible swooshing sound is typically in the 500 to 1,000 Hz range; it is neither infrasound nor low-frequency sound.

Dr Nina Pierpont had hypothesized the existences of "wind turbine syndrome" based on telephone interviews with 10 families who reported concerns with sleep disturbance, headaches, internal quivering, issues with concentration and memory, increased irritability and anger as well as issues with fatigue and motivation. Dr Pierpont's hypothesis was that low levels of airborne infrasound affect the vestibular system or cause vibrations in internal organs (visceral vibratory vestibular disturbance). The expert panel concluded that the proposed pathophysiological pathway is not plausible because low levels of sound from outside the body are not sufficient to exceed levels within the body, and the vestibular organs respond to head position and movement, not airborne sounds emitted by wind turbines. The expert panel noted that:

> *There are no unique symptoms or combinations of symptoms that would lead to a specific pattern of this hypothesized disorder.*

Wind turbine syndrome symptoms are similar to those of noise annoyance symptoms. The potential for annoyance is not unique to wind turbines and depends on various acoustic and non-acoustic factors.

The expert panel unanimously endorsed the following conclusions:

- *Sound from wind turbines does not pose a risk of hearing loss or any other direct adverse health effect.*
- *Subaudible, low frequency sound and infrasound from wind turbines does not present a risk to human health.*
- *Some people may be annoyed by the sound from wind turbines, but this is not a disease.*
- *A major cause of concern from wind turbine sound is its fluctuating nature. Some may find this sound annoying.*

2.2 Additional reviews

In May 2010, the Chief Medical Officer of Ontario, Canada reached similar conclusions to those of the 2009 expert panel, namely:

- *The scientific evidence available to date does not demonstrate a direct causal link between wind turbine noise and adverse health effects.*
- *Low frequency sound and infrasound from current generation upwind model turbines are well below the pressure sound levels at which known health effects occur.*
- *Community engagement at the outset of planning for wind turbines is important and may alleviate health concerns about wind farms.*
- *Concerns about fairness and equity may also influence attitudes towards wind farms and allegations about effects on health. These factors deserve greater attention in future developments.*

In July 2010, Australia's National Health and Medical Research Council issued a "Public Statement" and "Rapid Review of the Evidence" on Wind Turbines and Health. The review concluded with:

> *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 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 minimized by following existing planning guidelines.*

Additional reviews were published in the technical literature including in 2011 (Bolin et al; Fiumicelli) and in 2012, Oregon and Massachusetts each published reviews.

Challenges relating to community acceptance were specifically evaluated in Australia in the report *Exploring community acceptance of rural wind farms in Australia: a snapshot* (Hall et al., 2012) prepared for the Commonwealth Scientific and Industrial Research Organisation. The themes identified in this work identify several non-acoustic considerations such as:

- *Community members publicly opposing their local wind farm spoke as self-appointed representatives for others nursing grievances with wind farms.*
- *Most were hobby farmers with small acreages, former professionals and/or members of Landscape Guardian groups [groups concerned with visual impacts].*
- *This opposition has several origins including a symbolic response of rural communities to political neglect from cities, an anti-development stance, and also opposition to a green or climate action political agenda….*

Non-acoustic factors were also identified as influencing community acceptance in the 2012 Oregon and Massachusetts review. The importance of trust, fairness, equity, and the level of community engagement during the planning process as well as the perceptions related to other aspects of wind energy such as visual impact and benefits of wind energy were highlighted as key factors in these reviews.

At a 2012 conference in the United Kingdom, Dr Ian Flindell (2012) noted that wind turbines are:

> *…not unique in eliciting strong objections and that most people around airports are annoyed by aircraft noise but this does not necessarily mean that aircraft noise is not acceptable, rather, airports provide opportunities for air travel, airports are major employers, airports are net economic contributors and most airports have long history of noise management actions and public engagement.*

At the same conference, Dick Bowdler (2012) made a comparison to airports, noting Fields' 1993 work on airport noise and identified factors such as:

> *…perceived predictability, perceived control, trust and recognition, voice (are you listened to), personal benefits, compensation, sensitivity to noise, home ownership, accessibility to information and understanding (is information relevant and correct).*

Bowdler notes that rural communities in the United Kingdom perceive that "they gain no benefit, they pay subsidies, they pay more for electricity and developers make all the money" thus "people don't feel they are being treated fairly" and that the environment is ripe for turbine noise to be perceived negatively. These themes echo those of Paul Gipe's 1995 observations that "noise will always haunt wind energy, as do aesthetics, because the costs and benefits are distributed unequally". Such challenges are not unique to wind, and community engagement is crucial.

Bowdler astutely notes that acoustics does matter in that "bad noise management doesn't just affect your project, but future ones". However, it is also important to recognize the potential role of non-acoustic factors and that real or perceived personal or community benefits are important moderators. Health Canada's recently published study found that the 110 respondents who acknowledged personal or community benefits and benefits were associated with higher quality of life scores in physical domain (Michaud et al., 2016). Flindell observed in 2012 that consideration of

> *…attitudinal variables…could be much more useful for informing policy than has been taken into account in the past. Is the purpose of policy to control sound levels or to influence annoyance?*

A literature review conducted by the Australian National Health and Medical Research Council, *Review of Wind farms and Human Health (2015)*, noted the poor quality of direct evidence, that concerns were expressed by some members of the public, and that these concerns warranted additional high quality research. The timing was such that the Council did not have the opportunity to incorporate into its review and recommendations; the Japanese Ministry of Environment-sponsored studies or Health Canada's and Statistics Canada's published findings.

3. FROM REVIEWS TO NEW FIELD AND LAB STUDIES

During the second decade of the 21st century, literature and evidence reviews have transitioned to new field and lab studies. In addition to measurement campaigns undertaken in Australia to document levels of infrasound near wind farms and other environments, research efforts include Dr Fiona Crichton's nocebo experiments

(Crichton et al., 2013), the Japanese Ministry of Environment-sponsored research led by Dr Hideki Tachibana (Tachibana et al., 2013, 2014, Yano et al., 2013, Yokoyama, et al., 2013, 2014), as well as Health Canada and Statistics Canada research (Feder et al., 2015, Keith et al., 2016, Michaud et al., 2016abcd). The Japanese and Canadian government-funded efforts were both multi-disciplinary, multi-year, multi-million dollar efforts.

3.1 Infrasound measurement campaigns

Measurements have been collected near utility-scale wind turbines and other typical environments. Near the base of a wind turbine, Health Canada (2015) found the infrasound levels were "around the threshold of audibility that has been reported for about 1% of the people that have the most sensitive hearing". At approximately 1,200 feet from a wind turbine, measurements by Turnbull and Walsh (2012) yielded 61 dBG, while 75 dBG was measured near a beach and 76 dBG was reported in a downtown business district (Table 1).

Table 1: Measured levels of infrasound

Noise Source	Measured Level (dB(G))
Clements Gap Wind Farm at 85m	72
Clements Gap Wind Farm at 185m	67
Clements Gap Wind Farm at 360m	61
Cape Bridgewater Wind Farm at 100m	66
Cape Bridgewater Wind Farm at 200m	63
Cape Bridgewater Wind Farm ambient	62
Beach at 25m from high water line	75
250m from coastal cliff face	69
8km inland from coast	57
Gas Fired power station at 350m	74
Adelaide CBD at least 70m from any major road	76

(Turnbull and Walsh, 2012)

The South Australian Environmental Protection Authority (Evans et al., 2013) conducted a similar measurement campaign documenting levels of infrasound in urban and rural environments, both indoors and outdoors including at residences when a wind farm was operating and when it was shut down. This report notes that one of the residential locations near a wind farm has the "the lowest infrasound levels measured at any of the 11 locations" studied. The report concludes that:

> *…the level of infrasound at houses near the wind turbines assessed is no greater than that experienced in other urban and rural environments, and is also significantly below the human perception threshold.*

Lenchine and Song (2014) of the South Australia Environmental Protection Authority evaluated infrasound and blade pass frequencies and found:

> *…no significant difference between the BPF [blade pass frequency] prominency inside and outside the houses. Analysis of infrasound data measured at three locations inside and outside the dwellings does not bring evidence that the noise impact from wind farms may be excessive or have features that may exacerbate perception of the infrasound since the analysed levels were significant below the conservative perception thresholds.*

Stead and Evans (2014) assessed the level of infrasound that one experiences while walking and found that it was 75 dB, significantly higher than measured 1.5 kilometres away from a wind farm.

While less common, narrow band analysis of infrasound has been conducted by multiple parties including Walker et al. (2012), Cooper (2014), and Zajamsek et al. (2016). Zajamsek et al. (2016) evaluated both the narrow band infrasound and low-frequency noise. They found sound levels in one-third octave bands above 100 Hz "exceeds the hearing threshold at all times" when infrasound was detected (infrasound was evaluated at the fourth BPF). That is, when the wind turbines were operating and one could hear the low frequency sounds and measure the infrasound. This result is expected as wind turbines produce both low frequency sound and infrasound.

3.2 Nocebo experiments

The nocebo effect is the opposite of the more commonly referred to placebo effect, where a sugar pill or other sham treatment results in a beneficial response, such as pain relief. The American Cancer Society (2016), notes that, nocebo and placebo effects may be referred to as "expectation effects". Where there are expectations of harm, the nocebo effect may be realized and a sham treatment results in a negative outcome. The American Cancer Society states that:

> *…the nocebo effect can be seen in the brain: brain-imaging studies have shown that pain is more intense when a person expects more pain than when they don't.*

New Zealand's Dr Fiona Crichton was the first to investigate the potential role of the nocebo effect in the context of reported health effects related to infrasound and wind turbines (Crichton et al., 2013). In this original study, 54 university students were exposed to sub-audible infrasound and sham infrasound in a double blind study. Participants were divided into high- and low-expectancy groups where the high-expectancy group was shown materials related to adverse experiences related to operation of wind farms and the low-expectancy group was shown materials indicating that wind farms would cause no symptoms. The researchers conclude that:

> *Healthy volunteers, when given information about the expected physiological effect of infrasound, reported symptoms that aligned with that information, during exposure to both infrasound and sham infrasound. Symptom expectations were created by viewing information readily available on the Internet, indicating the potential for symptom expectations to be created outside of the laboratory, in real world settings. Results suggest psychological expectations could explain the link between wind turbine exposure and health complaints.*

Additional experiments by Dr Renzo Tonin (Tonin 2015, 2016) build on Crichton's 2013 work. Tonin noted that the levels of infrasound in the Crichton work were less than those documented at operational projects and also desired to increase the exposure period. Using a waveform that "simulated an environment allegedly causing residents to have experienced severe adverse health effects" and a headphone apparatus specifically designed for this study, Tonin conducted a double blind study of 72 volunteers in a manner similar to Crichton's experiment. Tonin concluded:

> *…volunteers who came into the experiment with pre-conceived 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 this experiment.*

3.3 Japanese research

The Japanese Ministry of Environment sponsored a multi-year, multi-disciplinary research study to support the development of regulations of sound from wind turbines (Fukushima et al., 2013, Tachibana et al., 2013, 2014, Yano et al., 2013, Yokoyama, et al., 2013, 2014). This effort was led by Dr Hideki Tachibana. The project was broken into four primary working groups: field measurement, social survey, auditory experiments, and material survey. The Research Committee consisted of 19 experts in acoustics, mechanical engineering, psychology, and medical science. Before conducting a comprehensive measurement campaign, they worked to develop an appropriate wind screen and found the double windscreen design to be the most effective. In addition to developing a suitable windscreen, they worked with RION Co., Ltd., to develop a very low frequency sound level meter with high-quality sound recording capabilities.

Field measurements and social surveys were conducted throughout Japan. Measurements were primarily taken outdoors near 29 wind farms for a total of 164 measurement locations. In addition, control measurements were located in 16 areas. Frequency spectra of the wind farm measurements were plotted and found to exhibit a general 4 dB decrease per octave, which was not uncharacteristic of other typical environmental noises. In addition, the measured levels were compared with various hearing thresholds. When compared to the hearing thresholds, the very low frequency and infrasound levels were not expected to be audible/sensible.

To test this assumption, a series of low-frequency listening tests was conducted in a specially constructed test chamber. This was only one of many listening tests conducted as part of the study. The researchers also conducted several evaluations of hearing thresholds for both pure tones and band limited low-frequency noise, evaluated the influence of amplitude modulation on perceived loudness, and compared various loudness metrics for both wind turbines and other sources of environmental noise.

To evaluate the audibility of low-frequency components, various recorded wind turbine sounds were identified for playback. The sounds were then low pass filtered with varying cut-off frequencies to evaluate whether the low-frequency components were audible/sensible. The sounds were presented as a series of sequences, and the test subject's response was compared to the test signal modulation. There were 10 listening subjects and 125 Hz was audible for all 10 subjects. When the cut-off frequency was set to 25 Hz, 7 out of 10 subjects responded. At 20 Hz, 3 out of 10 subjects responded. At 16 Hz and below, no test subjects responded. The researchers concluded that infrasound in this study was not audible/sensible.

Another aspect of the work was the loudness evaluation of wind turbines and other environmental sounds. The A-weighted metric is used as the basis for most other environmental sounds, and the researchers wanted to assess its applicability to wind turbine sounds. To do this, sound recordings from 38 typical environmental sounds were collected for playback and analysis. The spectral content and types of environmental noise were varied. Test subjects were asked to rate the loudness of each sound on a 7-point scale (with 7 being the loudest rating). These subjective rankings were then compared to various psycho-acoustical indices. The 7-point loudness rating response was compared for the LAeq, LCeq, Zwicker, and Moore-Glasberg ratings. The A-weighting was found to have the highest R squared, and the researchers concluded that the A-weighting is indeed applicable to wind turbines. It was noted that both amplitude modulation and tonal components are both potentially important audible characteristics and are the focus of ongoing research.

The researchers concluded that wind turbine sounds in the infrasound region were found not to be audible nor capable of being sensed by non-auditory mechanisms (non-auditory mechanisms can be involved in the detection of high levels of infrasound). However, at frequencies above 16 or 20 Hz, components of the sound are above the hearing threshold; therefore, it is appropriate to evaluate wind turbines as an "audible" environmental noise. To that end, the loudness evaluation of wind turbine sounds was noted to be similar to other environmental sounds and the A-weighting was determined to be a suitable metric.

3.4 Health Canada and Statistics Canada

Health Canada and Statistics Canada, Canadian federal agencies, embarked on a multi-year research study in July 2012. The principal researcher was Health Canada's Dr David Michaud, who was supported by a multi-disciplinary expert committee of 19 Canadian researchers and five international advisors. This work has been released as a series of peer-reviewed journal articles, including a special section in the March 2016 *Journal of the Acoustical Society of America* (Keith et al., 2016, Michaud et al., 2016abcd). The stated study objectives were to:

- *Investigate the prevalence of health effects or health indicators among a sample of Canadians exposed to WTN* [wind turbine noise] *using both self-reported and objectively measured health outcomes.*
- *Apply statistical modelling in order to derive exposure response relationships between WTN levels and self-reported and objectively measured health outcomes.*
- *Investigate the contribution of LFN* [low-frequency noise] *and infrasound from wind turbines as a potential contributing factor towards adverse community reaction.*

To support these objectives, representative sound power level measurements were collected for 10 wind turbine models ranging in electrical output from 660 kW to 3 MW, the vast majority of which had a hub height of 78 to 80 meters (Keith et al., 2016). The measurement results were found to be consistent with the manufacturer's stated sound power levels for all 10 wind turbine models. It was also determined that the C-weighted levels were "consistently 11.5 dB (SD 1.7 dB) higher than the overall A-weighted values". The researchers noted that this finding is similar to findings by the Japanese research team discussed above (Tachibana et al., 2014) and concluded that "there is unlikely to be a statistical benefit to a separate analysis of the C-and A-weighted results".

Sound pressure levels at the 1,238 dwellings in the study were predicted using International Organization for Standardization (ISO) Standard 9613-2 as well as a Swedish prediction method. A statistically significant difference between the two methods was not identified, and the ISO model was used because it was "consistent with Canadian practice". The parameters used in the model were 10 degrees Celsius, 70 percent relative humidity, a mixed ground factor of 0.7 (70 percent absorbing and 30 percent reflecting), and a receiver height of 4 metres. Ground elevation contours, bodies of water, and forested areas were also included in the model. The turbine vendors' stated sound power levels, not including an uncertainty adjustment, were used in the model; that is, if the stated level was 100 +/- 2 dB, a value of 100 dB was modelled. For this study area, the yearly average outdoor sound level was 4.5 dBA less than that predicted under a continuous 8 m/s winds (Keith et al., 2016), and the predicted levels were "as high as 46 dBA under conditions of 8 m/s wind speeds at 10 m heights for favourable propagation conditions" (Michaud et al., 2016a).

Both subjective (self-reported) and objective health measures (hair cortisol concentrations, blood pressure, heart rate, and sleep quality via actigraphy for more than 3,700 sleep nights) were collected in addition to more than 4,000 hours of wind turbine noise measurements. These results were analysed to assess the potential relationship between wind turbine sounds and illness, stress, sleep, annoyance, and quality of life. Health Canada's website summarizes the key findings as follows:

> ***Illness and chronic disease:*** *No evidence was found to support a link between exposure to wind turbine noise and any of the self-reported illnesses (such as dizziness, tinnitus, migraines) and chronic conditions (such as heart disease, high blood pressure, diabetes).*
>
> ***Stress:*** *No association was found between the multiple measures of stress (such as hair cortisol, blood pressure, heart rate, self-reported stress) and exposure to wind turbine noise.*
>
> ***Sleep:*** *The results of this study do not support an association between wind turbine noise and self-reported or measured sleep quality. While some people reported some of the health conditions above, their existence was not found to change in relation to exposure to wind turbine noise.*
>
> ***Annoyance and quality of life:*** *An association was found between increasing levels of wind turbine noise and individuals reporting to be very or extremely annoyed. No association was found with any significant changes in reported quality of life, or with overall quality of life and satisfaction with health. This was assessed using the abbreviated version of the World Health Organization's Quality of Life Scale.*

As indicated above, annoyance was the only factor found to be statistically associated with the sound level from wind turbines. Michaud et al. (2016b) presents a detailed evaluation of annoyance. It was found that the prevalence of being highly annoyed:

> *.. increased from 2.1% to 13.7% when sound pressure levels were below 30 dB compared to [40 – 46 dB] dB, respectively*

However, it is striking that when sound level was the only factor considered in the annoyance analysis, the r-squared was only 9 percent, thus:

> *any efforts aimed at mitigating the community response to WTN [wind turbine noise] will profit from considering other factors associated with annoyance.*

These other factors included concerns over visual impact of wind turbines and the blinking lights to alert aircraft. It is also identified that effective community engagement and education aimed at addressing concerns related to physical safety during the planning stages may reduce the level of annoyance. Personal benefits were also noted to be another factor to mitigate annoyance and these finding support strategies that expand direct or indirect benefits in communities that host wind projects.

4. INFLUENCING POLICY AND SITING DECISIONS

Dr Geoff Leventhall (2015) states that:

> *We now have a very confused situation in which many people hold sincere beliefs about infrasound, but these beliefs are based on false information….and that infrasound has become the Godzilla of acoustics.*

In this context, the section below discusses how two different project licensing authorities have interpreted the various studies and often conflicting testimony.

4.1 Alberta, Canada

In May 2016, the Alberta Utilities Commission granted approval for the Grizzly Bear Creek Wind Power Project, a 120-MW project consisting of fifty 2.4-MW wind turbines (Alberta Utility Commission, 2016). The approval decision notes from the 1980s NASA and National Renewable Energy Laboratory/Solar Energy Research Institute studies were used by interveners in such a manner as to support a position of adverse effects. One intervener stated that setbacks of 3 to 4 kilometres were appropriate. Another advocated that narrow band assessment of infrasound was necessary and made additional references to the 1980s era research. It was also asserted that impacts extend 7 kilometres from wind turbines. However, the Commission's decision states that they "did not consider useful" the above opinions, as they:

> *related to adverse health impacts from low-frequency noise and infrasound because such opinions were outside the scope of [the intervener's] expertise and were not borne out by the evidence in this proceeding*.

The Commission summarized the Turnbull (2012) findings, stating that the:

> *Turnbull studies which measured low frequency noise and infrasound in the dBG weighting scale and close to the turbines, at 100 metres, the measurements were in the low 70 dBG levels. Even at 85 metres from the wind turbines at the Clemens Gap Wind Farm in Australia, the highest level measured was 72 dBG, at 185 metres, it dropped to 67 dBG, and at 360 metres, it dropped to 61 dBG.*

The Commission found that a narrow band assessment was not necessary, noting that restricting:

> *"an assessment of disturbance from a wind farm to one-third octave bands, dBA or dBG. . . " does not "automatically produce an incorrect finding".*

The Commission also reviewed Health Canada's findings in detail and assesses Health Canada's statement:

> *that results may not be generalized to areas beyond the sample … that the results do not permit any conclusions about causality and should be considered in the context of all published peer reviewed literature*

in the following manner:

> *The Commission considers that such limitations may be overly cautious because such limitations would apply to all existing studies on wind turbines and health. The essential issue in these studies is whether the associations between wind farm exposures and health can be generalized. The Health Canada Study is a large and well-designed study and results of the study along with appropriate considerations and comparison to other evidence, can lead to conclusions about causality.*

4.2 Wisconsin, United States

Coincidently also in May 2016, the Wisconsin Public Service Commission staff prepared a detailed memorandum for the Commission that provided an updated review of studies relating to wind turbines and health for a project hearing, among other project-specific issues (Ripp, 2016). The memorandum summarized the results of a 2014 review by the State of Wisconsin as concluding:

> *… [b]ased on the available literature, what the Council can reasonably conclude is that some individuals residing in close proximity to wind turbines perceive audible noise and find it annoying. A small subset of these individuals report that this noise negatively affects their sleep and may result in other negative health effects. However, based on objective surveys near wind energy projects, it appears that this group is in the minority and that most individuals do not experience annoyance, stress, or perceived adverse health effects due to the operation of wind turbines. This conclusion is especially true if wind turbine siting is used to limit high noise exposure.*

It also summarized an updated 2015 review by the State of Wisconsin, noting that recent literature reviews:

> *…have found an association between exposure to wind turbine noise and annoyance for some residents near wind energy systems. Some studies show this as a causal relationship between wind turbines and annoyance. There is more limited and conflicting evidence demonstrating an association or a causal relationship between wind turbines and sleep disturbance. There is a lack of evidence to support other hypotheses regarding human health effects caused by wind energy systems. Overall, the research in this area is limited and insufficient to determine causal relationships between variables.*

The Health Canada studies are summarized as supporting:

> *…the findings that no evidence was found to support a link between exposure to wind turbine noise and self-reported illnesses, chronic conditions, stress, or sleep quality, while an association was found between increasing levels of wind turbine noise and the number of individuals reporting to be very or extremely annoyed. The two papers by Keith et al. describe how the study found that A-weighted and C-weighted sound results were strongly correlated, of relevance to discussions of whether sound measurements in dBA are able to accurately indicate how much low frequency or infrasound to which residents would be exposed.*

The memorandum refers to a comment made by an intervener who asserted that the Health Canada study indicates that:

> *there is a clear increase in the incidence of the subject adverse health effects as the sound level outside the test subjects' homes increase*,

noting that the above comment:

> *fails to mention that he omitted some of the data provided by the Health Canada study on the incidence of symptoms at sound levels below 25 dBA. He states the lowest exposure as that of 25-30 dBA when the Health Canada graph clearly has a column for respondents at levels less than 25 dBA. With the inclusion of this column of data, his trends are not illustrated*.

With this context, the Commission's August 2016 Decision (Wisconsin Public Service Commission, 2016) finds:

> *The additional evidence received supports the Commission's prior conclusion that a causal link between audible or inaudible noise at wind generating facilities and human health risks has not been established.*

and that the intervener's comment referred to above, was "incorrect and misleading".

5. FUTURE RESEARCH EFFORTS

In addition to the recently announced Australian National Health and Medical Research Council's $3.3 million study "to enrich the evidence-based understanding of the effects of wind farms on human health", the Danish Cancer Society is conducting an epidemiological study on "Noise from wind turbines and risk of cardiovascular disease". These and future, high-quality studies, will likely inform policy, both in their host country and beyond.

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