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# Wind Turbine Infra and Low-Frequency Sound: Warning Signs That Were Not Heard

**Richard R. James**[1]

**Abstract**

Industrial wind turbines are frequently thought of as benign. However, the literature is reporting adverse health effects associated with the implementation of industrial-scale wind developments. This article explores the historical evidence about what was known regarding infra and low-frequency sound from wind turbines and other noise sources during the period from the 1970s through the end of the 1990s. This exploration has been accomplished through references, personal interviews and communications, and other available documentation. The application of past knowledge could improve the current siting of industrial wind turbines and avoid potential risks to health.

**Keywords**

wind turbines, history, health complaints, acoustics, infrasound, low-frequency sound

## Introduction

Over the past 20 or so years, the wind industry has presented evidence implying that industrial-scale wind turbines are safe near people's homes. Yet reports of high levels of annoyance, sleep disturbance, and body/vestibular responses have been received from people living within 2 or more kilometers of wind turbines located in countries around the world. Is it possible that these adverse effects could have been foreseen by those who manufacture and/or install and operate industrial scale wind turbine utilities in quiet rural/residential communities?

This article reviews some of the history and early research regarding infra and low-frequency sound. This is not an exhaustive review. It explores what was known about infra and low-frequency sound from wind turbines and other noise sources during the period from the 1970s through the end of the 1990s.

The work of three groups of acoustical researchers provides valuable historical research relating to human response to low levels of infra and low-frequency noise. Their work will be referenced throughout this article to provide historical context.

- Group 1 was involved with other types of large machines that produce dynamically modulated infra and low-frequency sound.
- Group 2 was involved with identifying and correcting problems caused by dynamically modulated heating and cooling system fans used in high-rise office complexes.
- Group 3 conducted research into the specific nature of wind turbine sound emissions, propagation, and how sound could affect people living near wind turbines.

To better understand earlier work, the author established personal contact with several of the acoustical experts who were the primary investigators of infra and low-frequency sound problems incurred in the past. Past knowledge through personal conversations, review of the reports that were relevant to the solving of these earlier problems, e-mail exchanges in order to understand better what they had experienced or learned about infra and low-frequency sound is explored throughout the article.

This article acknowledges the adverse health effects (AHEs) of audible sound, particularly as it relates to nighttime sleep disturbance. However, most of the article will focus on infra and low-frequency noise. It is assumed that the reader has a basic understanding of how infra and low-frequency sounds are characterized and the terminology that is associated with this characterization. For further information, please refer to the article by Dr. John Harrison (2011, 2010b) for a review of terms and concepts.

The author is deeply indebted to the many people who have helped in this quest, including those who are disclosed in this article and the many others who are not.

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## How We Got to Here

Some wind turbine utilities locate wind turbines of 1.5 megawatts (MW) output and higher within distances of a few hundred meters (1,000 feet) of family homes. In many cases, people in close proximity to the wind turbines have no economic interest in the operation of the utility. Many of the communities where these utilities are installed or planned to be installed are rural or wilderness areas in which the people have little experience with nighttime noise and where the residual background sound levels at night may be as low as 20 to 25 dBA.

Within rural communities, there will be a number of residents who have self-selected a quiet lifestyle and may have a preference for quiet. Many of the people who move to these areas seek a lifestyle that avoids the sources of noise exposure that people in suburban and urban communities take for granted. For example, lifestyles often include open windows during the warm seasons instead of air conditioning, especially during nighttime hours, and more time spent outside the home.

Standards that rate land use compatibility against noise often account for this preference by applying a 10-dB penalty for new noise sources (American National Standards Institute-Acoustical Society of America, 2005). *Noise Assessment and Prediction of Long-Term Community Response* (American National Standards Institute-Acoustical Society of America, 2005) addresses this increased sensitivity as follows:

> F.3.4.1: In newly created situations, especially when the community is not familiar with the sound source in question, higher community annoyance can be expected. This difference may be equivalent to up to 5 dB.
>
> F.3.4.2: Research has shown that there is a greater expectation for and value placed on "peace and quiet" in quiet rural settings. In quiet rural areas, this greater expectation for "peace and quiet" may be equivalent to up to 10 dB.
>
> F.3.4.3: The above two factors are additive. A new, unfamiliar sound source sited in a quiet rural area can engender much greater annoyance levels than are normally estimated by relations like equation (F.1). This increase in annoyance may be equivalent to adding up to 15 dB to the measured or predicted levels.

The installation of modern upwind industrial-scale wind turbines in or near these communities has resulted in some finding them to be acceptable and others finding them annoying and the cause of sleep disturbance (Hanning & Nissenbaum, 2011; Harry, 2007; Krogh, Gillis, & Kouwen, 2011; Nissenbaum, 2009; Phipps, Amati, McCoard, & Fisher, 2007; Shepherd, McBride, Welch, Dirks, & Hill, 2011).

Some of the research has focused on the annoyance potential from audible sounds produced by wind turbines. However, there may be less obvious causes of the AHEs occurring. For example, it has been proposed that there could be responses mediated through the vestibular system's response to modulated infra and low-frequency noise. Pierpont (2009) has described a set of symptoms reported by individuals who participated in her study and proposed the term *wind turbine syndrome* to describe these. More recently, the research of Salt and Lichtenhan (2011) and Salt and Kaltenbach (2011) has confirmed that there is a physiological response to modulated infrasound at levels below the threshold of perception (for pure tones) that may start at amplitudes as low as 60 dBG. Swinbanks (2011) has demonstrated that as a direct consequence of the dynamic time domain stimulation of the auditory system by the modulating wind turbine infrasound, the "typical wind-turbine infrasonic and low-frequency noise can be readily audible at very much lower levels than has hitherto been acknowledged" (p.1).

The industrial wind energy industry, through its experts and trade associations, has denied that wind turbines can cause such AHEs. Highly recognized experts, some well known in the field of acoustics, have defended the wind industry position through white papers, reports, and testimony in hearings and through committees that are establishing guidelines for siting industrial-scale wind turbines.

This viewpoint has not been universally accepted by other experts. For example, another group of acoustical consultants and specialists has taken the position that the unique characteristics of wind turbine infra and low-frequency range may be related to the reports of AHEs that cannot be explained by the same mechanism as the annoyance and sleep disturbance caused by audible wind turbine sound. These experts tend to be independent regarding the outcome of discussions about the future of industrial-scale renewable energy projects. One fairly common characteristic of these acousticians is that many of them are either retired or close to retirement. They have been involved in acoustical consulting, teaching, and research since the 1960s or earlier.

Some of these independent experts have had experience with noise sources known to result in similar AHEs to those being described by researchers investigating the AHEs associated with wind turbines. In several cases, work done earlier in their careers found similar AHEs from other noise sources that were eventually determined to result from modulated infra and/or low-frequency sound. They found symptoms occurring at sound pressure levels (SPLs) below the commonly accepted thresholds of perception. These thresholds had been established by experiments using test participants who listened for single, steady-state pure tones under laboratory conditions.

The laboratory-based research established the thresholds of perception and the confidence limits that relate to the variation in individual sensitivity to steady pure tones. However, the threshold of perception for a steady pure tone is not the same as for a more complex set of tones or where the tones are not steady but instead are modulating in either frequency or amplitude. As a general rule, the audibility of a complex sound occurs at a SPL lower than what is needed for audibility of a steady pure tone in the same frequency range.

## Weather, Turbulence, Wakes, and Wind Turbine Sounds

An article by Hsu (2010) shows a photograph of clouds forming in the wake of the front row of wind turbines at the Horns Rev offshore wind farm near Denmark. The vortex (wake) on the downwind side of the front row of wind turbine is discernable. The churning of the air downwind of the turbine's blades is a problem for the next downwind turbine in that the airstream flowing into the plane of the blade rotation is already very turbulent. As the photo makes clear, the wake is a very significant source of turbulence, and for each turbine further downwind the turbulence increases.

Other techniques have also shown the downwind wake of wind turbines. Some, like Doppler radar, can show the high levels of energy associated with the wake from a turbine (National Oceanic and Atmospheric Administration, National Weather Service, 2011). When Doppler radar scans an area with active wind turbines, the wake of the turbines is seen as a localized burst of color as though it were a small weather front or storm. In areas like Western New York (United States), in some communities wind turbines can be seen on every ridge. The National Weather Service of the U.S. government has issued warnings that Doppler radar in those areas cannot be relied on as an effective tool for predicting weather patterns. A Doppler radar image of those areas shows the turbines as small colored circles that look like miniature "storms" along the ridge line. Because wakes are a visual representation of the pressure waves emitted by wind turbines, one way to understand the scale and scope of the emissions is through visual metaphors like the photographs of clouds and Doppler radar images.

## Overview of What Was Learned About Infra and Low-Frequency Noise During the 1970s to the 1990s

The author was actively engaged in acoustical consulting during between the 1970s and 1990s; however, much of the work was associated with occupational and community noise in the audible-frequency range. Several projects involving industrial processes where a high level of infrasound was a significant factor regarding an occupational hazard. One involved a diesel-powered electricity generation facility for a manufacturing facility in Indonesia. When installed it had been isolated from people, but over time workers had moved closer to the facility. When the diesel engines were operating, people reported symptoms similar to those reported by researchers of industrial wind turbines.

Other projects became of concern regarding occupational environments (R. James, unpublished work, 1970s-1990s). Examples where workers reported experiencing adverse reactions to audible and inaudible infra and low-frequency noise include the following:

- Processes used in foundry operations where large shaker tables were used to separate parts from scrap. The processes were monitored by workers on a platform along the shaker table.
- Metal-melting processes in foundries where the large combustion burners used to heat the metal produced the infra and low-frequency noise. Workers monitored the melting and pouring processes from inside small control rooms near the foundry's blast furnaces. Although not a part of these studies, anecdotal information was provided that the employees who worked those jobs were often self-selected to accommodate the palpable rumble at the workstations.

Later, in the early 1990s, there were reports that women who were pregnant might be exposing the fetus to high levels of sound when working in noisy occupational environments. The effect of low-frequency sound was a concern because it was not attenuated by the woman's body (Griffiths, Pierson, Abrams, & Peters, 1994; Lalande, Hetu, & Lambert, 1986).

These experiences were not seen as significant beyond the context of the problem being reported. The common thread of modulated infra and low-frequency sound was not the focus of the studies. Instead, changes to the processes were made. Alternatively, the worker was relocated away from the noise. Once that was accomplished, the issues regarding the cause were not pursued.

In 2006, the author started to investigate early reports of AHEs on people living near wind turbine utilities. There was already speculation about the possibility that the reported symptoms could be a result of infra and low-frequency noise from the wind turbines (Pierpont, 2009).

To obtain a more complete understanding of the potential for inaudible infra and low-frequency noise to cause the symptoms being reported, the author established contact with several of the retired acoustical consultants who had worked on problems that matched the acoustical conditions for people living in the vicinity of wind turbines.

The author researched two primary areas:

1. reports of problems with large turboprop jet engines, diesel engines, and other large rotating machines of the type found on large naval ships, large gas or oil

line pumping stations, and other processes involving rotating machines, particularly those that turn very slowly (Alves-Pereira & Branco, 2007; M. A. Swinbanks, personal communications, 2010, 2011)

2. reports given at conferences and published in journals about "sick buildings"[3] where the occupants' distress were related to noise from the heating, ventilating and air-conditioning (HVAC) system (Schwartz, 2008)

The author was successful in contacting the acoustical engineers who were the primary researchers (or managers of the research) on why some people reacted negatively to working or living near these noise sources.

The first contact was with Mr. Charles Ebbing, who was the head of Carrier Corporation's Acoustical Labs and one of the managers of a series of studies jointly supported by Carrier, Trane and American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). These studies were to find out why HVAC noise was affecting some occupants of high-rise office buildings (Ebbing, 1978; Ebbing, Fragnito, & Inglis, 1978; Flynn, 1978; Schwartz, 2008).

A second contact was made with another expert in infra and low-frequency noise, Dr. Malcolm Swinbanks. A chance meeting with Dr. Swinbanks resulted in a significant step forward for the author's understanding of the issues. As a consultant to U.K. companies such as Rolls Royce, Dr. Swinbanks has many years of experience with machines that produce infra and low-frequency sound. He also had personal experience with inaudible levels of modulated infra and low-frequency sound causing the type of symptoms being associated with industrial wind turbines. From 1975 to 1978, and then from 1985 to 1989, Dr. Swinbanks worked in collaboration with Dr. Geoff Leventhall.

As the author became more familiar with the research into noise-related sick building syndrome and to other sources of inaudible infra and low-frequency sound, more evidence was found that supported the link between the complaints and aspects of wind turbine infra and low-frequency noise. Review of the work of the other acousticians showed that some people who worked or lived near large rotating machines found that they felt uncomfortable or had other symptoms that were not related to any known illness or pathology. A common denominator of all of these machines is that they produced sounds in the infrasonic and very low–frequency range. A review of some studies conducted to determine why people reacted negatively to working near these machines or in these environments revealed a common thread—inaudible levels of infra and low-frequency sounds were present and were associated with the physical symptoms reported by some of the workers (Ebbing, 1977; Ebbing & Blazier, 1993; Ebbing et al., 1978; M. A. Swinbanks, personal communications, 2010, 2011).

Previous research had shown that at audible levels, infrasound and very low–frequency sound were able to produce physical responses. However, many scientists and engineers assumed that *inaudible* levels could not cause any problems. This was often stated as "What you can't hear, can't hurt you." Many acoustical engineers were taught this as part of their academic study regarding the perception of infra and low-frequency noise. Studies by researchers such as Swinbanks, Ebbing, and Ebbing's colleague Blazier, an independent acoustical consultant who worked with the HVAC industry, found evidence that some people responded to *inaudible* levels of infrasound and/or very low–frequency sounds produced by the machines (Blazier, 1996; C. E. Ebbing, personal communication, 2011).

## Noise-Induced Sick Building Syndrome

Based on information provided by Mr. Ebbing, high-rise office buildings were being constructed in the 1970s and early 1980s as office space for knowledge workers and other professionals (M. A. Swinbanks, personal communication, 2010, 2011). Many of these buildings used large fans, centrally located, often on the top floor or in a penthouse, to provide heating and air-conditioning for the building. Two companies, Trane and Carrier, were pioneers in this field. This was the province of engineers, such as Ebbing and Blazier, who specialized in acoustical issues related to the design and installation of heating, ventilating, and air-conditioning systems. They worked for the professional organization known as ASHRAE. After a number of these buildings had been constructed, complaints from building owners began to filter back to Carrier and Trane (Ebbing, 1977). Some tenants stated that workers did not want to work in these offices. Reports from workers and their employers included discomfort and other symptoms and low productivity. It is interesting to note that if we list the symptoms of the people in these buildings (productivity loss, effects on mood, lower social orientation, cognitive dysfunction, headaches, and mental tiredness) alongside those reported in the works of researchers such as Krogh et al. (2011), Nissenbaum (2009), Pierpont (2009), and Harry (2007), there is a close match. Considering that the exposure period for workers is 8 hours per day whereas the people exposed to wind turbine noise will frequently exceed 8 hours, the similarity in symptoms is remarkable.

As discussed earlier, Trane and Carrier had acoustical engineering expertise, through either internal departments or outside consultants. They were tasked with identifying why some of the buildings were the source of complaints, whereas others with similar HVAC systems were not reporting any problems (Ebbing & Blazier, 1993). The research by Ebbing (1997) and Blazier (1996) that started in the late 1970s continued into the 1990s. They were assisted by acoustical consultants, such as Dr. Leventhall (C. E. Ebbing, personal communication, 2011), who conducted the controlled tests needed to separate out the characteristics of HVAC sound associated with the reported symptoms and poor work

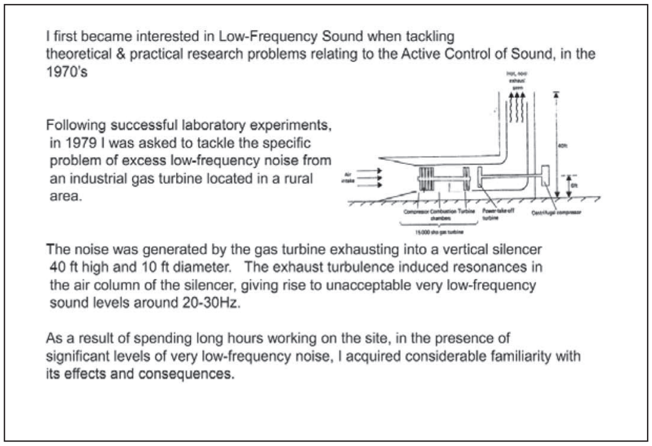



**Figure 1.** Wind turbines: Low-frequency noise and infrasound revisited
*Note.* Reproduced with kind permission from Swinbanks (2010).

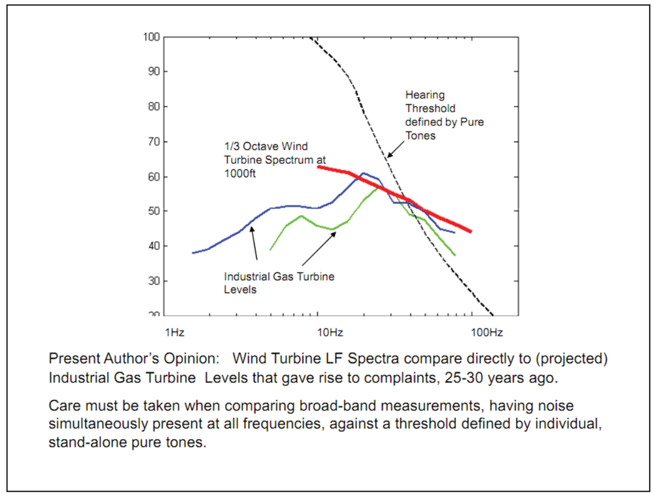



**Figure 2.** An example of low-frequency wind turbine spectrum
*Note.* Reproduced with kind permission from Swinbanks (2010).

performance. By the 1990s, based on the findings of these studies and research programs, the symptoms were linked to modulated low-frequency HVAC noise. Buildings where workers reported symptoms also had modulated infra and low-frequency noise (W. E. Blazier, personal communication to G. Leventhall, April 22, 1997).[2]

It is noted that HVAC systems, when properly designed and installed, do not produce the modulations in the infra and low-frequency range.

## Other Large Rotating Machines

During this same period, other large rotating machines were also found to cause symptoms of the type reported for the HVAC system "sick building" and industrial wind turbines. For these, we need to consider the work of Dr. Malcolm Swinbanks. As background, Swinbanks currently serves as an engineering consultant through his U.K. company, MAS Research Ltd. (Mathematical and Scientific Research), and is Chief Scientist to the U.S. company, Vibration & Sound Solutions Ltd., of Alexandria, Virginia. He holds several patents and has worked on projects for shipbuilders, jet engine manufacturers, and others who benefit from his expertise in infra and low-frequency noise–related problems.

At a conference held in September 2010 in Birmingham, United Kingdom, Swinbanks presented a short history of some of his work that had led him to conclude that inaudible levels of infra and low-frequency sound can cause AHEs in a portion of the exposed population. In his presentation, he describes studies related to gas turbines and turboprop engines.

Figure 1 is one of the slides Swinbanks (2010) presented at this conference.

Swinbanks (2010) states, "As a result of spending long hours working on the site in the presence of significant levels of very low-frequency noise, I acquired considerable familiarity with its effects and consequences."

Although this statement can be taken as a general observation, it is this author's opinion, confirmed in personal discussions with Dr. Swinbanks, that it also reflects a more personal observation. Based on comments shared with this author, Swinbanks became sensitized to infra and low-frequency noise during early work on noise sources with significant infra and low-frequency noise. He can perceive or "feel" inaudible infra and very low–frequency noise. He has conducted research into wind turbine noise, including at the homes of several of the author's clients and others. He has stated that in each of these homes, he was able to perceive the audible pulsations from the wind turbines (blade swish), and at author's clients' homes, he also perceived the inaudible pulsations from the infra and low-frequency modulations. Each of these homes has been studied by acoustical consultants working for the developer. Their reports state that the levels of infrasound are below the threshold of perception for steady pure tones. To date, there has been no mitigation regarding the source of the complaints.

Swinbanks offers a combination of engineering expertise related to low-frequency and infrasound problems and personal experience regarding the potential AHEs. He appreciates the reports of some regarding AHEs associated with industrial wind turbines (M. A. Swinbanks, personal communications, 2010, 2011).

Figure 2 is another slide from Swinbanks's (2010) presentation.

It displays a spectrum for a gas turbine and compares it with the hearing thresholds for pure tones. In the infrasonic range, the turbine sound is significantly below the hearing threshold. The spectrum for wind turbines contains a higher proportion of its total acoustical emissions as infrasound than does the spectrum for gas turbines. It is also below the threshold of audibility for steady pure tones in the infrasonic and very low–frequency range.

Regarding his experiences near upwind industrial-scale wind turbines, the primary sound at the blade passage frequency is located near 1 Hz (1 cps or 1 cycle per second) for a turbine with a hub rotation of 20 revolutions per minute and having three blades. From the partial spectrum in Figure 2, it can be seen that wind turbines have more infrasonic energy than the industrial gas turbine and that the energy increases in amplitude as the frequency decreases.

In this author's opinion, the most important part of Figure 2 is the last sentence. Swinbanks (2010) says, "Care must be taken when comparing broad-band measurements, having noise simultaneously present at all frequencies, against a threshold defined by individual, stand-alone pure tones."

This statement raises an important issue. There are competing claims between the position of wind industry experts and trade associations and other experts regarding auditory responses of people exposed to pure tones versus their response to complex modulated tones.

Based on research and acoustical experience, the claims that infra and low-frequency sound from wind turbines are insignificant and cannot be associated with reported symptoms are not supported (Salt & Hullar, 2010; Salt & Lichtenhan, 2011; Salt and Kaltenbach, 2011).

When an ear is subjected to a steady pure tone in a laboratory environment, it will be less sensitive to low-frequency sound than when presented with sound consisting of a complex mix of pure tones in the same frequency range. The threshold of perception curve in Swinbanks's (2010) graph shows the levels of infrasound from wind turbines (approximately 70-80 dBG during normal operation). They do not exceed it for frequencies below about 50 Hz. But perception of a steady pure tone is not the same as perception of the complex mix of tones emitted by wind turbines. These are neither steady nor pure tones. Instead, they are a complex mix of tones whose summed amplitude modulates in short, rapid bursts, sometimes lasting 10 milliseconds or less. The most active part of the spectrum is between the blade passage frequency at about1 Hz up to 10 Hz. Furthermore, these modulations, or pulsations, have high crest factors and large dynamic ranges. The peaks can be 30 to 40 dB higher than the SPL in the valleys between them.

Given the role that modulated infra and low-frequency sound played in sick buildings, the possibility that the presence of modulations in wind turbine infra and low-frequency noise relates to perception of wind turbine infrasound by some people must be considered, even if the SPLs in these frequencies do not exceed the thresholds of perception for pure tones.

In the preceding discussion on sick building syndrome, it was mentioned that Dr. Leventhall did much of the research needed to resolve the problem. A report published in 1997 by some of the same researchers who have since published articles on wind turbine noise and other effects (Persson Waye, Rylander, Benton, & Leventhall, 1997) highlight some compelling parallels:

From the Background:

> Some of the symptoms that are related to exposure to low frequency noise such as mental tiredness, lack of concentration and headache related symptoms, could be associated with a reduced performance and work satisfaction. (Persson Waye et al., 1997, p. 467)

From the Conclusion:

> The results showed that the low frequency noise was estimated to interfere more strongly with performance. The results also gave some indications that cognitive demands were less well coped with under the low frequency noise condition.
>
> The relation between the reduced activity and response time, which was especially pronounced in the low frequency noise condition, may also indicate that increased fatigue was of importance for the results. (Persson Waye et al., 1997, p. 473)

The AHEs reported by workers occurred with short-duration exposure (e.g., 8 hours a day or less). This is a much lower "dose" than what people living near wind turbines experience. This 1997 study found that some of the symptoms related to exposure to modulated very low–frequency sound are similar to those reported by people experiencing exposure to industrial wind turbines.

The primary mechanism for producing modulated infra and low-frequency noise in "sick buildings" was traced to the HVAC system. Not all workers reported complaints of audible rumble. When the problem was audible, one or more workers might hear a rumble or roar from the ventilation ducts. In those cases, there was little question about the problem. People could hear it and demand that it be fixed. But if it was inaudible, people did not associate their symptoms with the sounds that made them less productive. It required special studies and tests developed by Dr. Leventhall and others to identify that the workers' sense of being uncomfortable or having other symptoms while in their offices was associated with the modulated infra and low-frequency noise. These investigators convincingly showed that pulsations in the HVAC systems corresponded to times when workers reported symptoms of mental tiredness, lack of concentration, headaches, and reduced performance and work satisfaction.

Many of these symptoms are couched in the language of productivity and work performance. The study was not done specifically to examine the AHEs. It was initiated as a result of concerns of building owners because their tenants were complaining or threatening to relocate because of the productivity problems and loss of work satisfaction with their employees. However, the research revealed an array of symptoms that are reported by those experiencing AHEs from wind turbines.

An important conclusion of the study states,

> Low-frequency noise was estimated to interfere more strongly with performance, the results also gave some indications that cognitive demands were less well coped with under low-frequency noise and the relationship between the reduced activity and response time which is especially pronounced in the low-frequency noise condition may also indicate that increased fatigue was associated with the results. (Persson Waye et al., 1997, p. 473)

More recently, the World Health Organization (WHO; 1999) stated, "It should be noted that low frequency noise, for example, from ventilation system can disturb rest and sleep even at low sound levels."

If exposure to this type of sound can cause problems after an 8-hour workday, it is not unreasonable to believe that it will cause similar and potentially more serious problems for those who are exposed more than 8 hours a day on a continuing basis to modulated infra and low-frequency noise from wind turbines.

For individuals who have left their homes as a result of similar symptoms, it could be said they have a "sick home." One could refer to this type of AHE as a "wind turbine noise–induced sick building problem." During a conversation with Mr. Ebbing, he suggested to the author that had the class of symptoms reported by people living near wind turbines been identified as a subset of infra and low-frequency noise syndrome, the claim that there is no research supporting a link between AHEs and inaudible infrasound and low-frequency noise could not be made.

## NASA/Department of Energy Studies

While the effects of inaudible modulated infra and low-frequency sound were being investigated for buildings and large jet engines, NASA and the Department of Energy funded a series of research studies from the early 1980s to about 1991 on wind turbine noise. The two primary researchers, Hubbard and Shepherd (1990), reported the following:

- Wind turbines produce primarily infra and low-frequency sound.
- Sound propagates from wind turbines at a decay rate half that of common "point" sources.
- Wind turbine noise travels farther than other sounds.
- Wind turbine noise will be a significant indoor noise problem due to room resonance and a dominance of infra and low-frequency acoustic energy.

Other findings forecasted the problems people are reporting today from wind turbines. One of the differences between wind turbine noise and other common community noise sources is that sound propagation of the infra and low-frequency sound from wind turbines does not follow the "6 dB per doubling of distance" rule (Hawkins, 1987). Under common atmospheric conditions, wind turbine sound, especially the lower frequency sound, propagates at a rate of 3 dB per doubling of distance. It is not a simple relationship and is dependent on ground surface and atmospheric conditions, and it may transition from 6 to 3 dB decay rates at some distance from the turbines. The lower frequency sounds from wind turbines can propagate to much greater distances than would be expected (Zorumski & Willshire, 1989).

Given the potential to affect properties at greater distances than the mid- and higher frequency sounds, the infra and low-frequency noise emitted by wind turbines can be a significant indoor noise problem as a result of two factors. First, attenuation of the outdoor sounds through the walls selectively blocks more of the mid- to high-frequency sound than infra or low-frequency sound. Secondly, the infra and low-frequency noise penetrates the building walls and roof, resulting in the lower frequency noise from wind turbines being more easily heard. Also, room resonance can augment the sounds that penetrate to the interior. This process is dependent on the specific geometry of rooms of the home, but when it occurs, it can reinforce the sounds from outside, causing SPLs to be higher inside than those outside (Hubbard & Shepherd, 1990).

## How Wind Turbine Sound Is Displayed

During the 1980s and early 1990s, the preferred method for describing wind turbine noise was to present it as both A-weighted and unweighted SPLs. However, since the mid 1990s, about the time the ETSU-R-97 (1997) guidelines were introduced in the United Kingdom, the standard for reporting on wind turbine noise presented only A-weighted sound levels and spectra.

For example, hump-shaped traces for the 1/3-octave band sound pressure data shown in Figure 3 display the results of a study by DELTA (Danish Electronics, Light and Acoustics, 2007).

This study normalized the sound power levels for 37 different makes and models of commonly installed industrial-scale wind turbines (Sondergaard, 2008; Sondergaard & Hoffmeyer, 2007). The graph shows frequency from 10 Hz to 10,000 Hz with the vertical axis showing the SPL ranging from 30 dB to 120 dB. The original report displays the data after applying A-weighting to the sound power levels.

The graph shows the original view of the DELTA graph by the set of traces that start on the left with low dBA levels in the very low–frequency range. The general shape of the resulting curve is humped with a maximum at 1,000 Hz. It also shows the upper and lower confidence limits of their analysis, with the mean value represented by the line between the upper and lower boundaries. Given the narrow confidence limits, it appears there is relatively little variation in

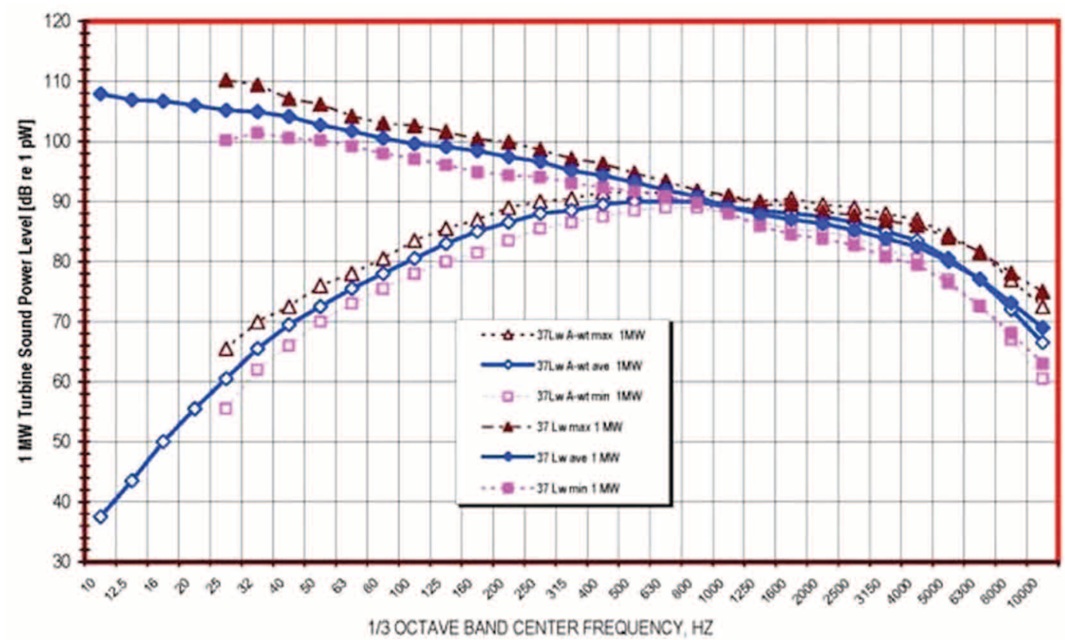



**Figure 3.** Danish Electronics, Light and Acoustics study data

*Note.* Data excerpted from a report to Danish Energy Authority, April 30, 2008, and replotted without A-weighting and provided with kind permission to use by G. W. Kamperman (personal communication, 2011).

the spectral shapes or overall sound power levels between industrial-scale upwind turbines once normalized for power output. This is also seen when reviewing the manufacturer's sound power–level specification reports that accompany the computer models constructed for projects. There is a very limited range of overall dBA sound power levels, the typical range being between 100 and about 110 dBA $L_{Aw}$.

Someone not familiar with the influence of A-weighting on the infra and low-frequency sound content from a noise source might be led to believe by the visual impression of the graph that there is little or no significant infra or low-frequency sound emitted by modern industrial-scale wind turbines. Someone with a background in acoustics should easily recognize that because the data are A-weighted, the shape of the curve means there is infra or low-frequency sound present and that before concluding anything about its significance it would be appropriate to see the spectral shape without A-weighting.

To demonstrate this, the data from the hump-shaped traces were "unweighted" to reflect the amplitudes of the 1/3-octave bands over the same frequency spectrum. The set of traces that begin high on the left-hand side in the low-frequency range are from this corrected set of data. This spectrum more clearly shows that wind turbine sound power levels are highest in the lowest frequency range and, in general, increase in amplitude as the frequency decreases.[3] The unweighted trace merges into the hump-shaped trace created from A-weighted sound power levels at 1,000 Hz. From that point onward to the higher frequencies, the two traces are roughly equivalent. However, to the left of 1,000 Hz the unweighted spectrum increases from a 1/3-octave band center level of 90 dB at 1,000 Hz to approximately 109 dB at the lowest frequency of 10 Hz. If we sum the energy of the spectral data from 500 Hz and higher into a single overall sound power level ($L_w$ in dBA), it yields a level in the range of low to mid 100 dBA. Then, summing the energy from 0 Hz to 500 Hz results in an unweighted overall level above 110 dBA. The infra and low-frequency sounds that are de-emphasized by the A-weighting process are, in fact, more significant than the higher frequency portion of the spectrum.

This raises the following question: Where did the practice of depicting wind turbine acoustical data in terms of dBA originate?

In the opinion of this author, the practice of depicting wind turbines acoustical data in terms of dBA can be traced back to the British wind turbine siting guidelines ETSU-R-97 (1997). The guideline was developed by the Working Group on Noise From Wind Turbines, which consisted of several acoustical consultants with ties to the wind industry in the United Kingdom, representatives of companies or their attorneys involved in or with the wind industry, several representatives of local governments, and the chairman, who represented the government's Department of Trade and Industry (DTI).

The introduction to the Final Report states,

> While the DTI facilitated the establishment of this Noise Working Group this report is not a report of Government and should not be thought of in any way as replacing the advice contained within relevant government guidance. This report presents the consensus view of the group of experts listed below who between them have breadth and depth of experience in assessing and controlling the environmental impact of noise from wind farms. This consensus view has been arrived at through negotiation and compromise and in recognition of the value of achieving a common approach assessment of noise from wind turbines. (ETSU-R-97, 1997)

In spite of the disclaimer, this guideline is used in decision making for many wind turbine projects in the United Kingdom as though it were an official government document superseding other more restrictive U.K. noise pollution regulations.

The ETSU guideline takes the position that wind turbine infra and low-frequency sound is not significant, and, accordingly, the appropriate way to depict acoustical data is to use the A-weighting adjustments. In other words, the guidelines suggest that all acoustical data should be presented as dBA values.

The guideline makes other presumptions that have also affected the way acoustical data are reported and even what aspects of its sound emissions require consideration. For example, the document takes the position that there is little or no audible blade swish (amplitude modulation in the frequencies between 200 and 500 Hz). It asserts that the $L_{A90}$ is within 1.5 to 2.5 dB of the equivalent energy level, $L_{Aeq}$. (ETSU-R-97 1996, p. vi). From this erroneous assertion, it concludes that wind turbine sound levels should be expressed as statistical values of $L_{A90,\ 10min}$ (which represents the quietest period of the measurement, not the noisiest) as a means to avoid contamination of the measurement by short-term transient sounds not from wind turbines. The ETSU working group members, including reputable acoustical experts, established constraints that measurements of wind turbine noise should be conducted using a procedure that ignores the 90% noisiest part of the measurement time. This is justified by an unsupported assertion that use of this method will filter out, without corruption, relatively loud, transitory noise events from other noise sources. The fact that it also ignores the 90% of the time when the wind turbine is noisiest whether from blade swish or any other cause is not discussed.

It is speculated that the line of reasoning in the ETSU-R document, presented as an authoritative document, led many to believe that modern upwind industrial scale wind turbines do not produce significant blade swish. People have reported

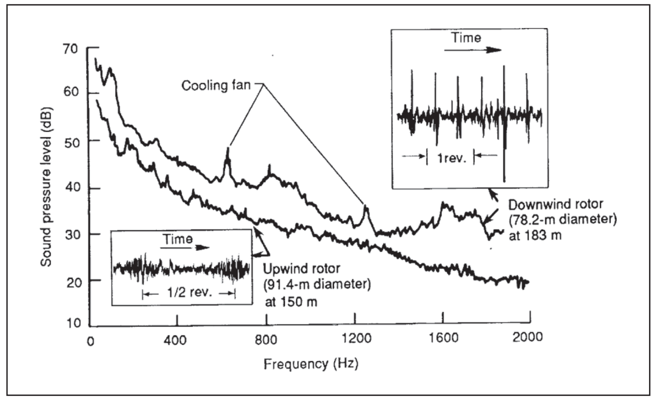



**Figure 4.** Acoustical spectra of downwind and upwind wind turbines

*Note.* Reproduced with kind permission from Hubbard and Shepherd (1990).

nighttime noise disturbance from blade swish, and acoustical consultants from the United States (Kamperman & James, 2008) and the United Kingdom (Hadden, 2007) have presented data showing amplitude modulation of blade swish exceeding normal operating sound levels by 5 to 10 dBA or more. This was also reported by other researchers, including Van den Berg (2006) in his thesis "the Sounds of High Winds." However, wind turbine noise regulations that are constructed around the position expressed by the working committee for the ETSU-R document remain in place around the world.

World Health Organization (1999) has identified the importance of measuring low-frequency components: "It should be noted that a large proportion of low-frequency component in a noise may increase considerably the adverse effects on health" (p. xiv). and that "The evidence on low frequency noise is sufficiently strong to warrant immediate concern" (p. 35).

## Blade and Tower Interactions

Figure 4 is an excerpt from the report on the NASA studies mentioned earlier (Hubbard & Shepherd, 1990).

This graph shows the acoustical spectra of two wind turbines, one that has the blades located downwind of the tower and the other with the blades located upwind of the tower. The downwind turbine was common during the early years of wind turbine installation but frequently resulted in complaints of a deep, heavy, thump synchronized with blade rotation speed. The cause of this thump was the interaction between the tower and the airstream before it enters the plane of rotation of the blades as they moved through the bottom part of their travel. The tower slows the airstream, causing the blade at its lowest point to encounter wind speeds significantly lower than they were just before they reached the bottom where the tower does not block the inflow airstream. The tower effect resulted in a deep infrasonic "thump." The top trace on the graph from the NASA study shows the spectral shape, whereas the insert in the upper right of Figure 4 shows level versus time to display the "thumps."

Because of this problem, wind turbines using an alternative design that placed the blades upwind of the tower became the dominant configuration for new projects. It was believed that by locating the blades upwind, the inflow airstream would not be disturbed by the tower and the "thump" would be eliminated. This change in design did make a significant improvement in reducing the tower induced "thump" but has not completely eliminated infrasound from wind turbine emissions. It should be noted that, at this time, downwind turbines are not manufactured for industrial-scale wind energy utilities.

If we look at the lower trace for the upwind configuration, we see that there has been a significant reduction in the "thump," and the overall level across the frequency spectrum is also lower than for the downwind turbine shown in the top trace. We also can see that the upwind turbine exhibits blade swish. This is seen in the insert to the lower left. In this case, because it is a two-bladed turbine, we see one swish every one-half revolution. However, it is clear that even with this blade swish, the upwind turbine trace is lower than the downwind turbine trace.

Whether this decrease is entirely a function of upwind versus downwind design or some other change in the design of the upwind turbines is impossible to say. Also, in spite of early beliefs that this change had eliminated noise from blade/tower interactions, there is new information that shows that it can still occur at significant levels. The impact of the tower on the airstream for the upwind style wind turbines cannot be assumed to be zero or even negligible. The airstream will begin to react to the tower before it reaches it. The distances between the blade and tower of modern industrial-scale upwind turbines can be small enough that under some weather conditions the inflow airstream speed just in front of the tower can be different from the inflow airstream speed at locations where the tower is not in the flow path.

Dr. Swinbanks has reviewed the analysis conducted in the original NASA research papers regarding tower interactions. His conclusion is that airstream-to-tower interactions may still occur with upwind turbines, although of less severity and under fewer conditions than for the downwind style of turbine. Thumps heard from upwind-style wind turbines may be a result of this airstream-tower interaction (M. A. Swinbanks, personal communications, 2010, 2011)

## Sound Propagation Computer Models

Development of a computer model simulating the decay in sound from a wind utility into the surrounding community is a common part of the process of seeking operating or other permits. Although there is commercial quality software available to assist an acoustical engineer in estimating the impact of a new wind utility on an existing community, there is no assurance that the software can accurately model any specific situation. Algorithms must be available that allow for the accurate mathematical representation of decay of acoustic energy across a frequency range from the infrasonic to the mid and high frequencies as it interacts with weather, topography, and other factors that affect the propagation path. Therefore, the first requirement is that acousticians have the necessary algorithms.

The second requirement is that the model's algorithms and input data represent the conditions that are most likely to cause complaints. This is often referred to as the "predictable worst case condition." Thus, the model developer must know what causes that predictable worst case condition and tune the model to represent sound propagation under those conditions.

If the predictable worst case condition is one where the sound power emitted from the wind turbines is different from the sound power levels reported in the manufacturer's sound test specifications, then adjustments to the sound power levels are required. Thus, model accuracy depends on the accuracy and completeness of the algorithms and on how close the conditions modeled are to the predictable worst case condition.

Earlier it was noted that the Hubbard and Shepherd (1990) report identified that sound propagation, particularly that of the infra and low-frequency sounds from wind turbines, occurred at a lower decay rate than what is normally assumed for noise sources where the acoustic energy expands in a spherical manner as the distance from the noise source increases. This effect is related to weather conditions and ground surface reflections that reduce the decay rate as a result of reinforcement of refracted and reflected sound. It is also one that is not considered in computer models of wind projects created to demonstrate that the project will be compatible with existing land use.

A second deviation from the rules for accuracy occurs because of the common presumption that acoustic energy from a wind turbine dissipates proportional to the surface area of an expanding sphere (e.g., spherical spreading) at a decay rate of 6 dB per doubling of the distance from the noise source. This is often associated with the term *point source* model. The effects noted by Hubbard and Shepherd (1990) are more properly modeled using cylindrical spreading (3 dB per doubling of distance). Cylindrical spreading is often associated with the term *line source*. Few, if any, models of wind projects have considered that wind turbines have line source properties and that the models using point sources do not address those properties.

The layout of the turbine project can also alter sound propagation in other ways. When noise sources that radiate sound in a spherical pattern are closely spaced in a linear configuration, for example, the cars in a long train, the sounds from each can interact and reinforce each other. This is also true for rows of wind turbines.

This reinforcement results in a decay rate of 3 dB per doubling of distance instead of the 6 dB per doubling predicted by the inverse square law. The energy spreads according to the surface of an expanding cylinder (line source) instead of an expanding sphere (point source). The cause of this is related to the similarity in the spectral shapes of each turbine and the similarity in temporal pattern caused by all of them turning at similar hub revolutions per minute. Plus, if there is amplitude modulation in any frequency range, sounds of two or more turbines may reinforce the sound at distances from the turbines. This increases the energy that is spread outward and causes increases in the SPLs where the turbine sounds reinforce each other.

The need to consider these effects in models should have been common knowledge to the acoustics experts creating the models.

Gipe (1995), who was awarded the World Wind Energy Award in 2008 by the World Wind Energy Association, states,

> Multiple wind turbines complicate matters further. From relatively long distances, an assembly of machines appears as a point source . . .
>
> Closer to the turbines, they begin to act as a line source. The decay rate for line sources is 3-dB, not 6 dB for true spherical propagation.
>
> The standard wind turbine computer model used to estimate sound levels for wind Project assumes "Spherical Propagation" not "Line Propagation" even though turbines are arranged in rows. This error means that the tables of sound levels and the contour maps grossly underestimate the true impact of the sounds on adjacent properties located along the rows. (p. 379)

The NASA research by Hubbard and Shepherd (1990) made similar observations.

One might think that models constructed by experts to represent wind turbine layouts would select the type of propagation, point or line, appropriate for the proposed layout. However, in the process of conducting and analyzing measurements and presenting testimony at hearings on wind turbine projects, this author has reviewed computer models of projects from Ontario, Canada; Southern California, United States; New Zealand; and the United Kingdom. With only a few exceptions, they all are based on the assumption that wind turbines are "point sources." Some do not even consider the sound propagation in different frequency ranges. Those use a single number representing the A-weighted sound power level and assume that all frequencies have the same propagation rates.

There are unanswered questions about why experts in acoustical models of wind turbine projects do not follow the advice of the NASA studies about propagation of the infra and low-frequency sound or the advice of an expert recognized by their own trade associations about turbines in rows being line sources. Models constructed using point sources when line sources should be used will understate the sound level at distances of 1,500 feet or more by a significant amount. This understatement could amount to 3 dB or more depending on the number and arrangement of wind turbines. Could it be that they do not know? Could it be they are following the work of others who have made this error without questioning it? Or, could it be that the results of this error accrue to the benefit of their clients when seeking permits to construct a wind utility?

Whatever the answer, it should be noted that many permits are granted based on point source models that do not account for infra and low-frequency propagation or other factors that cause propagation and do not follow the point source assumptions. These projects are generally granted permits based on guidelines that are supposed to prevent annoyance, assuming that the sound levels of the operating wind utility do not exceed the modeled sound levels. But it is likely that most of the models suffer from deficiencies of inaccurate algorithms and not being tuned to represent the predictable worst case condition.

What is the result of this practice? Do we find that communities are compatible with the wind turbine noise? Or do we find complaints of annoyance and nighttime sleep disturbance filed by property owners living near the perimeter or sometimes inside the footprint of the utility? It is not uncommon for acoustical consultants hired by these property owners to measure sound levels on the properties that exceed the modeled sound levels by 5 to 8 dBA.

## Alternative Methods for Modeling

Although the International Organization for Standardization (ISO) 9613-2 (1996)–based sound propagation software models such as Cadna/A are commonly used in the United States; Ontario, Canada; and the United Kingdom; this should not be construed to mean that there are no alternatives.

There are alternatives, some of which are specifically designed to address sound propagation from wind turbines. For example, the Swedish Environmental Protection Agency has been exploring alternative algorithms for wind turbine models for many years (Johansson, 2003). Recent work on improving wind turbine models has considered the need for the sound propagation path transitioning from spherical to cylindrical spreading (Boue, 2007). This is not a feature of the models commonly developed for wind turbine utilities that follow ISO 9613-2. Nor is the absence of this feature identified in developer's reports as a limitation of the model's findings.

A report published in 2005 presented the results of a study of modeling methods available for modeling wind turbine noise including the Danish and Swedish methods (Sondergaard & Plovsing, 2005). The purpose of the project was to establish a method for noise emission measurements for wind turbines on offshore locations. This report identified

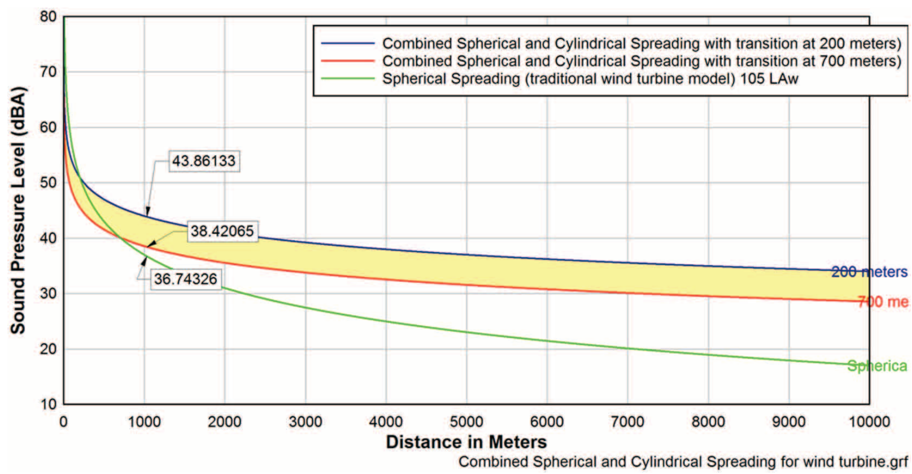



**Figure 5.** Sound propagation, combined spherical and cylindrical spreading
*Note.* Compiled by G.W. Kamperman (personal communication, 2011) with kind permission to reproduce.

an algorithm that could model sound propagation that uses spherical spreading for locations close to the turbine and then transitions to cylindrical spreading as distances increase.

The initial focus of the alternative models was for noise propagation from offshore wind turbines (over water), but subsequent research has shown that changes to the variable that controls the transition point from spherical to cylindrical spreading can account for the difference in reflection caused by water versus surface land. This allows the algorithm to be used for offshore wind utilities and for some onshore wind utilities. Harrison, a retired professor from the Department of Physics at Queen's University from 1969 to 2002 presented a paper discussing the combined formula and how to adapt it for use with on shore wind turbine utilities (Harrison, 2010a).

Dickinson, Professor of Acoustics at Massey University, has done work on verifying and extending the use of the alternative algorithm (Dickinson, 2010).

Given there is no general agreement on how to model wind turbine sound propagation, how the model is developed, and the conditions it represents, the modeling process along with its assumptions and limitations must be clearly explained in the reports. These will be submitted to government agencies as one element of the decision as to whether a particular project may be compatible or incompatible with a particular community, and they must provide sufficient detail and information to permit peer review. Sound propagation from a wind turbine utility is a complex set of interactions that are dependent on the weather and other factors along the sound propagation path that may require different algorithms for different frequencies of the emitted sound. Achieving a high degree of accuracy in modeling is important if the models are to be useful in making these decisions.

Yet, outside of the Nordic countries, the models based on the ISO 9613-2 general method are ubiquitous and relatively unchallenged. When one reads the explanations in the reports describing the modeling process, one might conclude that there are no other methods. In some countries, only models based on the ISO 9613-2 method are permitted according to government guidelines. For example, the Ontario and U.K. guidelines specify this as the required modeling method.

Just how different are the predictions between the ISO and the combination algorithms?

Figure 5 shows the sound propagation compiled by Kamperman (personal communication, 2011) for both methods over a large distance.

It shows the sound level at distances from near the turbine to 10 km (10,000 m) from use of the ISO model and point source propagation as the green line that is lowest traces beyond 1,000 meters from the turbine. The Swedish Environmental Protection Agency algorithm taken from the DELTA and Harrison reports combines both point (spherical, 6-dB) and line (cylindrical, 3-dB) decay rates. This decay rate is shown by two upper traces labeled 200 and 700 meters on the right.

The labels show which trace is for each of two transition points, one at 200 meters and the other at 700 meters. Because we do not have specific data for the reflectivity of the surface between the turbine and receiver locations, the area between these two transition points is shaded yellow to show that the sound level could vary over a range. The two transition values were selected based on the DELTA validation reports

(200 meters over surfaces as reflective as water) and the work of Dickinson (2010)—that is, approximately 700 meters for land surfaces.

The graph shows that for the selected input data (Lw = 105 dBA and no attenuation from air or surface features), the ISO method predicts a higher sound level for the first 100 meters or so and then drops to less than the top trace (200) for the DELTA formula at 200 meters. At a distance of 700 meters, the ISO method predicts sound levels of less than the DELTA formula with a transition point of 700 meters. At greater distances, the difference in the predicted sound level between ISO and DELTA algorithms continues to increase. At 2,000 meters (from a single wind turbine), the ISO method is predicting a sound level of just over 30 dBA, whereas the DELTA algorithm is predicting a level from about 35 dBA to just over 40 dBA.

In a rural community background (residual), sound levels at night can be as low as 25 dBA or less. Thus, at distances of 2,000 meters or more, the ISO method's 30 dBA prediction indicates there would be little annoyance or sleep disturbance potential. The DELTA method predicts that wind turbine–related sound levels would be 10 to 15 dBA higher than the background sound levels. The commonly used ISO modeling method implies that wind turbines would not be objectionable to people 2,000 meters away on otherwise quiet nights (about 1.25 miles), whereas the DELTA algorithm shows that the sound from the wind turbines would exceed the background sound levels by a high enough margin to result in likely complaints. One method makes it appear that the wind turbines are compatible with nearby residential property, whereas the other shows a potential for complaints.

Many of the reports reviewed by this author are ISO-based models that present results to the 10th of a decimal point with no stated confidence limits. Models projecting sound levels at locations where there are limits that cannot be exceeded must make an allowance for errors or tolerances. But this is seldom the case. More typically the models may show a predicted value that is only a few decimal points less than the criteria limit. The report will often conclude with a statement that the model proves the project will not exceed the criteria once in operation. The presumption that the model is accurate is not warranted.

Models of wind turbine utilities used for assessing land use compatibility should thus

1. recognize the research of the NASA reports and other research that wind turbine infra and low-frequency sound must be handled differently than mid and high frequency sound
2. be the best suited for representing wind turbine sound propagation
3. represent the predictable worst case condition
4. fully disclose assumptions, limitations, and tolerances
5. provide confidence limits to account for the inherent inaccuracy in any model representing a complex set of conditions

Expectations are that these requirements be part of models of complex processes similar to those related to climate change, economics, and other scientific projections.

Although it is unknown if one or the other of these algorithms is the most accurate for any specific situation, this may not be the salient point that should be taken from this discussion.

The author suggests at a minimum, to accept the alternative algorithm as a demonstration that there is no universal agreement that the ISO standard is the best method for modeling wind turbine projects. This is supported by other models that have been developed, such as the Nord2000 model. Instead, we should use modeling results with the understanding that the model may not be a definitive representation of the proposed utility.

Instead of claiming that a model based on the ISO calculations is a "worst case conservative" representation of operational sound levels, we should be disclosing the confidence limits for the algorithms (for wind turbines modeled using ISO 9613-2, at least ±3 dB) and for the measurements used to calculate the apparent sound power level emitted by the wind turbines determined according to International Electrotechnical Commission (IEC) 61400-11 (1-2 dBA or possibly higher).

We should also be disclosing that the IEC 61400-11 tests do not report the worst case sound power levels. Instead, they show the sound power levels for normal operation, generally under an atmospheric condition with wind shear of 0.2 or lower. Thus, a proper report on modeling should state that there are conditions that might require the sound power levels reported by the IEC 61400-11 tests to be adjusted to reflect operational differences for the turbine in weather or siting arrangements that were not part of the weather or siting present during the IEC 61400-11 tests for sound power. This is how models have been used in the past. Wind turbine models should not be treated any differently.

It is worth noting that the ISO 9613-2–based commercial models are referenced in the ETSU-R-97 guidelines as being the most appropriate for use on wind utility modeling.

## Wind Turbines Are More of an Indoor Problem Than an Outdoor Problem

During the preceding discussion regarding the NASA (Hubbard & Shepherd, 1990) research, it was mentioned that it was anticipated wind turbine noise, especially at moderate distances from the turbines, is more likely to be an indoor problem than an outdoor problem. This concern is not addressed in noise impact studies conducted for wind turbine utilities. In many cases, the opposite occurs. The noise reports may claim that wind turbine sound levels of 45 dBA outside a home will not be a source of indoor annoyance or sleep disturbance. This assertion has not been supported by recent

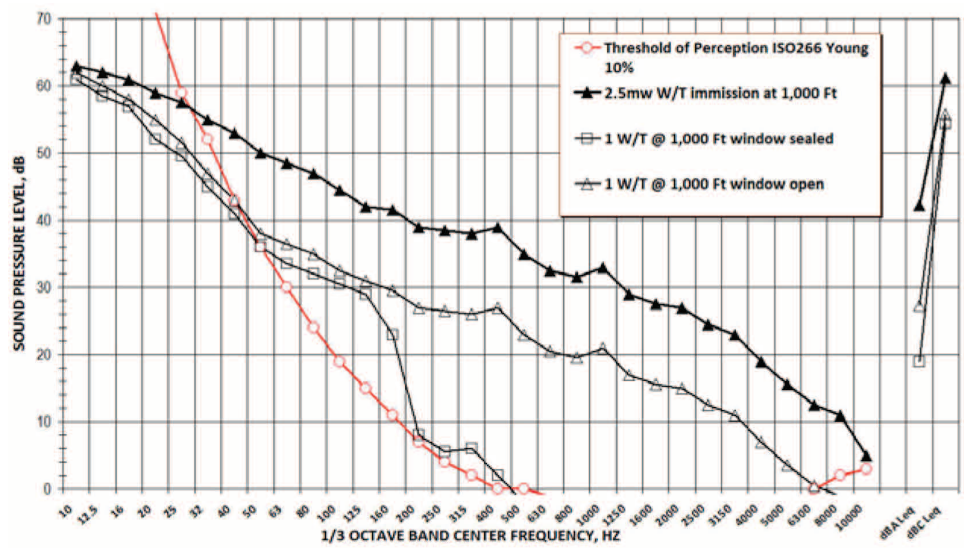



**Figure 6.** Wind turbine noise spectra inside a home
*Note.* Reproduced with kind permission from Kamperman and James (2008).

research conducted in Sweden and the Netherlands. A recent study found that for a wind turbine utility producing a steady 45 dBA (equivalent continuous noise level [Leq]) outside the walls of a home, 18% of the home's occupants would find the noise heard inside as highly annoying while 32% would be annoyed (Janssen, Vos, Eisses, & Pedersen, 2010).

In Figure 6, the sound received from a single 2.5-MW turbine located 1,000 feet away (303 m) is used to calculate the expected SPLs inside the home for the condition of a window open and closed. The predicted overall sound level outside the home is 42 dBA ($L_{Aeq}$). The graph presents frequency along the bottom axis and unweighted SPL for the vertical axis. The top trace (solid black line with triangular markers) represents the SPL in each 1/3-octave band from 10 Hz up to 10,000 Hz of the sound outside the home. The next lower trace, the black line with the hollow triangles, represents the sound level inside a standard wood frame home with a window open. The next lower line, a black line with hollow squares, represents the sound level inside the room with the same window closed. The final and lowest line, in red, represents the threshold of perception for the 10% most sensitive people as specified in ISO 266 for the threshold of perception based on data collected by Young. The example assumes that sensitivity to wind turbine infra and low-frequency noise is the same as sensitivity to a steady pure tone. The wind turbine infra and low-frequency sound will be perceived at some unknown level that is less than the threshold for a steady pure tone.

When the trace appears above the red line, the threshold of perception, the presumption is that the sound will be audible for at least 1 out of every 10 people. As can be seen from this graph, an open window would allow the sounds of the wind turbine to be clearly audible, at least for the subset of the population that is most sensitive and possibly for those at the median threshold (not shown). The frequencies from roughly 50 Hz on up through the speech range would be the ones most likely heard. Even for the situation with a window closed, we can see that in the frequency range from roughly 50 Hz to about 200 Hz, the turbine sounds will be audible if the room is quiet.

Before moving on from Figure 6, it is also worth noting that on the right-hand side of the graph, the corresponding dBA and dBC sound levels for each of the traces are shown. It is common for wind industry experts to claim that the walls of the home will provide 15 dBA of attenuation and that sound levels outside a home from wind turbines of 45 dBA will then result in bedroom sound levels of 30 dBA. This example shows that outside the home, the dBA sound level would be roughly 42 $L_{Aeq}$, while inside the home, with the windows open or closed, it would be less than 30 $L_{Aeq}$. This may be seen as supporting the wind industry position that 45 $L_{Aeq}$ would be acceptable to people inside their homes. However, as the WHO (1999) guidelines point out, if the noise source outside the home has significant infra or low-frequency sound, the use of dBC is more appropriate and lower limits may be needed.

Looking at the column for the dBC value, we see that the outside levels would be roughly 61 dBC, whereas inside the home with the windows open or closed, the levels would be roughly 55 dBC. That means that we are only seeing a 6-dBC decrease through the walls of the home. The reason is because wind turbine noise has significant infra and low-frequency sound, and as the WHO cautions, we cannot assume that a 15-dBA loss through the walls of a home is protective for people in that situation. This is especially true when the outdoor noise has significant infra and low-frequency energy as is the case for wind turbine noise.

During the night, sound levels in the bedroom are often well under 20 dBA, especially for people who sleep with windows open during warm-season nights. In this case, there is seldom any sound from household heating or ventilation systems to increase bedroom sounds above this level. Thus, for the 10% or more of the most sensitive members of the population, sleeping in the bedroom with the windows open and with a turbine located at a distance of 1,000 feet, the sound of the wind turbine is the dominant noise heard in their bedrooms.

The argument that there is a 15-dBA loss from the outside to the inside is a spatial average over the interior of the room. For those people who locate their beds near the windows, the sound level inside the window may only be a few decibels lower than it is outside. The 15 dBA attenuation used by the wind industry does not apply to wind turbine sounds associated with a home. Wind turbine noise at 45-dBA Leq outside a home will not provide the necessary quiet inside a home to protect against sleep disturbance. Current research supports the initial concerns identified in the NASA research.

During nights when amplitude modulation from blade swish is excessive, the rhythmic pulsations at a rate of about one per second are the cause of sleep disturbance. For those who are not experienced wind turbine blade swish, this condition is not dissimilar from sleeping in a bedroom with a nearby dripping water faucet. It is not that the water faucet is loud; it is that the repetitive drip, drip triggers arousals or awakenings that interfere with normal sleep patterns needed to reach Stage 4 sleep. However, people faced with a dripping water faucet can have it repaired and thus eliminate the sleep disturbance. People faced with wind turbines and blade swish have no such option.

**NASA Also Identified and Investigated Important Low Frequency Effects that are not Cured by Modern Upstream Rotors**

(1) Atmospheric Wind Gradients lead to Low Frequency Impulsive Noise, even from Modern Upwind Designs [1] (1989)

(2) The Threshold of Hearing can be up to 10 Times more Sensitive to the Dominant Components of Low-Frequency Impulsive Noise [2] (1982)

(3) The Threshold of Detection was found to be lower in level (7-10dB) for Coherent Phase (Repetitive) rather than for Random Phase Low Frequency Components [3] (1982).

**Some Parties Dismiss this NASA Research as Out-of-Date, 1980's, and No Longer Relevant**

**The Author believes it is Incorrect to do so – It is Directly Relevant**

**The properties of the winds, and the characteristics of human hearing, have not changed.**

[1] Low Frequency Acoustic Emissions from Large Horizontal Wind Turbines, H.H.Hubbard & K.P.Shepherd* Inter-Noise 89, 4-6 December 1989
[2] Acoustical Criteria Applicable to Large Wind Turbine Generators K.P.Shepherd* & D.G.Stevens Inter-Noise 82, 17-19 May 1982
[3] Guide to the Evaluation of Human Exposure to Noise from Large Wind Turbines D.G.Stephens, K.P.Shepherd, H.H.Hubbard,,F.W.Grosveld NASA Technical Memorandum 83288 March 1982/

**Figure 7.** NASA and low-frequency effects
*Note.* Reproduced with kind permission from Swinbanks (2010)

## Final Observations on NASA Research

At this point, it would be appropriate to consider another one of the observations Swinbanks (2010) made in his Birmingham, United Kingdom, presentation. Figure 7, a slide from Swinbanks's presentation is reproduced.

In Figure 7, Swinbanks (2010) refers to the Hubbard and Shepherd studies conducted for NASA where they reported the following:

1. Atmospheric wind gradients lead to low-frequency impulsive noise, even from modern upwind designs (1989).
2. The threshold of hearing can be up to 10 times more sensitive to the dominant components of low-frequency impulsive noise (1982).
3. The threshold of detection was found to be lower in level (7-10 dB) for coherent phase (repetitive) rather than for random phase low-frequency components (1982).

Each of these points has been known since the time of the report in the 1990s. Each point could and should have been incorporated into how we currently make decisions about siting wind turbines. Unfortunately, they have simply been ignored.

In Figure 8, Swinbanks (2010) elaborates,

> Some Parties dismiss this NASA Research as Out-of-Date, 1980s, and No Longer Relevant. The Author believes it is Incorrect to do so–It is Directly Relevant. The properties of the winds, and the characteristics of human hearing, have not changed.

This statement goes to the heart of some of the defenses raised by other experts regarding the findings of the NASA studies.

## Annoyance

Studies conducted from the year 2000 to the present consistently demonstrate that the particular characteristics of the sound of wind turbines results in annoyance at sound levels roughly 10 dB lower than the sound of other common community noise sources such as aircraft-, rail-, and vehicle-related community noise. Figure 8 shows the results of one such study (Pedersen, van den Berg, Bakker, & Bouma, 2009, p. 541).

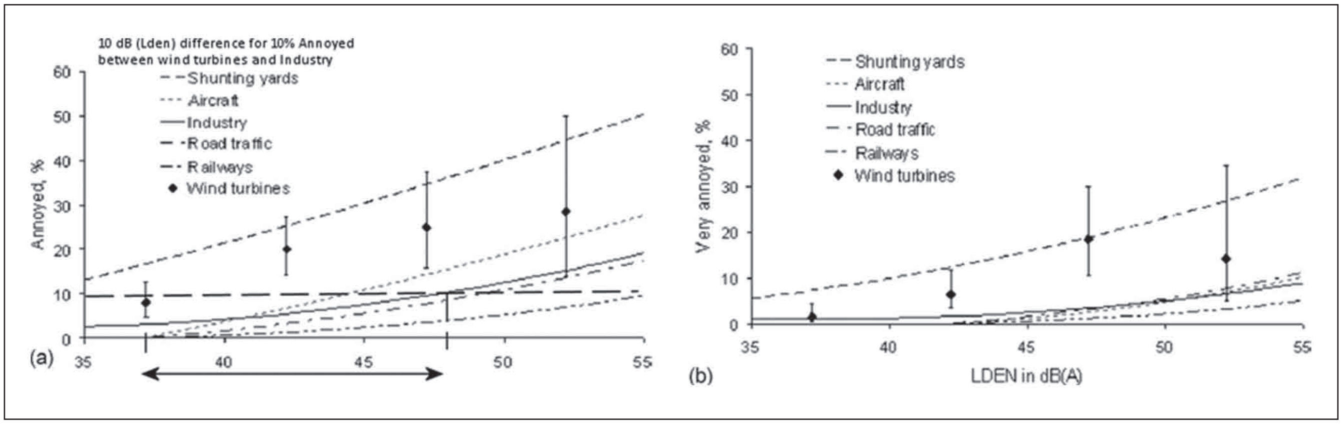



**Figure 8.** Noise exposure for aircraft, road traffic, and rail
*Note.* Reprinted with kind permission from Pedersen, van den Berg, Bakker, and Bouma (2009). Copyright: Acoustical Society of America.

In Figure 8, the relationship of annoyance and sound level for wind turbines is shifted roughly 10 dB lower than the annoyance for other common community noise sources. Studies continuing through to the present continue to confirm this finding. Yet the current position of wind industry trade associations and developers is that wind turbine noise has no characteristics that require special treatment or concern.

It is interesting to note that in many communities hosting wind turbines, background sound levels during the day are often between 30 and 40 dBA. At night, background sound levels are 10 to 15 dB lower. The trace representing wind turbine annoyance implies that annoyance starts at levels commonly experienced by people in rural communities during the daytime. Does this mean that there is something uniquely disturbing or annoying about wind turbine sounds? Based on anecdotal reports and studies of the type used to produce the curves relating annoyance to sound level, it appears that the answer may be "yes."

## A More Detailed View of Wind Turbine Infra and Low-Frequency Sound

Although NASA and other researchers anticipated that the new industrial scale wind turbines would have the highest acoustic energy in the infrasonic range and other researchers have reported that wind turbine infrasound is in the range of 70 to 80 dBG, there are instrumentation and analysis limitations that have prevented high resolution views of the infrasonic range that could show details of the short duration events (those that are as short as 10 milliseconds in duration) that constitute wind turbine infrasound.

Figure 9 is a spectrogram demonstrating that new technology can reveal a detailed view of the infrasonic emissions.

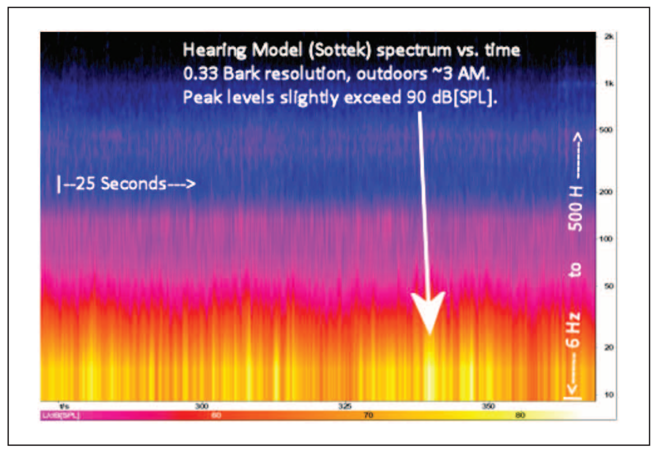



**Figure 9.** A spectrogram of infrasonic emissions
*Note.* Reproduced with kind permission from Wade Bray, Head Acoustics.

This spectrogram shows the sound of a 1.5 MW GE wind turbine measured at a distance of about 1,350 feet. The frequency range is shown along the left vertical axis as being from below 5 Hz to 45 Hz. The time scale is in units of seconds along the horizontal axis. The color shows the SPL, with yellow representing SPLs of 60 to under 70 dB and white implying levels over 70 dB. The vertical striations show the bursts of infrasound that are occurring at a rate of many times per second but lasting only a few milliseconds each.

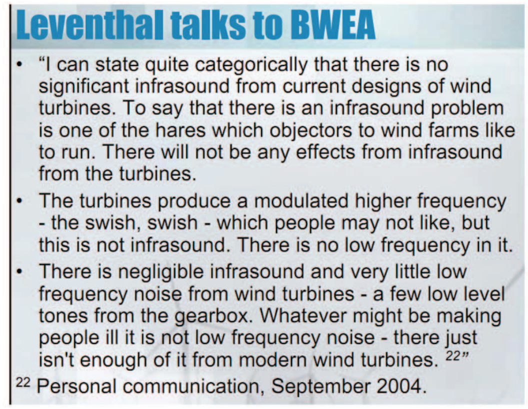
These data were collected and analyzed at the author's request by Mr. Wade Bray, Head Acoustics. The analysis was done using Head Acoustics' proprietary analysis software, ArtemiS, which provides an analysis mode that is based on the hearing model developed by Head Acoustics. This analysis mode, which uses a highly overlapped set of critical-bandwidth filters to model the time response of human hearing at all frequencies, was used to produce the spectrogram of wind turbine sound. The horizontal axis is time with each major division being 25 seconds. The vertical axis is frequency, starting at just under 10 Hz at the bottom and reaching 2,000 Hz at the top. SPL is indicated by color, with blue and black representing levels below 35 dB (Linear), purple 35 to 55 dB, red and orange 55 to 75 dB, yellow 75 to 85 dB, and white 85 dB and higher.

This spectrogram shows rapid, deep, modulation of infrasound in the frequency range from below 10 Hz that continues up to 20 to 30 Hz. The conditions that cause infrasound to increase are generally attributed to inflow turbulence. The energy at frequencies near the blade passage frequency (approximately 1 Hz for this example) pulsates in rapid short bursts lasting only a few milliseconds. This is seen as the striations of white-yellow to orange-red representing the peaks and valleys of the pulsations. With red representing approximately 55 dB SPL and white representing 85 dB SPL and higher, the pulsations have a range of about 30 dB with durations as short as 10 milliseconds. Although not shown in Figure 9, peaks of 90 dB and greater were observed. These are not data representing operation during an extreme weather condition. The turbine closest to the test site distinct from the others and the sound level was in the range of 35 dBA during much of the data collection period. This is not a worst case for this turbine and test site. It has been measured at levels over 45 dBA Leq during other measurement sessions when the atmosphere was disturbed due to an incoming storm front. When one considers that the turbine's dBA level is only 35 dB and the modulated sounds seen in the figure above are at levels of 80 dB and higher, it is reasonable to state that wind turbines do produce significant infrasound. As shown in the spectrogram, SPLs are less than 25 dB linear in the frequencies above 1,000 Hz. Wind turbines are primarily producing infra and low-frequency sound.

Information of this type shows that modern upwind industrial-scale wind turbines can produce significant levels of infrasound and that the sounds produced are a complex mix of tones with rapid modulation patterns. These sounds will likely be more easily perceived than steady pure tones in a laboratory. The potential for dynamically modulated infra and low-frequency sounds to cause AHEs has been known for other types of noise sources. There is sufficient infrasound and very low–frequency noise produced by modern wind turbines to warrant caution when locating turbines in communities proximate to residential properties based on the potential for AHEs.

## What Was the Wind Industry's Position on Noise and Health in 2004

Discussion of wind turbine utilities being located in rural communities, including those located in states east of the Mississippi, began in the early part of the past decade. The position of the wind energy industry at that time with respect to noise and health often referenced statements made by Dr. G. H. Leventhall. Others have also acted to support the wind industry's practice of locating wind turbines in quiet rural areas near residential properties. However, Leventhall is probably the most recognized and is one of the most senior acoustical experts to have expressed opinions about wind turbine sound and the potential for it to cause AHEs. Therefore, it is reasonable to review his position on wind turbine noise.


Leventhal talks to BWEA

- "I can state quite categorically that there is no significant infrasound from current designs of wind turbines. To say that there is an infrasound problem is one of the hares which objectors to wind farms like to run. There will not be any effects from infrasound from the turbines.
- The turbines produce a modulated higher frequency - the swish, swish - which people may not like, but this is not infrasound. There is no low frequency in it.
- There is negligible infrasound and very little low frequency noise from wind turbines - a few low level tones from the gearbox. Whatever might be making people ill it is not low frequency noise - there just isn't enough of it from modern wind turbines. [22]"

[22] Personal communication, September 2004.

**Figure 10.** Leventhall talks to British Wind Energy Association
*Note.* From the British Wind Energy Association website (circa 2010; http://bwea.com/)

Figure 10 summarizes several statements attributed to him and published in trade industry publications and handouts such as British Wind Energy Association. The author notes that British Wind Energy Association now calls itself Renewable UK.

The first statement "categorically" denies that wind turbines could produce infrasound that might cause AHEs.

Dr. Leventhall is confident that there will be no effects: "There will not be any effects from infrasound from the turbines."

In addition, he addresses blade swish and states that it is not infrasound. The author does not disagree with this statement. However, blade swish as it relates to infrasound is only a small piece of the issue regarding AHEs. Infrasound and other factors as described in this article can have significant negative effects on the health of those near wind facilities. It is uncertain whether this statement only intended to focus on infrasound in the context of blade swish. If this is so, then it may de-emphasize other legitimate concerns about infrasound. Based on past and current research, it is evident there is a need for better quality studies about infrasound and AHEs.

## What Is the Current Position of the American Wind Energy Association?

Figure 11 is an excerpt of the section relating to health effects of wind turbines.

**Wind Energy, Sound, and Science**
In 2009, the American Wind Energy Association (AWEA) and the Canadian Wind Energy Association (CanWEA) established a multidisciplinary scientific advisory panel comprising medical doctors, audiologists, and acoustical professionals to review current literature available on the perceived health effects of wind turbines. The panel, whose findings were published at the end of 2009, concluded that wind turbine sounds are not unique. Based on the levels and frequencies of the sounds, the panel found no reason to believe that turbines could plausibly have direct adverse physiological effects. An executive summary of the report is at http://www.awea.org/newsroom/releases/AWEA_CanWEA_SoundWhitePaper_ExecSumm.pdf.

**Figure 11.** Wind energy, sound, and science

## Conclusion

A review of the work of acoustical experts such as Swinbanks, Ebbing, Blazier, Hubbard, and Shepherd and others mentioned in this article shows that these problems were reported at professional conferences and in research papers.

There is sufficient research and history to link the sensitivity of some people to inaudible amplitude-modulated infra and low-frequency noise to the type of symptoms described by those living near industrial wind turbines.

This information should have served as a warning sign.

Experts, some well known in the field of acoustics, have defended the wind industry position through white papers, reports, and testimony in hearings, and through committees that are establishing guidelines for siting industrial-scale wind turbines.

The acoustics profession and individual acousticians should have recognized the early reports of symptoms by people living near wind turbines as a new example of an old problem. Instead of advocating caution in locating wind turbines near people, the rush for renewable energy took precedence. The position or belief that there was little or no possibility inaudible infrasound and very low–frequency noise could be causing the reported problems has delayed further research and the safe implementation of industrial wind turbines.

It is the author's opinion that had past experience and information, which was available prior to the widespread implementation of the modern upwind industrial-scale wind turbine, been incorporated into the government and industry guidelines and regulations used to siting wind turbine utilities, many of the complaints and AHEs currently reported would have been avoided.

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### Notes

1. Dr. Philip Dickinson noted during personal communications that the term *sick building syndrome* was coined by Dr William (Bill) Allen (ex-CEO Building Research Station, United Kingdom) and members of the Institute of Sound and Vibration Research when investigating such low-frequency noise problems in universities and schools in 1970/1971.
2. Letter to G. Leventhall regarding the presence of beat frequencies from HVAC systems noting that up to 58% of them may have modulated infrasound in the frequency range below 10Hz. This was offered as an explanation for why it was necessary to modulate the low-frequency spectrum used in the ASHRAE research to get "natural sounding" HVAC noise.
3. Conversion by G. Kamperman. It should also be noted that where the dark blue line representing the mean sound power level extends beyond the edges of the upper and lower confidence limits, the extension was based on data from a few additional turbines discussed in another DELTA report. For this graph, the additional data were incorporated to extend the mean level down to 10 Hz 1/3-octave band. The confidence limits were not recalculated for the entire data set, so the traces of confidence limits only cover the range of the initial 37 turbines.

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