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LOW FREQUENCY NOISE AND INFRASOUND ASSOCIATED WITH WIND TURBINE GENERATOR SYSTEMS A LITERATURE REVIEW

Ontario Ministry of the Environment RFP No. OSS-078696

Ontario Ministry of the Environment
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EXECUTIVE SUMMARY

Howe Gastmeier Chapnik Limited (HGC Engineering) was retained by the Ontario Ministry of the Environment (MOE) to provide a literature review of materials related to low frequency noise and infrasound associated with large, modern, upwind wind turbine generators. Materials including journal articles, papers presented at technical conferences, technical reports, as well as guidelines or regulations from various jurisdictions were reviewed.

Modern wind turbines produce broadband noise. In relation to human perception of the sound, the dominant frequency range is not in the low frequency or infrasonic ranges. Nonetheless, in the low frequency range, it should be expected that low frequency sound due to aerodynamic sources will routinely be an audible component of the acoustic impact. In instances where audible acoustic tones are present, these tones are typically in the low frequency range.

In the infrasonic range, at frequencies less than about 20 Hz, there is strong evidence that the sound pressure levels produced by modern upwind turbines will be well below the average threshold of human hearing at the setback distances typical in Ontario. Although some authors have concerns, most literature dealing with the subject indicates that infrasonic noise below the threshold of hearing will have no effect on health. As such, infrasound from wind turbines is not normally expected to be heard by humans or pose an issue for human health.

In the audible range, including the low frequency range, publications by medical professionals indicate that, at the typical setback distances, the overall magnitude of the sound pressure levels produced by wind turbine generators does not represent a direct health risk. The audible sound from wind turbines is nonetheless expected to result in a non-trivial percentage of persons being highly annoyed. As with sounds from many sources, research has shown that annoyance associated with sound from wind turbines can be expected to contribute to stress related health impacts in some persons.

The review of related assessment standards used in different jurisdictions shows that some countries have developed guidelines which generically address low frequency noise and infrasound. At this time, it is not common for international wind turbine noise assessment standards to have specific requirements for the consideration of infrasound or low frequency noise, with the exception that many standards explicitly consider and penalize tones, which when present tend to be in the low frequency range.

Because associated fields of study are relatively new, and research is ongoing, it is recommended that the MOE continue to monitor technical developments in this area and keep abreast of regulatory policies that may be introduced in other jurisdictions.

Complaints of low frequency noise described in the literature are commonly related to indoor noise. The measurement of indoor low frequency noise is complicated by a number of factors. Internationally, sophisticated measurement and assessment guidelines have been developed to address these problems in recent years. Since it is evident that complaints related to low frequency noise from wind turbines often arise from the characteristics of the sound impact indoors, and since the indoor low frequency sound levels and frequency spectra can differ markedly from those outdoors, it is recommended that the MOE consider developing or adopting a protocol to provide guidance for addressing indoor complaints. Given the large variation in indoor sound impact resulting as a function of room layout and sound transmission characteristics, this protocol cannot replace the current compliance guidelines designed to assess sound outdoor.

As infrasound from wind turbines is not normally expected to be heard by humans or pose an issue for human health, routine measurement of infrasonic sound pressure levels from operating wind farms is not warranted. Nonetheless, to allow the effective investigation of complaints and public concerns, it is recommended that the MOE consider adopting or endorsing a proven measurement procedure that could be used to quantify noise at infrasonic frequencies.

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1.0 INTRODUCTION AND BACKGROUND

Howe Gastmeier Chapnik Limited (HGC Engineering) was retained by the Ontario Ministry of the Environment (MOE) to conduct a review of research and other information pertinent to an understanding of what is known about low frequency noise and infrasound associated with modern wind turbine generator systems.

The work is divided into two main sections: a technical review, and a jurisdictional review. The technical review is intended to "collect, review and evaluate published scientific literature and reports from the past 10 years on … aspects of low frequency noise emissions from wind turbines to be used to build on the research previously undertaken by the Ministry and to enhance the Ministry's knowledge on the subject". The jurisdictional review is intended to "collect, review and evaluate information on approaches in other jurisdictions regarding requirements/limits for low frequency noise".

The International Electrotechnical Commission (IEC) defines infrasound as acoustic oscillations (sound) with frequencies below the low frequency limit of audible sound. This highlights the important concept that infrasound is sound at very low frequency, but may also strengthen a common misapprehension is that infrasound is always inaudible. Infrasound is in fact audible at sufficiently high amplitudes. Another common misunderstanding is that infrasound is in some radical or fundamental way different from sound at higher frequencies. According to Leventhall (2009), there is no evidence for a change in the way sound is perceived between infrasound and low frequency sound at some particular frequency boundary, and thus the distinction may have little practical value.

Nonetheless, this document refers to infrasound and low frequency sound when addressing sound in various frequency ranges. While "there is a very fuzzy boundary between infrasound and low frequency noise, which often causes confusion" (Leventhall, 2006), the common practice is to assign an upper limit of about 16 or 20 Hz. For simplicity, this document uses a 20 Hz upper cutoff for the infrasonic frequency range.

The upper and lower frequency limits of low frequency sound are certainly not universally acknowledged, and generally vary with context. In this document, the term low frequency sound is applied to sound in the frequency range from roughly 20 to 250 Hz.

2.0 SUMMARY

2.1 TECHNICAL REVIEW SUMMARY

This document deals with low frequency noise and infrasound from modern conventional industrial turbines. More specifically, the noise associated with large, upwind, horizontal axis designs, which typically have nameplate capacities of 1.0 MW or greater.

This review deals with a wide variety of topics related to low frequency noise and infrasound, including the mechanisms of generation of wind turbine noise, spectral content, propagation, methods of quantification, assessment methods and rating schemes, infrasound and low frequency noise associated with sound sources other than wind turbines, etc. For the most part, the review is based chiefly on literature published in peer reviewed journals, such as the *Journal of Sound and Vibration* and the Journal *of Low Frequency Noise, Vibration and Active Control*, and on information presented at their associated conferences. Where technical reports by consultancies, engineers, or other corporations or agencies appear to be widely circulated in some areas, and provide helpful insight into the concerns and practices of parts of the world, some discussion is given to these types of materials also.

However, an effective understanding of these issues requires familiarity with issues and concerns related to annoyance and potentially of human health associated with low frequency noise and infrasound, and HGC Engineering has been asked by the Ministry of Environment to ensure that the conclusions and recommendations contained in this document are informed by publications which touch on such matters. To the extent that health related subjects are discussed in this document, the review is for the most part restricted to existing summaries of published literature which have been undertaken by medically trained individuals, and intended for a more popular audience.

It should be noted that for a meaningful review of infrasound and low frequency noise issues related to wind turbines, some background drawn from scholarship dealing more broadly with infrasound and low frequency noise in general is certainly required. For example, scholarship dealing with the thresholds of perception in the infrasonic and low frequency range do not generally relate exclusively to any one particular source of sound. Also, an understanding of the significance of the level of infrasonic and low frequency noise produced by wind turbines requires an understanding of the level of noise produced by other sound sources. Thus, this review encompasses materials which do not specifically deal with wind turbine noise.

This document is not intended to serve as a primer in acoustics, and some familiarity with the basic concepts involved, such as sound pressure, the decibel, statistical sound level descriptors (L_n), oscillation frequency, frequency bands, narrowband spectra, and spectral weighting metrics is assumed.

For the most part, the sound of wind turbines is broadband in nature. Research indicates that the dominant broadband source of wind turbine noise heard at the ground is related to turbulence at the trailing edge of the turbine blades. For conventional modern turbines, literature and the experience of HGC Engineering indicates that the sound is still generally broadband in the low frequency range, but that some models can produce mechanical tones in this frequency range, at least under some conditions. Wind turbine manufacturers generally provide a statement showing the degree of tonality present in specific wind turbine models, but experience indicates that, at times, tones can be more prominent than the published data may indicate for some models. Strong infrasonic tones were present in some older downwind designs, but the phenomenon does not appear to be a concern with current upwind models.

Propagation of low frequency and infrasonic sound is not fundamentally different from the propagation of audio range sound. However, ground, air, and barrier attenuation effects are reduced, and are less sensitive to atmospheric conditions. The acoustic transmission loss of residential construction materials are often negligible at infrasonic frequencies.

An earlier draft of this report was issued for discussion and two consultation sessions were held on August 12, 2010. From a broader perspective, some individuals are of the opinion that wind turbines are a direct cause of serious health effects irrespective of whether the sound is audible or not. Herein, consideration has been limited to those submissions offering technical references specific to low frequency sound and infrasound.

Low frequency noise, and infrasound at amplitudes sufficient to allow perception by humans, can cause annoyance. Relatively modest levels of low frequency noise can cause annoyance in some individuals. Noise annoyance is a potential stressor, and in some individuals may contribute to stress-related health effects.

The 45 dBA broadband, overall criterion recommended by Health Canada is explicitly associated with a percentage of persons being highly annoyed, and use of criteria on this order should therefore be expected to result in some persons impacted by wind turbine noise being highly annoyed.

In general, the material reviewed by HGC Engineering, including a 2010 report by Ontario's Chief Medical Officer of Health, indicates that there are no direct health impacts of low frequency or infrasonic noise from wind turbines.

In dealing with complaints of excessive infrasonic noise from any source, it is important to realize that the range between 'just perceptible' and 'annoying' is very small for infrasonic noise, and it is typically recommended that for levels to be considered acceptable they should not exceed the threshold of hearing.

The thresholds of hearing described in the literature are relatively close to one another, but there is variability between papers, and there is also variability between the thresholds of different individuals. A degree of caution is required when comparing measured infrasonic noises to the threshold values for sound pressure levels which approach the threshold, and a margin of safety is appropriate.

For the most part, the literature indicates that infrasonic noise at levels which cannot be heard has no demonstrated adverse health effects will have no effect on the body, although the possibility of low amplitude effects has been suggested by some authors.

The literature indicates that modern upwind turbines generate noise at infrasonic frequencies, but that the level of this noise should be sufficiently far below the threshold values to be of no concern in the ordinary course of events.

Nonetheless, it is conceivable that some atmospheric conditions, or that some future designs of wind turbines, could result in audible levels of infrasound being produced at times.

Technically valid measurements of infrasound, particularly outdoors, are more difficult than other types of acoustic measurements. Similarly, repeatable and accurate quantification of indoor low frequency noise requires particular care.

Little information was found dealing with technologies currently under development to reduce low frequency noise. This may be due to the competitive advantage of such technology, or it may be due to the fact that it is not clear that low frequency or infrasonic noise is a particular problem for existing designs, compared to concerns relating to the overall broadband noise. Presumably, where low frequency tones are due to mechanical sources such as gearbox noise, any technology or mechanical design which either reduces the noise generated by these sources, or improves the isolation of the sources from the nacelle, blades, and tower will reduce low frequency noise emissions.

2.2 JURISDICTIONAL REVIEW SUMMARY

The existence of national guides or standards which specifically govern the prediction and measurement of wind turbine does not appear to be the norm at present. Where such guides exist, specific low frequency or infrasound guidance is generally not provided. However, some guides, such as the 2010 New Zealand standard do penalize wind turbine noise where mechanical tones exist (which, when present, are typically in the low frequency range).

Several national guides were found which provide a standardized method for dealing with low frequency noise complaints, for general application. While such guides could be applied to wind turbine noise, they generally do not relate specifically to wind turbines.

In addition, a number of technical reports recommending regulation or guidelines for application in a particular jurisdiction were found. In some cases these were expressly commissioned by governmental agencies, but it is not always clear what the status of the recommendations is.

In summary, there is no clear international indication at this time that low frequency noise or infrasound from wind turbines requires specific regulation or consideration, and there is no clear consensus as to the correct way to perform of such consideration.

3.0 TECHNICAL REVIEW

The original request from the Ministry of Environment made reference to eight separate areas of inquiry. These categories have largely been retained in this document, although they have been reordered, and some degree of recombination of subject matter has occurred similarities and a significant degree of overlap between the subjects make this appropriate.

3.1 GENERATION OF LOW FREQUENCY NOISE AND INFRASOUND FROM WIND TURBINES

Hau (2006) indicated that the total range of noise emitted by a wind turbine is made up aerodynamically generated noises and mechanically generated noises. Hau suggested that, in general the noise associated with mechanical sounds tends to be a greater factor in the case of small wind turbines, which are not the principal subject of this review. As Hau indicates, there are many different phenomena involved with the aerodynamically generated sounds. These include phenomena associated with the turbulent boundary layer, vortices at the blades' training edge, and aerodynamically induced loading fluctuations.

One of the most sophisticated studies investigating the dominant sources of the noise heard at the ground near large turbines involved acoustic measurements using an array of 148 ground-based microphones. This work is described in Oerlemans and Méndez López (2005) and in Oerlemans et al. (2007). The authors concluded that wind turbine noise heard at the ground is strongly dominated by broadband sound produced by the trailing edge of each blade during downward rotation. Other sources of noise such as produced during upward rotation, at the rotor hub "probably due to the gearbox" (Oerlemans et al., 2007), or at the blade tips was found to be less significant. Oerlemans and Schepers (2007) verified these conclusions with measurements on a different type of modern wind turbine, and through analytical prediction.

Predictions of aerodynamic noise associated with different trailing edge shapes for wind turbine blades were presented in Suetsuna et al. (2008).

Older models of wind turbine generator (especially downwind rotor, horizontal axis machines) are known to have produced significant noise at infrasonic and low frequencies. Papers which deal with these earlier designs, such as Shepherd and Hubbard (1991) illustrate these problems. The chief mechanism of generation of the low frequency noise for downwind system appears to have been blades passing through the aerodynamic wake of the tower. This phenomenon and other sources of low frequency noise of the older systems are described in Hubbard and Shepherd (1991). None of the turbines examined by that paper were three-bladed upwind models. Nonetheless, the data presented suggests that upwind models (two bladed upwind models were examined) produced lower levels of low frequency noise than the downwind models.

Another sophisticated study of the sources noise from large upwind wind turbines, and in particular the sources of low frequency noise are described in Madsen (2008a). This report described computational simulation of the generation of noise, and highlights turbulence in the inflow as a significant factor. This fact is also discussed in a technical report by DELTA (2010). The simulations also illustrate that the distance between the tower and blades plays an important role in the low frequency range, with greater clearances resulting in lower sound levels.

Madsen (2008b) presented the results of analytical modeling of various wind turbine designs, and provided additional discussion related to the distance from the rotor to the tower. The presentation showed that this distance is an important parameter for low frequency noise, both for upwind and downwind designs, with greater distances leading to lower low frequency noise levels. In what is presumably a fairly academic exercise, Madsen shows that in the frequency range of 20 to 50 Hz, upwind designs would be 20 dB quieter than downwind designs for a 2 metre rotor to tower distance, and more than 30 dB quieter when this distance increases to more than 2 metres.

The presence of low frequency tones due to mechanical gearbox sounds is described in Søndergaard (2008), and the possibility of low frequency tones is mentioned in other materials (DELTA, 2008).

3.2 PROPAGATION OF LOW FREQUENCY NOISE AND INFRASOUND FROM WIND TURBINES

Shepherd and Hubbard (1991) summarized two older papers dealing with low frequency noise propagation which may be of relevance here. One of these, Zorumski and Willshire (1989) compared the results of predictive modeling of noise at infrasonic frequencies to measurements made at distances of 0.35 to 20 km from a downwind turbine, and concluded that "both theory and experiment indicate a cylindrical spreading characteristic", i.e., 3 dB per doubling of distance, at least in some conditions. This phenomenon is also described in Jakobsen (2005). Jakobsen indicated that such variation in geometric attenuation is not unique to low frequencies, but are due to atmospheric phenomena such as inversions.

Jakobsen (2005) also described how changes in spectral content which typically occur over large propagation distances do not generally affect low frequency noise to the same extent, for several reasons: First, ground conditions are generally irrelevant at low frequencies (the ground generally behaves as an acoustically hard surface). Second, barrier effects are reduced or irrelevant due to the fact that the change in wavelength resulting from an obstruction is generally quite small at the long wavelengths involved. Third, air absorption is slight at low frequencies, and thus changes in temperature and humidity have little effect on air absorption.

A number of papers have been prepared which show the poor transmission loss of structures in the very low frequency or infrasonic range. Shindo et al. (2008) reported on a Japanese working group looking into "environmental vibration", and showed the very low transmission loss which can be expected for low frequency noise for different house constructions. A chart in Shindo et al. which is based on measurements does indeed show transmission loss values at and near zero in the infrasound range. Leventhall (2003) summarized the problem thus: "Infrasound is difficult to stop or absorb. Attenuation by an enclosure requires extremely heavy walls, whilst absorption requires a thickness of absorbing material up to about a quarter wavelength thick, which could be several metres". Jakobsen (2005) discusses papers which deal with indoor noise from outdoor sources of infrasound, and concludes that "assuming an outdoor-to-indoor correction in the infrasound region of 0 dB thus would appear to be on the safe side".

DELTA (2010) describes work undertaken to produce a noise reduction spectrum representing "outdoor to indoor level difference expected to be exceeded by 80-90% of typical Danish dwellings", a function that allows calculation of indoor sound levels due to wind turbine operation. Data is presented for the frequency range between 10 and 200 Hz.

At very low frequencies, it is also possible that Helmholtz resonances could occur in rooms with open windows, possibly leading to sound pressure levels which are higher indoors at times than outside (Hubbard and Shepherd, 1991).

At low frequencies, standing waves can result in significant local variations in rooms (Pedersen et al., 2007). To deal with this potential issue, Denmark and Sweden have both adopted indoor measurement techniques which use an average between three different locations in a room (Pedersen et al., 2007; Jakobsen, 2003). Both methods require that one of the three locations be chosen in a corner of the room, since above-average sound levels are assumed to be present in corners (Pedersen et al., 2007). However, Pedersen et al. found potential weaknesses in both methods, related to the way in which the corners are specified. In response to this, a new method was proposed, consisting of the logarithmic average four measurements made very close (≤0.1m) to room surfaces at three-dimensional room corners. The paper suggests that such a measurement would be reasonably close to a value representing a level exceeded in only 10% of the room.

Minnesota Department of Health (2009) notes that "Low frequency noise is primarily a problem that may affect some people in their homes, especially at night". The report also notes that it is not generally a problem for people outdoors.

3.3 LOW FREQUENCY AND INFRASONIC THRESHOLD OF HEARING

One of the principal questions related to environmental infrasound, and levels which can be considered acceptable, is the question of perceptibility.

Watanabe and Møller (1991) is a frequently cited paper dealing with the threshold of hearing of noise in the very low frequency range. The paper describes the results of listening tests in a controlled environment to obtain new data describing the threshold of hearing. Twelve subjects were included in the test. The presented threshold values range from about 107 dB at 4 Hz, to 79 dB at 20 Hz, and 60 dB at 31.5 Hz, and are summarized in Figure 1. The paper also presents a comparison between the new data and five previous studies. The data in all but one of the previous studies were in general higher than the new data, although one was “3-5 dB lower at all frequencies”.

Another threshold curve was provided by Møller and Andresen (1984), based on a weighted mean of four earlier studies. An estimate of these values is also shown in Figure 1.

Watanabe (2008) presented research into the masking of sounds in the low frequency and infrasonic range. As part of that research, the hearing threshold for three groups of subjects was measured. These are also presented in Figure 1.

Yeowart and Evans (1974) produced thresholds of hearing based on binaural headphone tests on a number of subjects, and on chamber (whole body) tests. Both threshold values are reproduced in Figure 1.

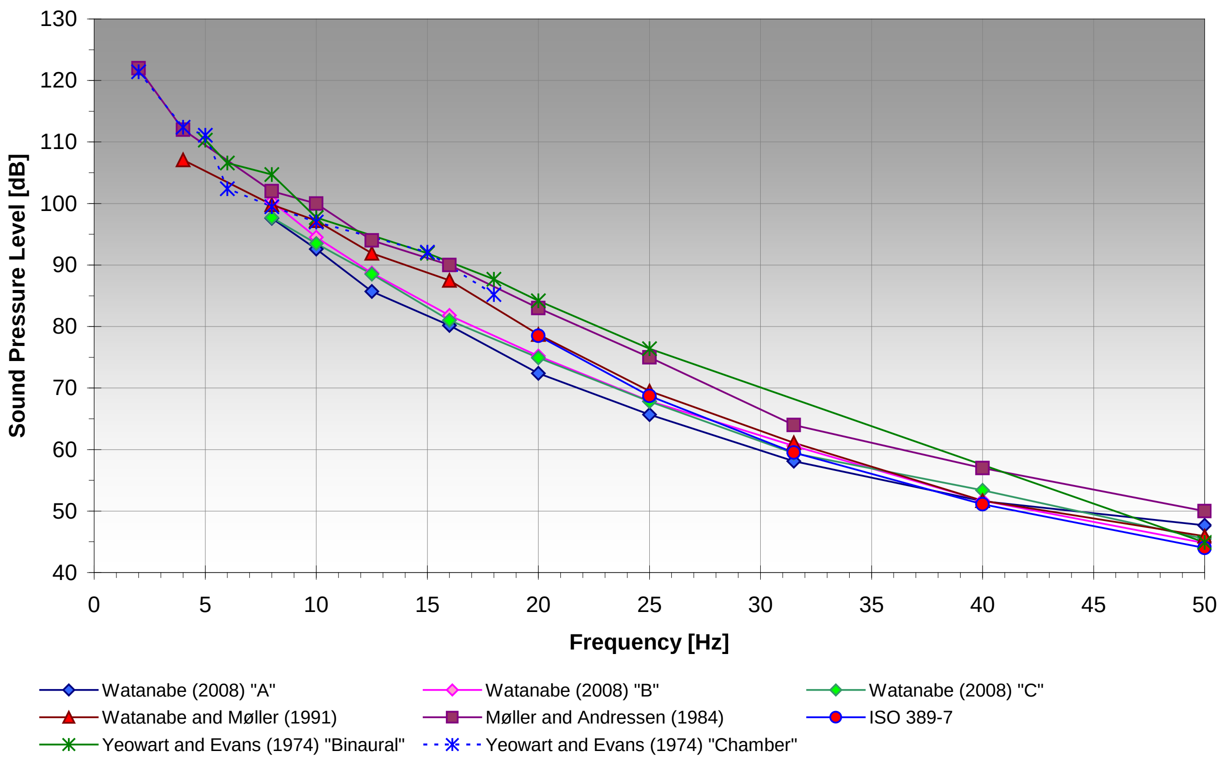
In the low frequency range, ISO standards 226:2003 and 389-7:2005 both describe a reference threshold of hearing which is based on a variety of other studies. 1/3 octave band levels for this threshold are specified in ISO 389-7:2005, and these are shown in Figure 1.

Kurakata et al. (2008) present a comparison of hearing threshold data for young people (around 20 years) and older people (over 60). The research found only slight (less than 10 dB) of degradation in the threshold of the older people, and also found only a weak correlation between the existence of hearing impairments at higher frequencies, and the degradation of low frequency thresholds. The low frequency data was based on tests involving tones at 10, 20, 40, 80, and 160 Hz.

Standard deviations of a selection of published threshold values were determined and presented in Kurakata and Mizunami (2008). The standard deviations for the threshold values at low frequencies are fairly high, on the order to 5 or 6 dB.

Vercammen (1992 and 1989) presented curves based on available threshold data and standard deviations, which represent threshold values which will be exceeded by 90 to 95% of the population. The threshold corresponds to a G-weighted sound level of 86 dBG.

Figure 1: Threshold of Hearing Data from Various Papers



As Figure 1 illustrates, there is generally fairly good agreement between the various studies which seek to establish a threshold of hearing for infrasonic and low frequency sound. However, the literature acknowledges that there are differences between individual sensitivities. Given the high standard deviations, it should be expected that, at a 95% confidence interval, some individuals could be more sensitive than the average by 10 dB or more.

3.4 COMPLICATING FACTORS AFFECTING THE THRESHOLD OF HEARING

It is understood that where considerable effort is put into hearing a barely perceptible sound, the brain can become unusually adept at detecting it: "If sufferers spend a great deal of time listening to, and listening for, their particular noise, it is possible that they may develop enhanced susceptibility to this noise" (Leventhall, 2003).

Frost (1987) indicated that threshold curve at low frequencies for any given individual is not necessarily smooth. Further, this leads to an "extremely diverse" range of individual responses to low frequency noise. The measurements of the individual spectral responses were made using pure tones. Frost does not indicate if, for more broadband noise, the individual variation would be expected to be as significant.

A different complication is suggested by Ryu et al (2008), which indicates that where sounds consisting of various tones at different frequencies in the low frequency range of 25-145 Hz are heard together, sound can be detected even when the amplitudes of the various tones are all somewhat below their hearing thresholds. Similar findings of other studies are described in Møller and Pedersen (2004), and the suggestion is made that there may be spectral peaks in the sound pressure humans detect at low frequencies, but the discussion ends with the statement that "differences [between the perception of sounds with different spectral complexity] seem to be relatively modest, and the pure-tone threshold can, with a reasonable approximation, be used as a guideline for the thresholds also for non-sinusoidal sounds".

This difficulty is further explored in DELTA (2008) and DELTA (2010) where the problem of comparing the same spectrum measured with several different spectral resolutions to a threshold is illustrated. The threshold data proposed by Vercammen (1989) is intended to be used with 1/3 octave spectra.

Schust (2004) provides a summary of several papers which deal with the threshold of hearing at infrasonic and low frequencies. Much of the paper deals with human responses to levels of infrasound and low frequency noise which are above the threshold of hearing. However, Schust highlights a few papers which identified possible effects ("somnolence, irritability, tiredness, tense and restlessness”) which were associated with infrasonic noise at levels below (although close to) a level equivalent to the mean threshold of hearing less one standard deviation. Schust also indicates that different people can experience different effects when exposed to similar sound levels, and recommends that sufficient factors of safety should be used. Both A- and G- weighting are deemed inappropriate by Schust, as predictors of health effects. Schust calls for more research in a number of related areas.

Additional potential concerns about relying too heavily on the threshold of hearing values are discussed in Salt (2010). The paper describes the functioning of various components of the inner ear, and points out that the ear’s outer hair cells are stimulated by sounds below those that are heard “at very low frequencies”. Salt acknowledges that “the fact that some inner ear components (such as the [outer hair cells]) may respond to infrasound at the frequencies and levels generated by wind turbines does not necessarily mean that they will be perceived or disturb function in any way”, but hypothesizes that there is a “possibility that wind turbine noise could be influencing function or causing unfamiliar sensations”. Salt also indicates that there are medical conditions where individuals may become hypersensitive to infrasound. Salt calls for more research.

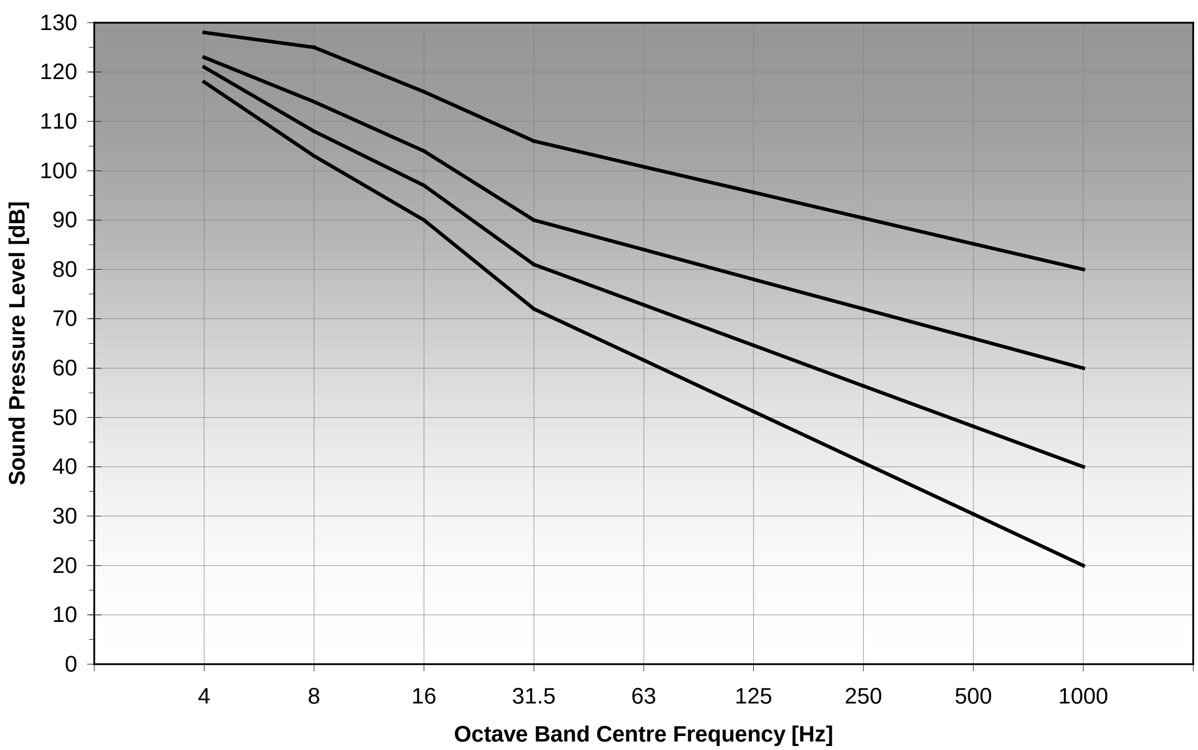
All in all, it is clear that some caution is needed when the judging audibility of sounds which approach the mean thresholds of hearing (Benton, 2007).

3.5 NOISE ANNOYANCE IN THE LOW FREQUENCY AND INFRASONIC RANGE

Noise annoyance is a complex subject. People live continuously in the presence of sound. It is presumably true that everyone would acknowledge that some sounds can be annoying, but it is difficult to articulate why certain sounds cause annoyance where others of similar sound level do not.

To investigate the annoyance associated with various levels of low frequency sound, Andresen and Møller (1984) described the results of listening experiments involving 18 subjects, and a variety of sound stimuli in a controlled environment. The goal of the work was to construct equal annoyance contours which extended in frequency down from the better understood audio range, through the low frequency range, and into the infrasonic range. A number of interesting points emerged. First, the study found that for a low frequency sound to be as annoying as a 1000 Hz sound at 20 dB (linear weighting), the sound level would need to be as high as about 70 dB at 31.5 Hz, and as high as 120 below 4 Hz. This steep rise with decreasing frequency was summarized as a slope of 12 dB per octave. Second, the study found that the equal annoyance contours grew very close together in the infrasonic range, and concluded that at these frequencies "small changes in sound pressure may cause relatively large changes in annoyance". Another interesting point is the suggestion that there was a large difference in how easily subject adapted to the sound exposures. The study cautions against the use of A-weighting when dealing with low frequency sounds. The narrowing of the dynamic range, and the narrowing of the range between just audible and annoying sound in the infrasonic and low frequency range was further explored in Møller (1987). Figure 2 illustrates equal annoyance curves through the low and infrasonic frequency range based on Møller (1987).

Figure 2: Equal Annoyance Contours Based on Møller 1987



While not specific to low frequency sound, there is a great deal of scholarship showing a wide variation in the tolerance of different individuals to noise (Belojevic and Kakovljevic, 2001; Job, 1999; Guski, 1999; Fields 1993). Belojevic and Kakovljevic (2001) claim that "noise level may not be of primary importance for the reactions of people living in noise areas, and individuals may react quite different in the same acoustical conditions". Thus studies such as Andresen and Møller (1984) may have a limited value in practice when real, complex sounds are at issue rather than simple tones.

The concept of noise sensitivity is frequently discussed to explain, at least in part, why some individuals find sounds more annoying than others. Job (1999) defines noise sensitivity as "the internal states (be they physiological, psychological [including attitudinal], or related to life style or activities conducted) of any individual which increase their degree of reactivity to noise in general". While often not specifically about low frequency noise or infrasound, these papers do discuss certain aspects of noise sensitivity which may be relevant for low frequency (or audio frequency, for that matter) noise associated with wind turbines: "beliefs about harmful effects of noise in general" (Job, 1999), "concern" and "uneasiness" (Guski, 1999). Similarly, Fields (1993) found that "a fear of the noise source increases annoyance" to be a hypothesis supported by 100% of the evidence examined in that study. The hypothesis was one of several examined based on an aggregation of more than 400 survey findings relating to noise annoyance.

It is interesting to note that people sensitive to low frequency noise may not necessarily be sensitive to noise in general (Pawlaczyk-Łuszczyńska et al., 2009).

There appears to be a degree of sensitization experienced by people who become annoyed with low frequency sounds. Broner and Leventhall (1984) described the results of a study of the subject. 21 participants had previously complained about low frequency noise annoyance, and 45 had not. Audible low frequency sounds in the 20 to 90 Hz range were rated by participants as to the sounds' annoyance and unacceptability. It was found that there was no significant difference between the groups for the annoyance rating, but complainants always rated the sounds as more unacceptable. The report concludes that in addition to acoustical factors, there are other factors "such as psychological, situational, biographic factors" which result in a predisposition to express dissatisfaction about a given noise. Poulsen (2003b) describes a similar study, indicating that when exposed to a selection of recorded sounds containing low frequency content, people who had previously reported annoyance with low frequency noise in their homes tended to rate the recorded sounds as more annoying.

3.6 NOISE ANNOYANCE AND STRESS EFFECTS

Noise annoyance in general is known to cause symptoms of stress in individuals suffering the annoyance (Leventhall et al. 2008): "any persistent and unwanted sound, low frequency or high frequency, is a stressor" (Leventhall, 2009). Many people are able to become used to potentially annoying noises, however low frequency noise seems to pose particular difficulties for this process (Leventhall et al. 2005). Once annoyance to a low frequency noise has begun, and if an individual is unable to habitualize to it or cope with it, there is a risk that despite the "non-biologically threatening" nature of the sound, the sense of wellbeing may begin to be compromised (Leventhall et al. 2005). "A characteristic aspect of [low frequency noise] effects is the incremental, yet steady, undermining of the individual's sense of wellbeing associated with elevated anxiety levels and stress symptoms" (Leventhall et al., 2005).

Unfortunately, poor experiences interacting with those tasked with investigating the noise problem can exacerbate the inability to cope (Leventhall et al. 2005). Leventhall (2009) indicates that when a person listens to an unwanted sound for a long time, they may develop a heighted sensitivity to the noise in addition to an aversion. Thus, interactions between authorities who cannot hear a noise, and a complainant who can, may be possible. When low levels of low frequency noise are in fact near the threshold, and annoyance occurs, the literature suggests that the annoyance can actually be exacerbated by the interaction with personnel tasked with resolving such problems, when investigations take much time, or are unable to effectively assess the situation (Benton, 2007; Leventhall et al. 2005).

Guski (1999) indicates that psychological stress results from an inability to effectively cope with an environment. Stress symptoms associated with noise annoyance, and in particular low frequency annoyance, include sleep interference, headaches, poor concentration, mood swings (Leventhall et al. 2005).

Leventhall (2004) describes moderating factors including "anxiety about the source" and "suspicion of those who control the sources". Unhelpful experiences with those tasked with dealing with noise problems can also exacerbate the problem (Leventhall et al. 2005).

The prevalence of low frequency noise problems and the possibly elevated potential for annoyance related stress effects has led some international jurisdictions to develop specific protocols and standards for investigating, measuring, and assessing low frequency noise in and around homes.

3.7 NOISE ANNOYANCE WITH NO IDENTIFIABLE SOURCE

Annoyance and annoyance related effects with perceived low frequency noise can and does occur in instances where no identifiable source of noise can be found, and cannot be detected by instruments (Leventhall, 2003, Leventhall, 2005; Leventhall 2004; Benton et al., 2008). Pedersen et al. (2008a and 2008b) describes an investigation of a randomly selected sample of 21 cases of low-frequency noise complaints from a pool of 203 cases. The study involved making recordings of sound in the homes of the complainants, and the subjects were exposed to the sounds in blind listening tests at a low-frequency test facility. The study concluded that some of the complainants were annoyed by physical sounds, and others were suffering from low frequency tinnitus. Physical sounds in the infrasonic range were not found to be responsible for the annoyance in any of the cases.

Because of the prevalence of low frequency noise problems for which no apparent source can be found, or which cannot be solved for one reason or another, there is effort in the UK to develop a technique for increasing the ability of individuals to cope with the perceived noise (Leventhall, 2008; Leventhall et al. 2005) by reducing the symptoms of stress. The technique involves relaxation therapies, explanations and other support, and stress management techniques.

Some former sufferers from low frequency sounds receive some relief when no sound can be found by "learning to live with [it]" so it no longer bothers them (Leventhall 2004).

3.8 OTHER HEATH EFFECTS OF MODERATE LEVELS OF LOW FREQUENCY NOISE

Potential impact on task performance of exposure to moderate levels of low frequency noise was examined in a controlled fashion by Pawlaczyk-Łuszczyńska et al. (2005). Subjects' ability to perform various tasks was evaluated while exposed to background noise, broadband noise, or to tonal low frequency noise with tones centered in the 25, 31.5, 80, and 100 Hz 1/3 octave bands. The sound pressure levels in these bands were between 60 and 80 dB. No effects due to the low frequency noise on mental performance were found compared to the background or other sounds. Subjects identified as sensitive to noise rated the low frequency sounds more annoying, but there was no difference in performance between the two groups.

3.9 HIGH AMPLITUDE EFFECTS ASSOCIATED WITH LOW FREQUENCY AND INFRASONIC NOISE

Where high levels of infrasound and low frequency noise are generated in laboratory settings, levels above and in some cases far above the threshold of hearing, a variety of effects have been observed.

Benton et al. (1996) provides a review of several papers and published works which describe research into various health related effects of low frequency and infrasonic noise. Nine studies are cited where temporary threshold shifts were found after exposure to high levels noise in the infrasonic region. The sound pressure levels involved in these studies ranged from 119 to 154 dB. The threshold of ear pain is cited as 155 dB at 5 Hz decreasing to 135 dB at 50 Hz. Respiratory effects associated with low frequency noise in the range of 150 dB are also discussed.

Effects of exposures at somewhat lower amplitudes are described in Qibai and Shi (2004). Subjects were exposed to high sound pressure levels at very low frequencies (levels of 120 dB at 4 Hz, and 110 dB at 2 Hz). Subjects reported symptoms of discomfort, and changes in heart rate and blood pressure were noted.

Edge and Mayes (1966) describe research done at the NASA Langley research facility in a facility designed for large scale environmental acoustic testing at 140 dB and above at frequencies of 1 to

50 Hz. Subjects were exposed to spectrum levels between 110 dB and 150 dB. Subjects experienced annoyance, discomfort, and fatigue and had a slower task performance rate. The same paper indicates that ear pain can be expected at levels of 170 dB at 2 Hz, and 140 dB at 50 Hz.

At high sound pressure levels, low frequency noise can also induce a sensation of vibration. Takahasi (2008) shows the result of experiments designed to determine thresholds for this sensation, with a threshold for "vibration in the head" established separately from a threshold for "vibration in the chest". The results shown indicate that the threshold for the sensation of vibration of the head induced by low frequency noise in the range of 16 to 80 Hz is 4-13 dB higher than the threshold of hearing at these frequencies, and generally increases with frequency. The threshold for vibration in the chest was found to be 3-12 dB higher again, and also tending to increase with frequency.

3.10 POTENTIAL EFFECTS OF LOW FREQUENCY AND INFRASONIC WIND TURBINE NOISE: ANNOYANCE

It is clear from the popular media that there are people highly annoyed by wind turbine noise.

There may be a number of non-acoustic factors which tend to increase the number of people annoyed with wind turbine noise. The wide availability of popular media items describing fears of direct health effects from wind turbine noise and infrasonic noise specifically may result in fears of the wind turbines in some people, leading to increased annoyance with the sound. This may be exacerbated by certain moderating factors (Leventhall, 2004; Job, 1999; Guski, 1999; Fields, 1993), including "anxiety about the source" and "suspicion of those who control the sources".

Several studies showing that visual cues can exacerbate noise annoyance have been undertaken in the past, and several are discussed by Persson Waye (2009). One such study, Pederson and Persson Waye (2007), suggests that there is a correlation between the ability to see turbines, and the annoyance with the turbines. However the study does note dependence between the ability to see them and the sound level. Other correlations between a negative aesthetic judgment and annoyance were noted.

Pedersen and Larsman (2008), found a similar correlation between a subjective evaluation of wind turbines as “ugly” or other similar descriptions, and the risk of noise annoyance.

The three authors of Keith et al. (2008) are representatives of Health Canada. In Keith et al. (2008) a limit for wind turbine sound at a house (45 dBA) is proposed which is explicitly based on a target of 6.5% of receptors being highly annoyed. Given that for a large wind farm in southern Ontario, there may be many hundreds of receptor dwellings exposed to similar sound levels (many presumably home to more than one individual), it is clear that some highly annoyed individuals should certainly be expected if the target ratio holds true. Of the people suffering annoyance with the sound, and perhaps in particular with low frequency components of the sound, the literature indicates that some of those annoyed may suffer stress related health effects which are influenced by the annoyance.

Other papers suggest the ratio of highly annoyed persons may be higher. Pedersen et al. (2009) reported on a field study in The Netherlands and indicated that close to 20% of people were ‘very annoyed’ by wind turbine sound levels in the range of 40 to 45 dBA, more than for other types of sound at similar sound levels. Pedersen et al. concluded that non-acoustic factors, such as the visibility of the wind turbines and whether one benefitted economically from the wind turbines, also contributed to the annoyance.

3.11 POTENTIAL EFFECTS OF LOW FREQUENCY AND INFRASONIC WIND TURBINE NOISE: DIRECT HEALTH EFFECTS

In *Wind Turbine Sound and Health Effects: An Expert Panel Review*, dated December 2009, (Colby et al., 2009) a panel of “independent experts in acoustics, audiology, medicine, and public health”, the results of a literature review of biomedical publications, examining the potential health effects of exposure to wind turbines, and a review of the potential exposure to low frequency sound and infrasound from wind turbines.

Colby et al. (2009) addresses the concerns, widely discussed by members of the public opposed to wind farms, regarding “vibroacoustic disease” (VAD) and “wind turbine syndrome”.

The VAD concern is discussed, with specific references to certain papers, principally by Alves-Pereira and Castelo Branco[1]. The report indicates that VAD has been previously described as being caused by low frequency sound at large amplitudes, and has been associated with aircraft engine technicians, military pilots, and disk jockeys. The critique of the assertion that the very much lower levels of infrasound and low frequency sound from wind turbines can cause VAD concludes:

> "Wind turbines produce low levels of infrasound and low frequency sound, yet there is no credible scientific evidence that these levels are harmful. If the human body is affected by low, sub-threshold sound levels, a unique and not yet discovered receptor mechanism of extraordinary sensitivity to sound is necessary – a mechanism which can distinguish between the normal, relatively high-level "sound" inherent in the human body and excitation by external, low-level sound."

And:

> "The attribution of dangerous properties to low levels of infrasound continues unproven, as it has been for the past 40 years. No foundation has been demonstrated for the new hypothesis that exposure to sub-threshold, low levels of infrasound will lead to vibroacoustic disease."

Regarding VAD, Ontario's Chief Medical Officer of Health stated in the recent report of the health impact of wind turbines (Chief Medical Officer of Health, 2010): "This research group also hypothesized that a family living near wind turbines will develop vibro-acoustic disease from exposure to low frequency sound, but has not provided evidence to support this".

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[1] Alves-Pereira, M. and Castelo Branco, N.A.A., "Public health and noise exposure: the importance of low frequency noise", in *Proceedings of Inter-Noise 2007,* Istanbul, Turkey, 2007; Alves-Pereira, M. and Castelo Branco, N.A.A., "In-home wind turbine noise in conductive to vibroacoustic disease", in *Proceedings of Inter-Noise 2007*, Istanbul, Turkey, 2007; Alves-Pereira, M. and Castelo Branco, N.A.A., "Infrasound and low frequency noise dose responses: Contributions", in *Proceedings of Inter-Noise 2007,* Istanbul, Turkey, 2007; Castelo Branco, N.A.A., Araujo, A., Jonaz de Melo, J. and Alves-Pereira, M., "Vibroacoustic disease in a ten year old male", in *Proceedings of Inter-Noise 2004*, Prague, 2004.

Regarding the wind turbine syndrome described by Nina Pierpont in her book[2], Colby et al. (2009) characterizes the argument as being based on two hypotheses, one involving low levels of infrasound causing effects directly on the vestibular system, and the second involving low levels of infrasound causing vibration in the body. Colby et al. indicates that the body's own systems generate both infrasound and vibration, and suggests that the natural levels exceed vibration caused by external sounds, making the two hypotheses unlikely. It is perhaps worth noting that research by Dr Neil Todd at the University of Manchester, is cited as a basis for the first hypothesis, but that Dr Todd, in a letter to *The Independent* indicated that "our work does not provide the direct evidence suggested" and "I do not believe that there is any direct evidence to show that any of the above acoustico-physiological mechanisms are activated by the radiations from wind turbines"[3]. The critique of wind turbine syndrome in Colby et al. concludes "This syndrome is not a recognized diagnosis in the medical community. There are no unique symptoms or combinations of symptoms that would lead to a specific pattern of this hypothesized disorder. The collective symptoms in some people exposed to wind turbines are more likely associated with annoyance to low sound levels."

Ontario's Chief Medical Officer of Health states "it should be noted that no conclusions on the health impact of wind turbines can be drawn from Pierpont's work due to methodological limitations including small sample size, lack of exposure data, lack of controls and selection bias" (Chief Medical Officer of Health, 2010).

Other recent documents and presentations are available refuting the wind turbine syndrome concept (Epsilon Associates, 2009; Leventhall, 2010)

3.12 ACCEPTABILITY

Noise at infrasonic frequencies which is below the threshold of hearing is generally considered to have no demonstrated adverse health effects (Leventhall, 2006; Berglund and Lindval, 1995). Jakobsen (2003) expresses a similar point "It is assumed that infrasound that cannot be heard is

[2] Pierpont, N., *Wind Turbine Syndrome: a report on a natural experiment*, pre-publication draft, 2009.
[3] The Independent, August 9, 2009.

not annoying and it is believed that it has no other adverse or health effects". A similar conclusion was presented in a presentation at the Ontario Agency for Health Protection and Promotion on September 10, 2009: "No published data that confirm the claims of adverse health effects for low-frequency sound of low pressure (i.e. below 20 Hz and 110 dB)". Berglund and Lindval (1995), prepared for the World Health Organization states that "there is no reliable evidence that infrasounds below the hearing threshold produce physiological or psychological effects".

That relatively high sound pressure levels at very low frequencies which are nonetheless below the threshold of perception can be benign is demonstrated by an observation of Geoff Leventhall: "a child on a swing experiences infrasound at a level of around 110 dB and frequency 0.5 Hz, depending on the suspended length and the change in height during the swing" (Leventhall, 2006).

Because of the narrow range between a just audible infrasonic noise and an annoying one, and because of potential differences between persons, and uncertainty as to where a universally adopted threshold should lie, acceptable levels of infrasound should be below the threshold, rather than above it (Jakobsen, 2003).

At low frequencies (i.e., at low frequencies above the infrasonic range), the situation is necessarily different. It must be understood that humans are continually exposed to low frequency noise which is neither annoying nor (presumably) harmful: the lowest 'A' on a piano corresponds to a frequency of less than 30 Hz (Rossing, 1990); the male voice relies on frequencies as low as 110 Hz for speech (Rossing, 1990). Setting criteria for acceptable levels of environmental noise in the low frequency range is not appreciably different from setting criteria in the full audio range. In fact, the 63 Hz octave band is typically included as part of an audio range assessment, and extends down to about 45 Hz. Some jurisdictions do have specific low frequency noise criteria, and some discussion of this topic is provided in the jurisdictional review in Section 4 of this document.

3.13 LOW FREQUENCY AND INFRASOUND LEVELS ASSOCIATED WITH WIND TURBINES

In a presentation at Noise-Con 2010 (O'Neal et al., 2010), the results of measurements made near 1.5 MW GE 1.5sle turbines and 2.3 MW Siemens SWT-2.3-93 turbines were presented, as part of a study for NextEra Energy Resources, LLC. The presented results are somewhat confusing, but show infrasonic sound at 305 metres which is at least 25 dB below the thresholds suggested by Watanabe. In the low frequency range, the sound crosses the threshold at about 40 Hz, indicating audibility above this value.

Nordex (2004) is a test report by a wind turbine manufacturer describing measurements of infrasound made at 200 metres from a Nordex N80 turbine. A G-weighted infrasound level of 65 dBG is cited.

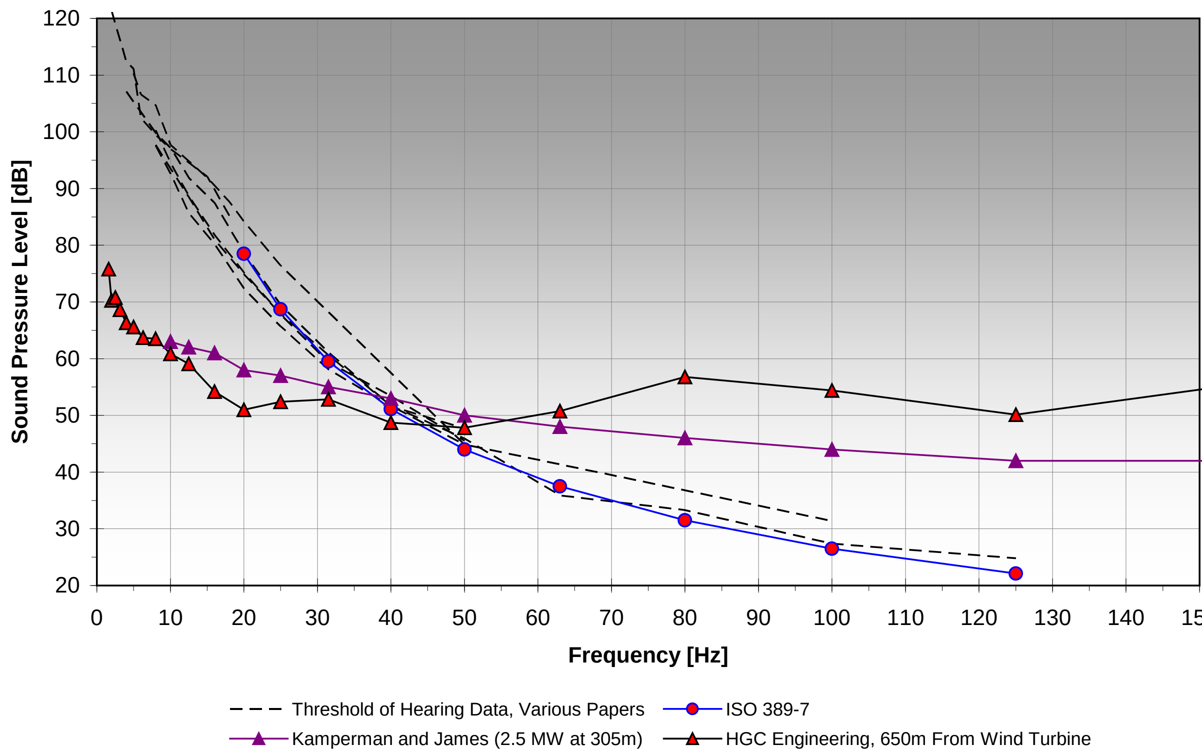
The DELTA report (DELTA, 2008) concludes that while infrasound is not an issue, low frequency sound is certainly present at relevant levels, but that “the levels are in general close to the hearing and/or masking threshold”. The report also notes that the low frequency component of road traffic noise is higher than wind turbine noise.

A similar conclusion was found by Hayes McKenzie Partnership (2006). Indoor low frequency noise measurements indicated compliance with relevant criteria for low frequency noise.

To illustrate the situation, Figure 3 shows sound pressure level data recently obtained by HGC Engineering near wind turbines using a 1” diameter microphone. At the location, there are three turbines located within a distance of approximately 1 km, and the closest turbine is approximately 650 metres away. The measurement data represents a logarithmic average of several sound pressure levels. Similar data described in Kamperman and James (2008) is also shown. As shown by Figure 3, sound at infrasonic frequencies is at least 20 dB below the threshold data at each 1/3 octave band (and below by as much as 40 dB in some bands). In the low frequency range, the sound crosses the threshold boundary (and thus would be considered to become audible) near, in this case, the 40 or 50 Hz 1/3 octave bands.

Figures similar to Figure 3, based on other measurements of infrasound and low frequency sound near with turbines made elsewhere in the world, have been presented elsewhere (Hayes Mckenzie Partnership Ltd., 2006; DELTA, 2010;) and show similar results. DELTA (2010) indicates that “there seems to be solid evidence and general agreement among researches and technicians that wind turbines do not emit audible infrasound. The levels are far below the hearing threshold.”

Figure 3. Example Sound Level Data at Low and Infrasonic Frequencies



3.14 LOW FREQUENCY AND INFRASOUND LEVELS ASSOCIATED WITH OTHER SOURCES OF NOISE

Leventhall (2003) reports on three papers from the 1960s in which the possibility of infrasound due to remarkable weather conditions causing biological effects was discussed. The same report lists "earthquakes and wind" as well as "automobiles, rail traffic, aircraft, industrial machinery, artillery and mining explosions, air movement machinery including wind turbines, compressors and ventilation or air-conditioning units, household appliances such as washing machines, and some therapeutic devices" as sources of infrasound.

Berglund et al. (1996) presented low frequency noise data ("low frequency" defined as less than 250 Hz) from a variety of sound sources. The report contains a figure summarizing spectral sound pressure data obtained in a variety of vehicles, as presented in a variety of papers from the 1970s and 80s. The vehicles described range from passenger cars to trucks. The average value appears to peak at roughly 10 Hz, where most of the data indicates a sound pressure range of about 90 to 110 dB. One of the “examples of regional noise situations” in Appendix B to the World Health Organization community noise guide (WHO, 1999), indicates a similar statistic, with a peak in the infrasonic range: “Vehicle noise has strong low-frequency peaks at ~13 Hz, and at driving speeds of 100 km/h noise levels can exceed 100 dB”.

Johnson (2006) described measurements of the infrasound generated by an Ecuadorian waterfall. The waterfall is 145 metres in height, dropping in two stages. The infrasonic noise was found to peak at 2.5 to 3 Hz. The infrasound was initially measured accidentally, while the author was studying a nearby volcano. Johnson et al. (2006) provided additional information on the same subject, and shows comparative data on the infrasound produced by a volcano, thunder, and the waterfall.

Infrasonic content in noise from an Alaskan volcano is described in Wilson et al. (2006).

Sisto et al., (2000) described measurements of high amplitude low frequency pressure waves occurring in high speed trains entering and leaving tunnels. The researchers found sound pressures levels reaching 136 to 152 dB. Such a level is certainly in excess of the hearing threshold, and the authors stated that the 152 dB level is “close to the acoustic pressure threshold value for hearing impairment”.

Hama et al. (2008) report on infrasound radiated by a bridge in Japan while trucks drove over the bridge. Adjacent to nearby houses, individual 1/3 octave band levels in the range of 8 to 16 Hz peaked in the range of 80 to 90 dB.

DELTA (2008) contains a chart illustrating the low frequency content of various sounds including wind turbines at various distances, the sound of various vehicles when inside them and at distances from then, and a miscellany of other sources. The chart illustrates that there are many common sources of low frequency noise with greater amplitudes than wind turbines at reasonable distances of a few hundreds of metres. The chart is based on the $Lp_{A,LF}$ descriptor used by Denmark to quantify low frequency sound levels (refer to the Jurisdictional Review). The $Lp_{A,LF}$ descriptor is the A-weighted energy sum of the sound in each of the 1/3 octaves between 10 and 160 Hz, and thus contains energy in both the infrasonic and low frequency ranges. For example, the report indicates that the $Lp_{A,LF}$ level inside a car with “rock on the radio” may be nearly 80 dBA, or “inside a passenger car, 80 km/h” may be about 60 dBA. The level in other vehicles and near roadways is indicated to be in the range of about 50 to 60 dBA ($Lp_{A,LF}$). By contrast the $Lp_{A,LF}$ level at 250 metres from a 3.6 MW wind turbine is indicated as about 35 dBA, and at distances of 1800 metres or more, less than 20 dBA.

3.15 TECHNICAL REVIEW: SPECTRAL LOW FREQUENCY AND INFRASONIC CONTENT OF WIND TURBINE NOISE

Wind turbine sound is in general broadband (Oerlemans and Méndez López, 2005; Oerlemans et al., 2007).

However, Søndergaard (2008) presented narrowband spectra measured near several wind turbines, showing strong, audible, low frequency (but not infrasonic) tones from some of the turbines, attributed to gearbox sounds.

Older, downwind rotor machines produced high-amplitude tones at infrasonic frequencies (Shepherd and Hubbard, 1991; Leventhall, 2006). The chief mechanism of generation of the low frequency noise for downwind system appears to have been blades passing through the aerodynamic wake of the tower.

Infrasound due to pressure pulses from upwind models are at low levels, well below the hearing threshold (Leventhall, 2006). Leventhall concluded “Infrasound from wind turbines is below the audible threshold and of no consequence”.

3.16 TECHNOLOGICAL SOLUTIONS

Little information was found dealing with technologies currently under development to reduce low frequency noise.

Madsen (2008a, 2008b) showed that the distance from the rotor to the tower is an important parameter for low frequency noise, with greater distances leading to lower low frequency noise radiation.

Presumably, where low frequency tones are due to mechanical sources such as gearbox noise, any technology or mechanical design which either reduces the noise generated by these sources, or improves the isolation of the sources from the nacelle, blades, and tower will reduce low frequency noise emissions.

3.17 MEASUREMENT OF LOW FREQUENCY NOISE AND INFRASOUND

This section describes measurement techniques for use with low frequency noise, including any recommended approaches and challenges associated with measuring low frequency noise from wind turbines

It is well known that wind induced noise begins to be a problem for acoustic measurements as wind speed increases, a particular problem for any noise measurements of wind turbines, since turbines only operate in the presence of wind. Wind causes a microphone diaphragm to deflect in response to turbulence introduced in the airstream by the presence of the microphone, which creates false signals in the microphone (Hassall and Zaveri, 1979). This can introduce serious errors in the sound level data (Harris, 1979). Hessler, et al. (2008) described the difficulty of measuring sound in the presence of wind in quiet rural settings where wind-induced background sounds are generally low. Shimura et al. (2008) presented findings on wind-induced microphone noise. The researchers concluded that turbulence in the air upstream of the microphone is a significant factor in wind-induced noise, as is the angle of orientation of the microphone to the wind.

The international Comprehensive Test Ban Treaty Organization, tasked with monitoring the planet for clandestine nuclear tests operates a network of detection stations using various detection methods such as hydroacoustic monitoring, seismic monitoring, radionuclide monitoring, and infrasound monitoring. There are 60 existing or planned infrasound monitoring stations around the world associated with this system. The stations consist of a small number of microphones or microbarometers. Each unit is connected to a radial network of pipes or porous hoses so that wind noise can be reduced by allowing the pressure incident on the detector to be averaged over an area (Evers, 2005). Further wind noise reduction is accomplished through the use of multiple detectors at each station. While such a setup is very sensitive (and presumably able to detect explosions and blasts around the world), it is likely impractical and excessive for measurement of infrasound due to wind turbines.

It is interesting to note that at the 2005 Infrasound Workshop sponsored by the French Atomic Energy and Alternative Energies Commission, a presentation was given (Ceranna et al., 2005) which dealt with the interference of infrasound emissions of nearby wind turbines with such a monitoring station.

A simpler approach to dealing with the wind-induced sound problem at low frequencies has been developed by researchers at the NASA Langley Research Centre. Shams et al. (2005) described the development of a windscreen which can perform well for long duration measurements of noise in the infrasonic range, but is not useful for higher frequencies. The system was based on the use of a cylindrical windscreen sealed around a microphone. The windscreen had a thin wall (around ½”) and was constructed of a rigid nonporous material with a low acoustic impedance ratio (the specific acoustic impedance of the material divided by the impedance of air). Thus, the windscreen takes advantage of the difficulty associated with attenuating infrasonic noise. For the windscreen material, NASA has experimented with a variety of materials including space shuttle tile foam, but obtained good results with a common closed-cell rigid polyurethane foam. Tests of the transmission coefficient of windscreens constructed to this pattern show no loss below about 20 Hz (and in fact some gain), with a rapid falloff above about 20 Hz. Tests of the reduction in wind-induced microphone noise suggested about 20 dB of reduction at 10 Hz, and 10 dB at 0.7 Hz.

Following the development of the cylindrical windscreen, researches at NASA Langley began examining sub-surface windscreens, partly because the cylindrical design was prone to vortex shedding noise[4]. In a presentation to the Acoustical Society of America in 2008 (Shams et al., 2008a) windscreens consisting of a box placed in the ground, and covered with a ½” thickness of closed-cell polyurethane foam are described. In another report, available online[5] (Shams et al, 2008b) use of the sub-surface windscreen together with a 3” diameter low frequency microphone developed by NASA Langley. The system has been incorporated into a fixed array at the research

[4] Personal communication with Qamar A. Shams.
[5] http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20080034649_2008034482.pdf

centre, and was able to detect a space shuttle launch 660 miles away. Other applications have included the detection of infrasound generated by the atmosphere, helicopters, sonic booms, and people walking.

Jakobsen (2005) described measurements of wind turbine generated infrasound using sub-surface windscreens.

Spherical windscreens involving polyester urethane foams were also described in Imaizumi and Takahashi (2008)

Indoor measurements are less prone to wind-induced problems, but are subject to other potential problems. At low frequencies, variation in sound pressure levels for pure tones can be found from place to place in a room, in the range of 20 – 30 dB. Less variation is expected for more broadband noise (Pedersen et al., 2007). Various potential methods to minimize this issue have been proposed, and are discussed in Section 4.

Various procedures have been developed for the identification of tonal noise. Three possible techniques are described in DeGagne and Lapka (2008). The first of these techniques involves a comparison of A-weighted and C-weighted sound levels, with a figure of 20 dB representing the demarcation between acceptable and unacceptable impacts. The second technique also examines the difference between A- and C-weighted levels, but adds a quantitative procedure for identifying tonality in the low frequency range. The third technique involves the use of a table showing acceptable spectral values. Examples provided in the paper of such tables are based on the Oregon Administrative Rules referred to in Section 4.2 of this report.

4.0 JURISDICTIONAL REVIEW

Although several jurisdictions do have specific guideline documents for wind farm noise, many do not. Some such guidelines do explicitly reference low frequency noise requirements. Other jurisdictions may or may not have specific wind farm guidelines, but also have guidelines or protocols for dealing with low frequency noise complaints. This review looks at both categories of documents, where they are known to HGC Engineering: wind farm guidelines dealing with low frequency noise, and general purpose low frequency noise guidelines. In addition, journal articles recommending or describing the development of national standards are also described, although in some cases it is not clear what the status of the recommendations currently is.

An interesting comparison of low frequency assessment rating schemes is provided in Poulsen (2003a). Poulsen describes a laboratory listening tests where 18 subjects rated the annoyance of various recordings of industrial noise with significant low frequency components. The annoyance data was then correlated with the ratings established using Swedish, German, Dutch, Polish and Danish assessment schemes. Poulsen indicates that the Danish method (see below), relying on an $Lp_{A,LF}$ descriptor, correlated best.

4.1 CANADA

Health Canada (2010) recommends that sound source mitigation be applied when the energy sum of sound levels in the 16, 31.5 and 63 octave bands exceeds 70 dBA to prevent possible noise-induced rattling based on ANSI standard 2005.

The same document also discusses the application of a +5 dBA penalty to sound levels which are tonal in nature.

4.1.1 Alberta

Directive 038 of the Energy Resources Conservation Board (formerly part of the Alberta Energy and Utilities Board) describes the requirements for noise assessment and control for energy related projects. The February 2007 revision to the guideline added sections dealing specifically with wind turbines and low frequency noise issues.

With regard to wind turbines and low frequency noise, the Directive indicates that “studies indicate that wind turbines do not present a significant source of environmental noise, although [low frequency noise] has been identified with some designs.”

Regarding the general assessment of low frequency noise (i.e., not specific to wind turbines), the Directive indicates that when data are available, the dBC – dBA quantity should be computed as part of a new assessment. A procedure for investigating low frequency (<250 Hz) complaints is also provided, which includes the identification of any low frequency tones. A quantitative definition of a tone is provided.

4.2.3 Ontario

In Ontario, the noise assessment guidelines of the MOE do not currently require a regular assessment of low frequency noise or infrasound associated with wind turbines. The 2008 document *Noise Guidelines for Wind Farms* (MOE, 2008) does not mention low frequency noise or infrasound, although it does require a +5 dB adjustment to the manufacturer’s sound data if the data indicates that the sound is tonal. As described in this document, mechanical tones generally occur in the low frequency range.

In the 2009 document *Proposed Content for the Renewable Energy Approval Regulation under the Environmental Protection Act* available from the MOE[6] it is proposed that wind farm proponents be required to monitor and address low frequency noise and any perceptible infrasound.

4.2 USA

In Oregon, the Department of Environmental Quality (DEQ) has published environmental noise guidelines. The guidelines are contained in Oregon Administrative Rule Chapter 340, Division 35. Broadband wind turbine noise is explicitly covered. The general industrial regulations provide criteria for sound levels at low frequencies down to the 31.5 Hz octave band (65 dBA at night) and there is a section on tonality. Certain quantitative procedures are provided for establishing if a given tone is prohibited.

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[6] Available at http://www.ene.gov.on.ca/envision/env_reg/er/documents/2009/010-6516.pdf

Likewise, Illinois, in their regulations provide criteria for sound levels in the 31.5 Hz octave band (69 dBA at night), but they do not specifically address wind turbines.

According to Bastasch (2009), the DEQ "no longer has the authority or funding to work on noise-related issues" even though other agencies still require use of the DEQ guideline.

Hessler (2005) proposed general-purpose low frequency noise limits for industrial sound in the USA, observing that "there is a need in the United States for some Federal or prominent standards organization to publish limits in residential areas for low frequency noise attributable to industrial sources". For a continuous industrial sound source impacting a quiet area, the limit proposed is 60 dBC, but Hessler notes that the proposed limit contains no safety factor, and "should not be considered the maximum allowable".

The Minnesota Department of Health publication (Minnesota Department of Health, 2009) recommends consideration of the difference between a C-weighted sound level and an A-weighed sound level "to evaluate the low frequency noise component", following guidance provided by the World Health Organization (1999) as summarized in section 4.6.1 of this report.

4.3 EUROPE

4.3.1 Denmark

Jorgen Jakobsen of the Danish Environmental Protection Agency describes general purpose Danish guidelines on environmental low frequency noise and infrasound in Jakobsen (2003). The paper indicates that "an environmentally acceptable infrasound level must be below the hearing threshold", and describes a criterion curve which is 10 dB below the average threshold data, to reflect possible individual differences. In order to simplify the comparison, the Danish guideline uses a recommended G-weighted sound level (ISO 7196:1995) of 85 dBG. To assess noise in the low frequency range, the A-weighted level of noise in the frequency range of 10 to 160 Hz is also computed ($Lp_{A,LF}$). The recommended $Lp_{A,LF}$ limits for different settings are 5 to 15 dB lower than the typical full-spectrum A-weighted limits. A 20 dBA $Lp_{A,LF}$ limit is stated for dwellings at night, as is a 85 dBG infrasound level.

Given the popular idea that A-weighted underestimates the amplitude low frequency sounds, it will seem inappropriate to some that A-weighting is used at all. Jakobsen (2003) indicates that while A-weighting may underestimate the annoyance of higher amplitude low frequency sound, the A-weighting factors actually overestimate the loudness at low levels at the lowest frequencies. Thus, the use of A-weighting with a specific criterion designed for A-weighted low frequencies is considered to be conservative.

The limits described in the paper are to be applied to measurements made indoors, and that measurements are to be made in at least 3 points in each room. Narrowband measurements are made, generally averaged over at least 5 minutes. The paper indicates that due to excessive tolerances at low frequencies in the A-weighting specifications, "the A-weighted level of the low frequency noise cannot be measured with a normal sound level meter supplied with a low pass filter. The level instead must be synthesised from a narrowband frequency analysis by addition of the nominal weighting function". Presumably, any instrument capable of accurate linear-weighted fractional octave band measurements could also be used, in place of narrowband data, simplifying the analysis.

4.3.2 England

There is currently no specific requirement in the UK to test for low frequency noise or infrasound from wind turbines, and the subjects are not considered a specific issue for wind turbines.[7]

The UK Department for Environment Food and Rural Affairs commissioned Salford University to propose criteria and a method of assessing low frequency noise issues. A report is available (Moorhouse et al., 2005). The proposed criterion is a curve 5 dB below the ISO 226:2003 curve describing the threshold of audibility.

4.3.3 The Netherlands

Vercammen (1989) reports on a study undertaken for the Dutch Ministry of Environment and Housing, although it is not clear if and to what extent the recommendations were adopted. The paper describes recommends spectral low frequency sound level limits for the 1/3 octave bands

[7] Personal communication with practicing UK consultant.

from 4 to 160 Hz for different categories of low frequency sounds. Fluctuating low frequency sounds are assigned lower limits than continuous sounds.

4.3.4 Sweden

The Swedish National Board of Health guidelines for indoor noise were translated into English in Pettersson (1997). The guideline contains procedures for assessing a low frequency noise by examining individual 1/3 octave bands against a specified band limit (56 dB at 31.5 Hz ranging to 32 dB at 200 Hz).

4.3.5 Poland

Mirowska (2001) describes the development of recommendations from the Polish Building Research Institute for identifying low frequency noise problems in buildings. The recommended method consists of comparing a 1/3 octave spectrum of sound in a home (the particular range of 10 to 250 Hz is discussed) to a criterion curve computed by adding 10 dB to the magnitude of the 1/3 octave band A-weighting correction. Thus the criterion would be 10 dB at 1000 Hz, but in the low frequency range, would be 80.4 at 10 Hz down to 18.6 at 250 Hz. A comparison to background is also required.

4.4 ASIA

4.4.1 Taiwan

Kuo et al. (2008) describes the development of an environmental noise standard for low frequency noise from industrial operations in Taiwan. The authors indicate that Taiwan has adopted Denmark's practice of using an A-weighted low frequency noise descriptor covering the 10 through 160 Hz bands. A 20 dBA (low frequency) limit applies in dwellings at night.

The Hualein county Environmental Protection Bureau website[8] makes reference to certain recent additions to the Noise Control Act, governing low frequency noise.

[8] http://english.hlepb.gov.tw/index.php?option=com_content&view=article&id=606%3Anoise-control-policy-in-taiwan&catid=34%3Anews&Itemid=79

4.5 AUSTRIALASIA

4.5.1 New Zealand

New Zealand standard NZS 2808:2010, *Acoustics – Wind Farm Noise* provides a detailed method for the prediction and assessment of wind turbine noise. The publication gives little specific consideration to low frequency sound. In explanation of this, regarding claims of related illness and other physiological effects of low frequency noise, the standard states "the paucity of evidence does not justify at this stage, any attempt to set a precautionary limit more stringent than those recommended [in this standard: typically 40 dBA overall]". The standard also indicates that any infrasound "will be well below the threshold of human perception".

However, the standard does require that tonality in the wind turbine noise requires a special assessment, and can adjust the predicted sound level by up to +6 dB. A detailed procedure for assessment of tonality is provided. Since audible mechanical tones can occur in the low frequency range, this component of the process is relevant here.

4.5.2 South Australia

A publication entitled *Wind Farms. Environmental Noise Guidelines* provides guidelines for the assessment of wind turbine noise. Regarding infrasound, the guide states that "annoying characteristics that are not fundamental to a typical wind farm should be rectified. Such characteristics may include infrasound … or adverse mechanical noise". Thus the guide suggests that infrasound problems should not be common ("not fundamental to a typical wind farm"), and may be corrected.

As with the New Zealand standard, tonal noise can result in a sound level penalty, +5 dB in this case.

4.6 INTERNATIONAL

4.6.1 World Health Organization

WHO (1999) indicates that for continuous noise, an indoor noise criterion of 30 dBA should be applied. The document assumes a 15 dB noise reduction through exterior bedroom walls with open windows, suggesting a 45 dBA outdoor criterion. However, it should be noted that the document indicates that where significant low frequency noise is present, lower criteria should be applied to avoid disturbing rest. No guidance specific to wind turbine noise or infrasound is provided, although there is a general recommendation to perform a "frequency analysis" when the difference between a dBC (or dBLin) weighted sound level exceeds the dBA weighted level by more than 10 dB

A more recent document by WHO (2009) addresses night noise guidelines for Europe, but again is not specific to low frequency noise, infrasound and does not provide guidance for wind turbines.

5.0 CONCLUSIONS

Based on a review of technical research with respect to low frequency noise and infrasound from wind turbine generators, and the regulatory practices in various jurisdictions, several conclusions can be made.

1. Modern wind turbines produce broadband noise, and research indicates that the dominant sound source is chiefly related to turbulence at the trailing edge of the blades. In relation to human perception of the sound, the dominant frequency range is not the low frequency or infrasonic ranges.

2. In the low frequency range, it should be expected that low frequency sound due to aerodynamic sources will routinely be an audible component of the acoustic impact. The degree of audibility depends on the wind conditions, the degree of masking from noise induced by ground-level winds, traffic, etc., and the distance from the wind turbines, In instances where acoustic tones are present, typically related to mechanical noises (e.g., gearbox noise), the frequency of these tones can be within the low frequency range. Such tones can be audible.

3. In the infrasonic range, at frequencies less than about 20 Hz, there is strong evidence that the sound pressure levels produced by modern upwind turbines will be well below (on the order of 20 dB below) the average threshold of human hearing, at the setback distances typical in Ontario. Although some authors have raised concerns, most literature dealing with the subject indicates that infrasonic noise below the threshold of hearing will have no effect on health. As such, infrasound from wind turbines is not normally expected to be heard by humans or pose an issue for human health. It should be acknowledged that this does not conclusively eliminate the possibility that under exceptional circumstances – rare atmospheric conditions or some alternate designs – infrasound levels could be heard. There are also large variations in individual sensitivities to infrasound.

4. Publications by medical professionals indicate that, at the typical setback distances in Ontario, the overall magnitude of the sound pressure levels produced by wind turbine generators does not represent a direct health risk. This includes noise at low and infrasound frequencies.

5. The audible sound from wind turbines, at the levels experienced at typical receptor distances in Ontario, is nonetheless expected to result in a non-trivial percentage of persons being highly annoyed. As with sounds from many sources, research has shown that annoyance associated with sound from wind turbines can be expected to contribute to stress related health impacts in some persons. The relationship between the sound level and the prevalence of annoyance is complicated, and is often influenced by other non-acoustic factors. It should also be noted that this situation does not relate exclusively to the low frequency component of the audible noise impact of wind turbines.

6. Indoors, the low frequency components of a sound from the outside can become emphasized by room and structural characteristics. There is evidence to suggest that some people may be particularly prone to annoyance from sounds with strong low frequency components. Complaints of low frequency noise described in the literature are commonly related to indoor noise. The measurement of indoor low frequency noise is complicated by a number of factors and, internationally, more sophisticated measurement and assessment guidelines have been developed to address these problems in recent years.

7. The measurement of infrasonic sound pressure levels is more difficult than the measurement of sound levels in the audible range. More sophisticated instrumentation and transducers are required to extend the range down to a very low frequency, on the order of 1 Hz. In addition, the wind itself can strongly excite the microphone, leading to acoustic signals at frequencies in the infrasonic range. Conducting infrasound measurements using an in-ground system, such as that developed by NASA, or conducting measurements within residences can reduce the influence of the wind on the microphone.

8. Issues related to low frequency noise and infrasound have been noted world-wide and can be caused by noise from many different industrial and transportation related sources. Some countries, such as Denmark and Sweden, have developed comprehensive regulatory guidelines which address generic low frequency noise and infrasound assessment. Other countries have guidelines specifically addressing sound from wind turbines, which do not specifically address low frequency noise and infrasound. For instance, the recent New Zealand guideline addresses tonality, but does not provide cautionary low frequency limits due to the "paucity of evidence" of related health impacts.

9. There is audible sound in the low frequency range associated with the sound of wind turbines. Nonetheless, because the outdoor sound level impact is not chiefly a low frequency issue, the use of overall A-weighted criteria is still appropriate for the assessment of overall sound impact, and the instrumentation specifications and measurement procedures currently in use by the Ontario Ministry of the Environment are suitable in this context. The concept of penalizing the acoustic impact if the sound from the wind turbines is tonal – often a low frequency problem – is also appropriate. Currently, the Ontario Ministry of the Environment uses a 5 dB penalty, and the identification of a tone is a subjective judgment; other jurisdictions use a quantitative approach.

10. The Ontario Ministry of the Environment has not published measurement procedures or criteria for addressing indoor noise intrusions due to wind turbines or other industrial sources of sound. Although some jurisdictions have developed standards governing the assessment of indoor low frequency noise, many other jurisdictions have not. There are only a few jurisdictions which have guidance, instrumentation specifications, or measurement procedures that could be used to appropriately address infrasound, and the MOE also does not currently have such a guide.

6.0 RECOMMENDATIONS

The following recommendations are provided to assist the Ontario Ministry of the Environment.

1. A review of the current technical literature and international assessment standards concerning low frequency noise and infrasound does not indicate that there is a need for the MOE to change the fundamental approach used in Ontario for the assessment of wind turbine noise. It is recommended that outdoor A-weighted sound levels at sensitive receptors continue to be used to evaluate the compliance of sound from wind turbines. Additionally, penalties for audibly distinctive characteristics of the sound should continue to be used by the MOE. In particular, sound with strong mechanical tones which often occur within the low frequency range should be penalized.

2. There is a degree of disagreement and uncertainty in the literature of some of the subjects discussed in this review, and research efforts are ongoing. It is recommended that the MOE continue to monitor technical developments in this area and keep informed of regulatory policies that may be introduced in other jurisdictions. Should the MOE develop guidelines in respect of low frequency noise and infrasound, these guidelines should retain a degree of flexibility in order to adapt to changes or improvements offered by international research in the future.

3. Since it is evident that complaints related to low frequency noise from wind turbines often arise from the characteristics of the sound impact indoors, and since the indoor low frequency sound levels and frequency spectra can differ markedly from those outdoors, it is recommended that the MOE consider adopting or developing a protocol to provide guidance for addressing such complaints. Given the significant variation in sound impact from house to house as a function of room layout and sound transmission characteristics, this protocol cannot replace the current compliance guidelines, but would prove helpful in assessing unique situations. The Danish model, and the conclusions of Pedersen et al. (2007), as discussed in the main body of this report, could be considered in this regard.

4. Infrasound from wind turbines is not expected to be heard by humans or pose an issue for human health, and as such, routine measurement of infrasonic sound pressure levels from operating wind farms is not warranted to the same degree that the measurement and monitoring of overall A-weighted sound pressure levels are. Nonetheless, there are aspects of infrasound from wind turbines that are not unanimously accepted by all technical and medical practitioners and there remains a degree of public apprehension associated with infrasound. It is therefore recommended that the MOE consider adopting or endorsing measurement procedures described in the literature that could be used to quantify the infrasonic levels in specific situations.

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