

**LOW FREQUENCY NOISE AND INFRASOUND FROM
WIND TURBINE GENERATORS:
A LITERATURE REVIEW**

Prepared for:

Energy Efficiency and Conservation Authority

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TABLE OF CONTENTS

1	ABSTRACT.....	1
2	BACKGROUND	2
3	INTRODUCTION.....	2
4	LIST OF DOCUMENTS/STUDIES REVIEWED.....	3
5	ACOUSTIC TERMINOLOGY	4
6	REVIEW OF THE WORLD HEALTH ORGANISATION (WHO) REPORT.....	10
7	REVIEW OF COMMUNITY NOISE, 1995: B BERGLUND	13
8	REVIEW OF DEPARTMENT FOR ENVIRONMENT, FOOD AND RURAL AFFAIRS (DEFRA) REPORT	19
9	ADDITIONAL MATERIAL.....	29
10	INTERNATIONAL AND NATIONAL STANDARDS	31
11	LOW-FREQUENCY SOUND OR INFRASOUND FROM WIND TURBINE GENERATORS	35
12	REVIEW OF NEW ZEALAND STANDARD: NZS6808:1998.....	35
13	CONCLUSIONS	37
14	ACRONYMS.....	38
15	BIBLIOGRAPHY	39

1 ABSTRACT

The debate surrounding the existence and measurement of infrasound in relation to Wind Turbine Generators is addressed by the review of numerous studies including, *Guidelines for Community Noise*, a World Health Organisation document published in 1999, and a report written for the United Kingdom's Department of Environment, Food, and Rural Affairs by Dr Geoff Leventhall in 2003 titled *A Review of Published Research on Low Frequency Noise and its Effects*.

Other written material available, including National and International Standards has also been assessed in connection with infrasound. Though National Standards dealing with noise from wind farms include assessments using the A-weighted level of noise and do not include the assessment of infrasound directly, there are International Standards that are concerned with such assessments.

Although there is the possibility of effects on people exposed to noise in the low-frequency sound and infrasound range of frequencies, the effects would only ever occur when the sound is audible (above the hearing threshold). The evidence available is that the level of emissions of low frequency sound and infrasound from wind turbine generators is so low that it is inaudible. There is no reliable evidence to indicate any effects on people when infrasound is present at an inaudible level (below the hearing threshold).

There is no evidence to indicate that low-frequency sound or infrasound from current models of Wind Turbine Generators should cause concern.

2 BACKGROUND

There has been debate surrounding the existence and measurement of infrasound and in order to eliminate some of the confusion relating infrasound to wind turbine generators, there is a need for a literature review on the subject of low frequency sound and infrasound from wind turbine generators.

Recently there has been some concern in New Zealand and overseas that low frequency sounds and infrasound from wind turbine generators could cause a range of adverse psychological and physiological effects on people living nearby. The methods for the measurement and assessment of sound from wind turbine generators in New Zealand are detailed in the New Zealand Standard *NZS 6808:1998: Acoustics — The Assessment and Measurement of Sound from Wind Turbine Generators*. There is also some concern that low frequency sounds and infrasound from wind turbine generators are not adequately addressed in this Standard, and therefore the potential for adverse effects on people living near wind turbine generators could be overlooked in the planning stages and development of wind farms.

Recent media reports on low frequency sound and infrasound often cite two overseas studies: specifically, *Guidelines for Community Noise*, a World Health Organisation document published in 1999, and a report written for the United Kingdom's Department of Environment, Food, and Rural Affairs (DEFRA) by Dr Geoff Leventhall in May 2003 titled *A Review of Published Research on Low Frequency Noise and its Effects*.

3 INTRODUCTION

The Energy Efficiency and Conservation Authority (EECA) is seeking an impartial, neutral and accurate review of low frequency sound and infrasound from wind turbine generators and their effects on people. Accurate and up to date information on the effects of noise from wind turbine generators is required in order to be best able to address some of the concerns about the development of wind farms, especially when they are sited near residents.

Of primary concern is whether there is sufficient evidence to show that low-frequency or infrasound from wind turbine generators should cause concern to residents living near wind turbines.

Bel Acoustic Consulting has been commissioned by EECA to conduct a review of the two overseas studies cited above, and other relevant studies on infrasound to establish whether, and to what extent, there are linkages to wind turbines.

4 LIST OF DOCUMENTS/STUDIES REVIEWED

Guidelines for Community Noise, 1999: World Health Organisation

Community Noise, 1995: Birgitta Berglund: Institute of Environmental Medicine, Karolinska Institute and Department of Psychology, Stockholm University

A Review of Published Research on Low Frequency Noise and its Effects, May 2003: Dr Geoff Leventhall, Department of Environment, Food, and Rural Affairs (DEFRA), United Kingdom

Environmental Noise Guidelines, Wind Farms, 2003: Environmental Protection Agency, South Australia

Low Frequency Noise, Technical Research Support for DEFRA Noise Programme, 2001: Casella Stanger

Noise Annoyance from Wind Turbines - a Review, Report #5308, August 2003: Eja Pedersen, Högskolan i Halmstad, Swedish Environmental Protection Agency

Wind Turbine Noise Issues, June 2002, amended March 2004: A white paper prepared by the Renewable Energy Research Laboratory, Center for Energy Efficiency and Renewable Energy, Department of Mechanical and Industrial Engineering, University of Massachusetts, Amherst, MA

Assessment and Rating of Noise from Wind Farms, ETSU-R-97, Final Report September 1996: Working Group on Noise from Wind Turbines, Department of Trade and Industry, UK

ISO 7196, 1995: Acoustics — Frequency-weighting characteristic for infrasound measurements

Draft Australian Standard, DR 04173, 2 June 2004: Acoustics — Measurement, prediction and assessment of noise and wind turbine generators

IEC 61400-11, 2002: Wind turbine generator systems – Part 11: Acoustic noise measurement techniques

NZS 6808, 1998: Acoustics — The assessment and measurement of sound from wind turbine generators

5 ACOUSTIC TERMINOLOGY

A general interpretation of what is meant by acoustical terms used in the many documents is described below.

SOUND PRESSURE

Sound consists of pressure fluctuations through an elastic medium. When that medium is air, and the pressure fluctuations fall on the ear, the sensation of hearing is produced. Sound is a form of energy and is transmitted by the interaction of air molecules one against another.

When sound propagates from a source, it sets up pressure variations in the surrounding air. These variations are very small when compared to atmospheric pressure, which is approximately 100kPa (kilopascals, or 10^5 pascals). The audible range of sound pressure variations is wide, ranging from 20 micropascals (20 μ Pa) at the threshold of hearing to 100 pascals (100Pa) at the threshold of pain.

It can be seen that the ratios involved are large. For example, from the threshold of hearing to the threshold of pain the pressure ratio is about 5 million to one.

DECIBEL (dB)

A decibel is the logarithm of the ratio between two values of some characteristic quantity such as power, pressure or intensity, with a multiplying constant to give convenient numerical factors. The expression is normally denoted by the term dB. Logarithms are useful for compressing a wide range of quantities, such as sound pressure, into a smaller range.

For example:

The logarithm to the base 10 of 10 is 1 and this is normally stated as: $\log_{10}10 = 1$ or more often as $\log 10 = 1$

Similarly, $\log 100 = 2$

And, $\log 1000 = 3$

and so, the ratio of 1000 to 1 is compressed into a ratio of 3 to 1.

This approach is advantageous for handling sound levels, where the ratio of the highest to the lowest sound which we are likely to encounter can be as high as 5,000,000:1. A useful development, many years ago, was also to take the ratios with respect to the quietest sound we can hear. This is the threshold of hearing at about 1,000Hz, which is taken as 20 μ Pa (2×10^{-5} Pa) of pressure for the average person. When the word "level" is added to the word that describes a physical quantity, decibels are implied. Thus, "sound level" is a decibel quantity and is related to the sound pressure by the expression:

$$\text{Sound Pressure Level in dB} = 10 \text{ Log } (p/p_0)$$

Where p is the sound pressure and p_0 is the reference sound pressure of 20 micro-pascals.

When the sound pressure level increases by 3dB the intensity of the sound is doubled. Sound pressure level is often shortened to SPL.

SOUND POWER LEVEL (SWL)

It is important to differentiate between the terms “Sound Power Level” and “Sound Pressure Level” since they are completely different quantities.

Sound power is the quantity of sound that is generated and released at the source of sound. The Sound Pressure Level at some location away from the source is the result of that radiation of sound and depends on the surrounding environment and the distance from the source.

The relationship between these parameters is:

$$\text{Sound Pressure Level (dB)} = \text{Sound Power level} - 20 \times \text{Log}(r) - 11 \text{ dB}$$

Where r is the distance in metres of the receiving point from the source of sound and

Sound Power Level is in dB re 10^{-12} watts.

This relationship represents the “inverse square law” by which the sound pressure level decreases by 6dB per doubling of distance from the source.

The above relationship applies to the condition where the source radiates in all directions. Where the source is close to the ground the sound that is radiated downwards is now reflected by the ground and radiated into the hemisphere above the ground. The result is that the sound pressure level at any point from the source will be 3dB higher than in the spherical radiation case. Therefore for hemispherical radiation:

$$\text{Sound Pressure Level (dB)} = \text{Sound Power level} - 20 \times \text{Log}(r) - 8 \text{ dB}$$

This relationship applies to all frequencies of sound – including infrasound.

For example, if a wind turbine generator has a sound power level of 100dBA (an A-weighted level). At a distance of 400 metres from the turbine the sound pressure level will theoretically be:

$$\begin{aligned} \text{Sound Pressure Level in dB} &= 100 - 10 \times \text{Log}(400) - 11 \\ &= 100 - 52 - 11 \\ &= 37\text{dBA} \end{aligned}$$

The sound pressure level at this distance will also be further reduced by effects such as ground absorption and molecular absorption together with other effects.

Low frequency noise and infrasound

The frequency range of human hearing is normally taken to be a range of 20 to 20,000Hz, but there are variations including the fact that as we age our ability to hear high frequency sounds diminishes.

Infrasound is normally taken to be below 20Hz. However, frequencies below 20Hz are also audible in humans, illustrating that there is some lack of clarity in the interpretations of infrasonic and audible noise.

Some large mammals can also hear infrasound and may also use it to communicate.

FREQUENCY AND WAVELENGTH

The frequency of a sound is the number of oscillations which occur per second and normally referred to in Hertz (Hz), for example, 100Hz.

Sound travels in air at about 340ms^{-1} (metres per second), and this velocity varies slightly with temperature.

Since each compression travels at about 340ms^{-1} , after one second the first compression is 340m away from the source. If the frequency of oscillation is, say 10Hz, then there will be 10 compressions in the distance of 340m, which has been travelled in one second, or 34m between each compression. This distance is called the wavelength of the sound, leading to the relationship:

$$\text{velocity} = \text{wavelength} \times \text{frequency}$$

written in symbols as $c = \lambda \times f$

where c is the velocity of sound in metres per second, λ the wavelength in metres and f the frequency in Hertz.

The equation gives the relation between frequency and wavelength as in the Table below.

Frequency (Hz)	1	10	25	50	100	150	200
Wavelength (m)	340	34	13.6	6.8	3.4	2.27	1.7

Frequency and wavelengths of low frequency sound

In the frequency region 25Hz to 150Hz, wavelengths are of similar size to room dimensions, which can lead to resonances in rooms.

FREQUENCY WEIGHTINGS

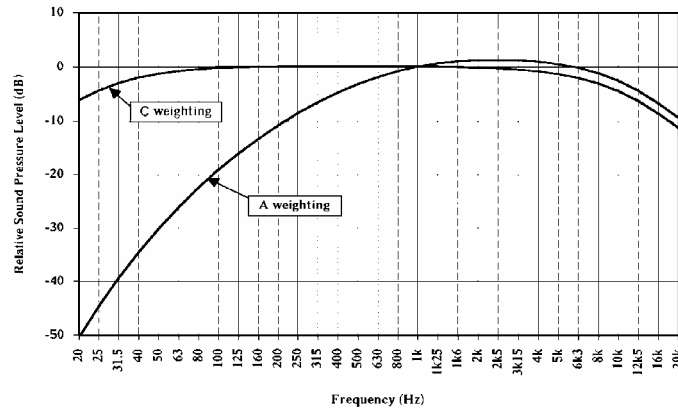
A-WEIGHTING

The A-weighted frequency response is designed to approximate to the inverse of the equal loudness curve that passes through 1,000 Hz at 40dB (the 40phon⁽¹⁾ contour). It is recognised internationally as the frequency-weighting to be used when assessing both environmental and occupational noise. The A-weighting curve is illustrated in the figure below. Sound levels measured using A-weighting are denoted by the symbol **dB(A)** (sometimes also referred to as **dB(A)**), the "A" denoting that the A-weighting characteristic has been used.

It can be seen that when using A-weighting for a given sound pressure level the response of the instrument falls as the frequency falls. For example, a tone of 1,000 Hz at a sound pressure level of 90dB will give an indication on the meter of 90dB (90 minus 0dB) and a 250Hz tone at the same sound pressure level will give an indication of 81.4dB (90 minus 8.6dB). For the same level of input, low frequencies will not have the same effect on the meter as the higher

⁽¹⁾ **Phon:** The unit of loudness is the "phon", which is the level of a 1,000Hz tone that has the same loudness as the test tone when the tones are presented as plane waves, with the subject facing the direction of the waves.

frequencies. The sound level meter is responding to sound in approximately the same way as the human ear.



Frequency-Weighting Curves

C-WEIGHTING

The C-weighted frequency response is designed to approximate to the inverse of the equal loudness curve that passes through 1,000 Hz at 100dB (the 100 phon contour). It is recognised internationally as an alternative frequency-weighting to be used for particular purposes. The C-weighting curve is also illustrated in the figure above. Levels measured using C-weighting are denoted by the symbol **dB(C)** (sometimes **dB(C)**), the “C” denoting that the C-weighting characteristic has been used.

NOTE: When no frequency-weighting is applied in the measurements, the levels are denoted by the symbol **dB**, or sometimes dB(Lin) – the measurements are unweighted.

The C-weighting characteristic gives the meter a flat response characteristic over a wide range of frequencies, from approximately 50 Hz to 4,000 Hz. The response falls at the higher and lower frequencies. C-weighting may be used together with A-weighting to assess the broad-frequency content of a particular sound, particularly whether low frequencies are present at a significant level.

G-WEIGHTING

The G weighting, specifically designed for infrasound, falls off rapidly above 20Hz, whilst below 20Hz it follows assumed hearing contours with a slope of 12dB per octave down to 2Hz. This slope is intended to give a subjective assessment to noise in the infrasonic range. A G-weighted level of 95 - 100dBG is close to the perception level. G-weighted levels below 85-90dBG are not normally significant for human perception. However, too much reliance on the G-weighting, which is of limited application, may divert attention from problems at higher frequencies, say, in the 30Hz to 80Hz range.

BROAD-BAND NOISE

Sound from wind turbines can be normally described as **broad-band** noise. This means that the noise has no distinctive frequency (tonal) characteristics but is composed of a broad spectrum of frequencies covering the entire audible spectrum.

RESONANCE

Resonance occurs in enclosed, or partially open, spaces. When the wavelength of a sound is twice the longest dimensions of a room, the condition for lowest frequency resonance occurs. From the $c = \lambda \times f$ relationship already mentioned, if a room is 5m long, the lowest resonance is at 34Hz – above the infrasonic range.

However, a room with an open door or window can act as a Helmholtz resonator. This is the effect which is similar to that obtained when blowing across the top of an empty bottle. The resonance frequency is lower for greater volumes, with the result that Helmholtz resonances in the range of about 5Hz to 10Hz are possible in rooms of a suitable size and with a suitable door, window or ventilation opening.

MEASUREMENT PARAMETERS

A number of different parameters are used in the measurement of sound or noise. These include:

L_{eq}

The term equivalent continuous sound level, usually referred to as L_{eq} , is the level of the steady continuous noise that contains the same sound energy as the noise under consideration whose level varies with time, over some time interval, T.

The term is often also referred to as L_{Aeq} or $L_{Aeq,T}$ or $L_{Aeq,10m}$ or indeed many other variants. For example, the term $L_{Aeq,10m}$ means that A-weighting was used and the measurement period was 10 minutes ($L_{Aeq,10m}$). The use of a C-weighting or a G-weighting would necessitate the use of "C" or "G" instead of "A" in the expression.

Sound Exposure Level (SEL)

The sound exposure level is a special kind of L_{eq} measurement. It is normally used for transient events and similar situations. An example of its use is for the measurement of aircraft fly-overs where the sound level rises and falls as the aircraft approaches and recedes. The SEL is measured by measuring the L_{eq} for the duration of the event and then compressing this value into a one second period. In effect it is the level of sound present of one second that is equivalent to the actual time varying levels of sound actually present for the duration of the measurement. It is a convenient method of determining the sound energy content of an event so that a number of such events can then be combined to determine an average level of sound.

L_{Amax}

The maximum A-weighted sound pressure level is the highest level of sound present over the measurement period. It is normally used in the case of short duration and transient sound and

is a measure of how high the sound was in level for a short period of time. The averaging time of this measurement parameter is normally of the order of 1/8 of a second.

Averaging

Sound level meters give a numerical representation of the noise.

However, this is obtained by averaging over a period of time that, for fluctuating noises, is generally longer than the period of the fluctuations, leading to a loss of information on the fluctuations. The widespread use of the equivalent level discards important information on the quality of the noise, its spectral properties and corresponding perceived sound character.

6 REVIEW OF THE *GUIDELINES FOR COMMUNITY NOISE: 1999 WORLD HEALTH ORGANISATION (WHO)* ⁽²⁾

At a WHO/EURO Task Force Meeting in Düsseldorf, Germany, in 1992, the health criteria and guideline values were revised and it was agreed upon updated guidelines in consensus. The essentials of the deliberations of the Task Force were published by Stockholm University and Karolinska Institute in 1995. In a recent Expert Task Force Meeting convened in April 1999 in London, United Kingdom, the Guidelines for Community Noise were extended to provide global coverage and applicability, and the issues of noise assessment and control were addressed in more detail. This document is the outcome of the consensus deliberations of the WHO Expert Task Force.

The WHO *Guidelines for Community Noise* dated 1999 is therefore based upon the document entitled *Community Noise (1995)*, written by BIRGITTA BERGLUND of the *Institute of Environmental Medicine, Karolinska Institute and Department of Psychology, Stockholm University* and THOMAS LINDVALL of the *Institute of Environmental Medicine, Karolinska Institute, Stockholm, Sweden*.

This Community Noise document dated 1995 is a revision of the earlier WHO document “Noise” (WHO Environmental Health Criteria 12, Geneva: World Health Organization, 1980) but is expanded largely and supplemented with sections on physiology of hearing and related mechanisms, on psychoacoustics, and on mental and behavioural effects of noise.

WHO COMMUNITY NOISE GUIDELINES

The WHO Guidelines are very sketchy on the subject of low frequency noise, particularly as it relates to low level environmental noise rather than the considerations of much higher levels causing damaging effects on hearing.

There is no reference to wind turbines in the section dealing with industrial noise and the environment or indeed anywhere else in the document.

THE COMPLEXITY OF NOISE AND ITS PRACTICAL IMPLICATIONS

“... the frequency content of each noise will also determine its effect on people, as will the number of events when there are relatively small numbers of discrete noisy events. Combinations of these characteristics determine how each type of environmental noise affects people. These effects may be annoyance, sleep disturbance, speech interference, increased stress, hearing impairment or other health-related effects. Thus, in total there is a very complex multidimensional relationship between the various characteristics of the environmental noise and the effects it has on people. Unfortunately, we do not completely understand all of the complex links between noise characteristics and the resulting effects on people. Thus, current practice is to reduce the assessment of environmental noise to a small number of quite simple quantities that are known to be

⁽²⁾ This WHO document, *Guidelines for Community Noise*, is the outcome of the WHO-expert task force meeting held in London, United Kingdom, in April 1999. It is based on the document entitled “Community Noise” that was prepared for the World Health Organization and published in 1995 by the Stockholm University and Karolinska Institute.

reasonably well related to the effects of noise on people ($L_{Aeq,T}$ for continuing sounds and L_{Amax} or SEL where there are a small number of distinct noise events). These simple measures have the distinct advantage that they are relatively easy and inexpensive to obtain and hence are more likely to be widely adopted. On the other hand, they may ignore some details of the noise characteristics that relate to particular types of effects on people.”

In essence, the report recommends that though the topic is highly complex the best approach is to adopt a pragmatic one — to use a system/methodology that has a reasonable relationship between the measurement parameters and the effects that the noise may have on people. The “errors” associated with this approach are relatively small compared with the benefits accruing from the approach in all other respects. The report does not elaborate on what these details of the noise characteristics or the types of effects concerned are. It can be assumed from the Berglund, however, report that one of the characteristics includes the fact that certain types of low frequency sounds can be more annoying than a simple A-weighted measurement might indicate.

Combinations of the characteristics of, for example, the level, variability in the level, duration, frequency content and apparent loudness determine how each type of noise affects people. These effects may include annoyance, sleep disturbance, speech interference, increased stress, hearing impairment or other health-related effects. Of these the most significant characteristics in the complexities of sound and its practical limitations are probably the frequency content and loudness of a sound.

Noise can be characterized by its frequency content. This can be assessed by various types of frequency analysis to determine the relative contributions of the frequency components to the total noise. The combined effects of the different frequencies on people, perceived as noise, can be approximated by simple frequency weightings. The A-weighting is now widely used to obtain an approximate, single-number rating of the combined effects of the various frequencies. The A-weighting response is a simplification of an equal-loudness contour. There is a family of these equal-loudness contours (ISO226-1,1987) that describe the frequency response of the hearing system for a wide range of frequencies and sound pressure levels. These equal-loudness contours can be used to determine the perceived loudness of a single frequency sound. More complicated procedures have been derived to estimate the perceived loudness of complex sounds (ISO532, 1975). These methods involve determining the level of the sound in critical bands and the mutual masking of these bands.

Many studies have compared the accuracy of predictions based on A-weighted levels with those based on other frequency weightings, as well as more complex measures such as loudness levels and perceived noise levels (see also Berglund & Lindvall 1995). The comparisons depend on the particular effect that is being predicted, but generally the correlation between the more complex measures and subjective scales are a little stronger. A-weighted measures have been particularly criticized as not being accurate indicators of the disturbing effects of noises with strong low frequency components (Kjellberg et al. 1984; Persson & Björkman 1988; Broner & Leventhall 1993; Goldstein 1994). However, these differences in prediction accuracy are usually smaller than the

variability of responses among groups of people (Fields 1986; see also Berglund & Lindvall 1995). Thus, in practical situations the limitations of A-weighted measures may not be so important. In addition to equal-loudness contours, equal-noisiness contours have also been developed for calculating perceived noise levels (PNL) (Kryter 1959; Kryter 1994; see also section 2.7.2). Critics have pointed out that in addition to equal-loudness and equal-noisiness contours, we could have many other families of equal-sensation contours corresponding to other attributes of the noises (Molino 1974). There seems to be no limit to the possible complexity and number of such measures.

The conclusion is broadly that the perceived limitations in using A-weighting rather than some more complex analytical technique is probably not particularly important. The use of other much more complex parameters and techniques has the disadvantage that they will tend to inhibit the use of such methods for use in evaluating problems. The use of a relatively simple method (A-weighting) in effect is probably the best cost-benefit associated with the technique. It should be noted with regard to the disturbing effects of noises with strong low frequency components, that the inaccuracy of using a simple A-weighted measurement are usually smaller than the variability of responses among groups of people, and therefore its use even for this purpose can be considered as a valid method.

The basis for all noise assessments whether they are dealing with infrasound or higher frequency sound is that of reasonableness. This is the requirement in Section 16 of the Resource Management Act 1991. The range of hearing sensitivities within a population are taken into account in setting the appropriate limits of exposure of these populations. It is to be expected that some individuals within a population may be affected in some way, but it would be unreasonable to set exposure limits to account for all sensitivities.

However, although the A-weighted measurement can be considered a valid method of measurement for most sources including wind turbine generators, if there is evidence that levels infrasound from a particular source may be above the threshold of audibility, it may be necessary to evaluate using an alternative weighting or frequency analysis.

The report does not address the effects of low frequency sound or infrasound on people in any more depth than this and there is no reference specifically to wind turbine generators. Broadly speaking it merely indicates that there is a question mark over the relationship between simple A-weighted noise measurements when dealing with low frequency sounds and their effect on people. It could be reasonably assumed therefore that the matter is not particularly important or significant, otherwise it would presumably have been dealt with in a much more rigorous and in depth manner.

7 REVIEW OF COMMUNITY NOISE: 1995 B BERGLUND

As previously stated, the WHO *Guidelines for Community Noise* dated 1999 is based upon this document entitled *Community Noise (1995)*, written by BIRGITTA BERGLUND of the *Institute of Environmental Medicine, Karolinska Institute and Department of Psychology, Stockholm University* and THOMAS LINDVALL of the *Institute of Environmental Medicine, Karolinska Institute, Stockholm, Sweden*.

The document is a critical review of the adverse effects of community noise, including interference with communication, noise-induced hearing loss, annoyance responses, and effects on sleep, the cardiovascular and psychophysiological systems, performance, productivity, and social behaviour.

PHYSICAL ASPECTS OF NOISE

Human hearing is sensitive to frequencies in the range from about 20,000Hz to below 20Hz (the "audio frequency range"). Downwards there is no established limit; frequencies down to at least 2Hz can be detected by the ear (B. Berglund, Hassmén, & Job, 1994). Sound components lower than 16Hz are named infrasound and those higher than 20,000 Hz ultrasound. The human hearing has a very "narrow" range of sensibility at infrasound frequencies. Whereas the sensibility range within the audio frequency range is 120 to 140 dB, the sensibility from barely perceptible to pain is 30 to 40 dB at infrasound frequencies.

Frequencies of sound down to 2Hz or even less can be heard by humans. However, the sensitivity of human hearing at the low frequency end of the scale is very much less than it is in the middle frequencies. The range from the threshold of perception to that of pain is much less in the low frequencies than it is at higher frequencies of sound. This means that a relatively small increase in the level of a very low frequency sound after it is just perceived (heard) can result in a dramatic increase in the loudness of that sound – it doesn't take a large increase to progress from being just audible to being unbearable (a 30dB to 40dB increase at infrasound frequencies whereas the increase is 120 to 140dB in the 20 to 20,000Hz (audio) range of frequencies). In the audio range of frequencies a 10dB increase in the level of a sound in broad terms sounds about twice as loud, however it is ten times as intense. At the lower frequencies around 20Hz and lower this doubling of loudness occurs when the level of the sound is increased by 5dB (about three times as intense).

Thus, at low frequencies, subjective loudness changes more rapidly with changes in sound pressure level than it does at higher frequencies. On the other hand, to become just audible (the threshold of perception or hearing) the sound pressure level of a 20Hz sound needs to be about 75dB whereas one of 1,000Hz needs to be about 4dB. Sound pressure levels lower than this at these frequencies cannot be heard. It should be appreciated therefore that at low frequencies (between 2Hz and 20Hz) the sound pressure level required for a sound to become audible needs to be substantially higher than 75dB (and is frequency dependent).

LOUDNESS

Loudness not only depends on sound energy but also on frequency and other physical parameters. At moderate levels, low-frequency sounds (those below 900Hz) are judged to be less loud than high-frequency sounds (those between 900 to 5,000Hz) when sounds are of equal physical intensity. The frequency weighting function, referred to as A-weighting, was developed to simulate this effect at low sound levels and for pure tones. It is well known that with the use of this weighting it is necessary to use different level limits for different types of sources. Not only the source itself but also the listener's attitude is of importance.

The A-weighting function is widely used to obtain index measures of community noise. One should realize, however, that a single weighting function used for various sound pressure levels cannot reflect the perception or other adverse effects of different noises. For example, two sources of community noise that are equal in dBA may differ substantially in loudness (e.g., B. Berglund, U. Berglund, & Lindvall, 1975a, 1976; Goldstein, 1994).

The conclusion is that the equal loudness contours based on broad-band noise often are not applicable to community noises.

It should be appreciated that low frequency sound is normally taken to mean sounds with frequencies between 20 and 900Hz (and many people quote other ranges such as 16 to 400Hz etc) and infrasound is normally taken to be frequencies below 20Hz (and some people consider the break point to be 16Hz rather than 20Hz). The use of a relatively simple parameter such as A-weighting sometimes tends to "break down" and may not be truly applicable. In some circumstances a more complex approach is needed. The debate concerning the use of the measurement of loudness is seen to be inconclusive. The term "loudness" is often used in the broadest sense to indicate the subject's feeling about a noise.

LIMITATIONS OF A-WEIGHTED SOUND PRESSURE LEVEL (SPL) AS A MEASURE OF LOUDNESS

In the past, sound pressure level has been measured widely by A-weighting. At the same time, both in the laboratory and in the field evidence has accumulated that A-weighting predicts loudness and annoyance of community noise rather poorly. Not only does A-weighted sound pressure level underestimate the impact of the low-frequency components of noise (Goldstein, 1994), but it is also strongly dependent on the exposure pattern with time.

The A-weighting filter is unrepresentative of the loudness of sounds containing a mixture of noises and tonal components. In such cases, A-weighted sound pressure level is less suitable for the prediction of loudness or annoyance. That is also true for noise containing most of its energy in the low-frequency range of 15Hz - 400Hz. It may then under-predict perceived loudness by 7 to 8dBA, relative to a 1,000Hz target noise (Kjellberg & Goldstein, 1985). The reason is that loudness increases due to bandwidth increase and that spectrum shape is not accounted for to a satisfactory degree by the A-weighting filter (cf. Zwicker, 1987). A decrease in A-weighted sound pressure level can

result in a corresponding increase in loudness (Hellman & Zwicker, 1982) or annoyance. This clearly reveals the shortcoming of using overall SPL, either un-weighted or A-weighted, as an indicator of loudness and annoyance.

Though this indicates that there are some deficiencies in the use of the simple A-weighted noise measurement parameter, it also indicates that the deficiencies are relatively small – an underestimation of perhaps 7 – 8dBA when using A-weighting as opposed to use of more complex analysis methods when dealing with noise containing most of its energy in the frequency range of 15 to 400Hz.

EFFECTS OF NOISE ON HUMANS

Frequencies below 16Hz (or 20Hz) are referred to as infrasonic frequencies. Infrasound is audible. However, the human hearing has a very narrow dynamic range at infrasonic frequencies; the range from the first soft perception to pain is only 30-40 dB. Perception of sound from 100Hz down to about 2Hz is a mixture of auditory and tactile sensations. For example, frequencies around 10Hz, can cause discomfort through a modulation of the vocal cords. But the main sensitive organ for sound at frequencies below 20Hz is within the ear and not in the breast or stomach. There is no reliable evidence that infrasounds below the hearing threshold produce physiological or psychological effects. Infrasounds slightly above detection threshold may cause perceptual effects but these are of the same character as for "normal" sounds.

It is important to understand that infrasound, which is normally considered to be below the range of human hearing (20Hz), is still in fact heard through the hearing mechanism. It is also heard rather more than it is felt as vibration through other parts of the body. It is also important to realise that there is no reliable evidence that would indicate any effects when infrasound is present at a level below the hearing threshold. This is probably the most important fact that should be borne in mind. This could be interpreted as, "if it is not heard it results in no effect". This also applies to all the other audible frequencies of sound.

In order to assess whether there is likely to be a problem with low frequency sound from wind turbine generators, it is therefore important to determine the level of infrasound and low frequency sound that is present at places where people live to determine the potential for any effects. However this requirement has problems when predicting the likely level of sound near wind turbines, in that there appears to be little if any data on the sound emissions from wind turbine generators in the very low frequencies.

EFFECTS ON RESIDENTIAL BEHAVIOUR AND ANNOYANCE

Low frequency noise is common as background noise in urban environments and as an emission from many artificial sources: road vehicles, aircraft, industrial machinery, artillery and mining explosions, and air movement machinery including wind turbines, compressors, and indoor ventilation and air conditioning units (Tempest, 1976; Leventhall, 1988). The effects of low-frequency noise are of particular concern because of its pervasiveness due to numerous sources, efficient propagation and reduced efficacy

of many structures (dwellings, walls, and hearing protection) in attenuating low frequency noise compared with other noise (B. Berglund, Hassmén, & Job, 1994). ...

There appears to be particular concern because low frequency sound travels through the air more efficiently than high frequency sound. There are three main factors affecting by how much the sound reduces in level as it travels away from the sound source:

- Ground Effect – as sound travels through the air close to the ground, some of the energy in the sound wave is removed because of sound absorption by the ground cover.
- Molecular Absorption – there is an interaction of air molecules as a sound propagates (travels away from the source) and this causes sound energy to be removed by this interaction – a sort of frictional effect.
- Spherical Radiation – a sound wave spreads out in all directions from the source of sound and as it does so the sound energy is spread out over a larger and larger area (it becomes diluted) and this diminishes the level of the sound as the distance from the source increases.

The amount of ground absorption is dependent on a number of factors, including: how close to the ground the sound is travelling (is the source close to the ground or is it high on a hill with the sound travelling across a valley?); the frequency content of the sound (lots of high frequencies or low frequencies), the type of ground cover (trees and shrubs, long grass, bear earth, concrete). The amount of ground absorption adds to the amount of sound that is reduced as it travels across the ground:

The effect of molecular absorption is greater for high frequency sound than low frequencies. This means that there is a greater reduction for high frequency sound as it travels away from the source than for low frequency sound.

It is important to understand that the ground absorption effect and the molecular absorption effects are additional to the reduction due to spherical radiation. All frequencies of sound reduce in level as they travel away from the source of sound. The sound level reduces by 6dB every doubling of the distance travelled.

When sounds contact buildings the amount that penetrates depends on the frequency of the sound. For a given weight of structure, low frequencies penetrate more efficiently than higher frequencies – low frequency sound is hard to stop

Although the effects of lower intensities of low frequency noise are difficult to establish for methodological reasons, evidence suggests that a number of adverse effects of noise in general may be greater for low frequency noise than for the same noise energy in higher frequencies:

- *loudness judgments and annoyance reactions are greater for low frequency noise than other noises for equal sound pressure level regardless of which weighting scheme is employed (Goldstein, 1994);*
- *annoyance is exacerbated by rattle or vibration induced by low frequency noise;*

- *speech intelligibility may be reduced more by low frequency noise than other noises (except those in the frequency range of speech itself because of the upward spread of masking) (Pickett, 1959; Loeb, 1986).*

Noises with low-frequency components contribute to annoyance in at least three different ways (Lindberg & Backteman, 1988):

- (1) A feeling of static pressure is produced by low-frequency components if they reach levels and frequencies above a certain threshold. Such "ear-pressure" may be produced, for example, by riding in a car for at least half a minute with the window slightly opened so constituting a Helmholtz resonator. (A cavity that is used to absorb sound – the effect is like blowing across the top of a partly filled bottle producing a particular frequency of sound that depends on the volume of the bottle).*
- (2) Low-frequencies produce periodic masking effects in medium and higher frequencies. Speech sounds are strongly amplitude modulated, and conversation is disturbed although speech remains intelligible. The effect can be measured quantitatively by so-called masking-period patterns.*
- (3) Strong low-frequency components produced by aircraft may rattle doors, windows, and other contents of houses.*

These secondary physical sound sources may be much more annoying than the original primary low frequency component. The general use of the A-weighting filter attenuates the low frequencies so that the A-weighted sound pressure level does not reflect the true impact of the noise load. A common practice is, therefore, to measure both A-weighted and C-weighted sound pressure levels, and by comparison identify the potential impact of low-frequencies in exposures. With various sources, such as heavy trucks and trains or particular industrial plants, both noise and vibration effects occur. People are disturbed and annoyed by both factors; they also tend to "mix up" these effects or to perceive vibration as noise (Kryter, 1985, 1994; Griffin, 1990; Howarth & Griffin, 1990; Meloni & Krüger, 1990; Kastka & Paulsen, 1991).

Although firm scientific evidence is lacking, some consider by experience, that noise with a high proportion of low frequency components in some instances may be better tolerated by people than noises with a high proportion of high frequency components. However, comparison of socio-acoustic survey results from different noise sources supports a greater reaction (for equal loudness) to sources with more low frequency noise. Reaction to aircraft noise is, thus, generally greater than reaction to road noise and this difference has been identified in direct comparison (Hall, Birnie, Tayler, & Palmer, 1981).

The effects described concerning behaviour and annoyance are of course, related to the levels of the sound that can be heard. They are also relevant to broad band types of noise at a relatively low loudness level. The effects from low frequency sounds can be greater (pro rata) than for higher frequency sound spectra. The amount is not stated but this is indicated elsewhere as being perhaps of the order of 7 to 8dBA. C-weighting also reduces the level of

the very low frequencies of sound (below about 50Hz) but to a lesser degree than does the A-weighting.

The secondary effects such as rattling windows may tend to highlight to a person that there is something present even though they may not be able to hear it. When the term “strong low frequency components” is used, this is not elaborated upon, but the example used of aircraft noise indicates that what is probably meant is that there are tonal components present in the sound as opposed to a broad band type of noise containing different frequencies of sound on a continuum. This being the case, the effects described may not be applicable to wind turbine generators since they do not normally have any tonality (do not consist of strong individual low frequency components of sound).

SUMMARY

The annoyance-inducing capacity of a noise depends mainly upon its intensity and spectral characteristics, and variations of these with time. However, annoyance reactions are sensitive to many non-acoustic factors of a social, psychological, or economic nature and there are considerable differences in individual reactions to the same noise. Furthermore, community annoyance varies with activity (speech communication, relaxation, listening to radio and TV, etc.). Annoyance is affected by the equivalent sound level, the highest sound level of a noise event, the number of such events, and the time of the day. The method of combining these parameters of noise exposure to an indicator for the observed annoyance level has been extensively studied. The data are not inconsistent with the simple, physically based equivalent energy theory, which is represented by the L_{eq} index, and which in many cases is a fairly acceptable approximation. However, there is a growing concern that all the parameters mentioned should be assessed in noise exposure investigations, at least in the complex cases. The reason for this is that the non-acoustic factors are known to interfere in annoyance and, therefore, simple measures such as L_{Aeq} may only have face validity. It should be noted that a large proportion of low frequency components in the noise may increase annoyance considerably. Where prominent low frequency components are present, they should be assessed.

The use of the L_{eq} parameter is accepted as a valid and workable method of measurement.

The variables mentioned including variable levels, events and frequency if events, impulses etc all relate to types of sound sources significantly different from and more complex than wind turbines. The limitations in the use of an A-weighted L_{eq} measurement may not apply to the same extent to the relatively simple case of a constant broadband noise source such as a wind turbine.

The case of wind turbine generators is not complex compared with other sources of sound, The frequency spectrum of these types of devices is also relatively simple – it is normally broad banded in nature and should not require any further assessment than the simple case scenario.

8 REVIEW OF A REVIEW OF PUBLISHED RESEARCH ON LOW FREQUENCY NOISE AND ITS EFFECTS BY DR GEOFF LEVENTHALL (DEFRA REPORT)

The DEFRA report entitled *A Review of Published Research on Low Frequency Noise and its Effects* by Dr Geoff Leventhall and assisted by Dr Peter Pelmeare and Dr Stephen Benton was published in May 2003. It is therefore the most up to date critical review of all the known recognised research data on the subject of low-frequency sound. It addresses all aspects of low frequency and infrasound including the effects at high levels of exposure. The review document includes consideration of various levels of low frequency sound and infrasound including those possibly associated with wind turbines, but it is limited with regard to the levels of sound that can be expected from wind turbines.

The study considers some properties of low frequency sounds, their perception, effects on people and the criteria which have been developed for assessment of their effects. Proposals are made for further research, to help to solve the continuing problems of low frequency environmental noise.

LOW FREQUENCY NOISE AND INFRASOUND — The frequency range of infrasound is normally taken to be below 20Hz and that of audible noise from 20Hz to 20,000Hz. However, frequencies below 20Hz are audible, illustrating that there is some lack of clarity in the interpretations of infrasonic and audible noise. Although audibility remains below 20Hz, tonality is lost below 16-18Hz, thus losing a key element of perception. Low frequency noise spans the infrasonic and audible ranges and may be considered as the range from about 10Hz to 200Hz. The boundaries are not fixed, but the range from about 10Hz to 100Hz is of most interest. In later chapters infrasound and low frequency noise will not be separated, but consider the range from 10Hz to 200Hz as continuous.

This essentially reiterates the content of the Berglund review but with some differences in the meanings of terms such as low frequencies (10 to 200Hz). Obviously the term “low frequency sound” is a grey area and has different meaning to different people. The common approach is to class 20Hz to a few hundred Hz as low frequency, a few hundred Hertz to a few thousand Hertz as middle frequencies and those above that to 20,000Hz as high frequency sound.

INFRASOUND — There are a number of misconceptions about infrasound, such as that infrasound is not audible. It can be shown that frequencies down to a few hertz are audible at high enough levels. Sometimes, although infrasound is audible, it is not recognised as a sound and there is uncertainty over the detection mechanism. Very low frequency infrasound, from a fraction of a hertz to several hertz, are produced by meteorological and similar effects and, having been present during all of our evolution, are not a hazard to us. Much of what has been written about infrasound in the press and in popular books is grossly misleading and should be discounted.

This latter reference, I believe, probably includes reference to the use of infrasound as a destructive weapon etc.

RESONANCE — Resonance occurs in enclosed, or partially open, spaces. When the wavelength of a sound is twice the longest dimensions of a room, the condition for lowest frequency resonance occurs. From $c = \lambda \times f$, if a room is 5m long, the lowest resonance is at 34Hz, which is above the infrasonic range. However, a room with an open door or window can act as a Helmholtz resonator. This is the effect which is similar to that obtained when blowing across the top of an empty bottle. The resonance frequency is lower for greater volumes, with the result that Helmholtz resonances in the range of about 5Hz to 10Hz are possible in rooms with a suitable door, window or ventilation opening.

This Helmholtz resonator effect is likely to change however as the doors and/or windows are opened and closed – a bit like putting the cap on the bottle. In order to achieve resonance in the 5 to 10Hz range, with a standard size door or medium sized window, the room volume will need to be large.

It is therefore possible that this effect could occur where high enough levels of infrasound are present. However, it is unlikely to occur to any significant extent in the situations where the level of infrasound is low.

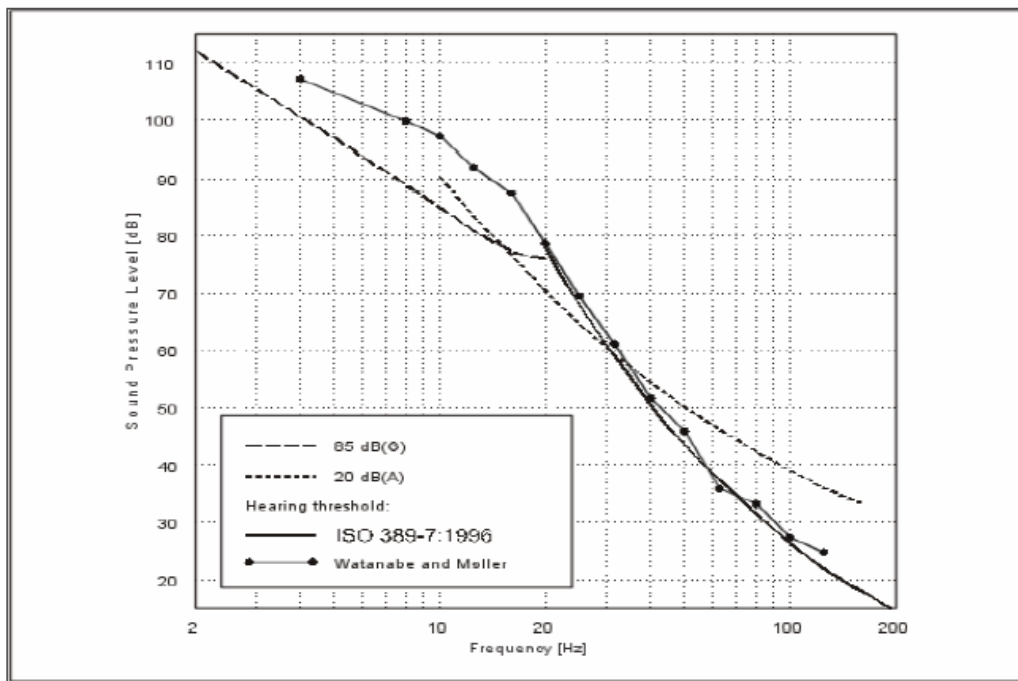
LOW FREQUENCY NOISE — The range from about 10Hz to 200Hz covers low-frequency noise. For comparison, the lowest C note on a full range piano is at about 32Hz whilst middle C is at about 261Hz. All the low frequency noise range is audible, although high levels are required to exceed the hearing thresholds at the lower frequencies.

This is a good simple explanation of the effect. See the section on threshold values for further explanation.

MEASUREMENTS — For environmental noise it is normal to use the sound level meter A-weighting, which gradually reduces the significance of frequencies below 1,000Hz, until at 10Hz the attenuation is 70dB. The C-weighting is flat to within 1dB down to about 50Hz and then drops by 3dB at 31.5Hz and 14dB at 10Hz. The G weighting, (ISO7196, 1995), specifically designed for infrasound, falls off rapidly above 20Hz, whilst below 20Hz it follows assumed hearing contours with a slope of 12dB per octave down to 2Hz. This slope is intended to give a subjective assessment to noise in the infrasonic range. A G-weighted level of 95 — 100dBG is close to the perception level. G-weighted levels below 85 — 90dBG are not normally significant for human perception. However, too much reliance on the G-weighting, which is of limited application, may divert attention from problems at higher frequencies, say, in the 30Hz to 80Hz range.

The G-weighting curve can be seen in the section dealing with National and International Standards later in this report. The G-weighting is an attempt to enable the measurement of infrasound in the presence of higher frequency sound – a normal state of affairs. The weighting characteristic is designed to cut out the higher frequency sounds than about 20Hz and at the same time apply a weighting that is consistent with how people hear infrasound – the lower the frequency the higher the level needs to be to have the same subjective loudness as a higher frequency.

CURRENT THRESHOLD VALUES — The thresholds found by Watanabe and Møller (1990b) are shown in the figure below, which also includes the limit of 85dBG up to 20Hz and 20dBA in the range 10-160Hz. The threshold measurements from 20Hz to 125Hz are very close to the ISO 389-7 threshold (ISO389-7, 1996). The figure below gives the threshold at 4Hz as about 107dB, at 10Hz it is 97dB, at 20Hz it is 79dB and at 50Hz it is 46dB. Note that, at about 15Hz, there is a change in threshold slope from approximately 20dB/octave at higher frequencies to 12dB/octave at lower frequencies. This is a consistent finding by different experimenters, occurring within the range 15Hz to 20Hz, depending on which frequencies have been used in the measurements. It has not been fully explained, but is thought to be due to a change in the aural detection process, occurring in the frequency region at which tonality of the auditory sensation is lost.



Threshold levels after Watanabe and Møller (1990b).

The change in the slope of the threshold curve (the top one in the diagram above) at around 16Hz to a less sloping characteristic means that the fall off in the sensitivity of hearing versus frequency at very low infrasound frequencies is not as great as it is at frequencies above about 16Hz. This is one of the reasons why the A-weighting characteristic underestimates the subjective loudness of these infrasound frequencies. This “break point” at 16Hz is probably why some writers consider infrasound to be below 16Hz rather than 20Hz.

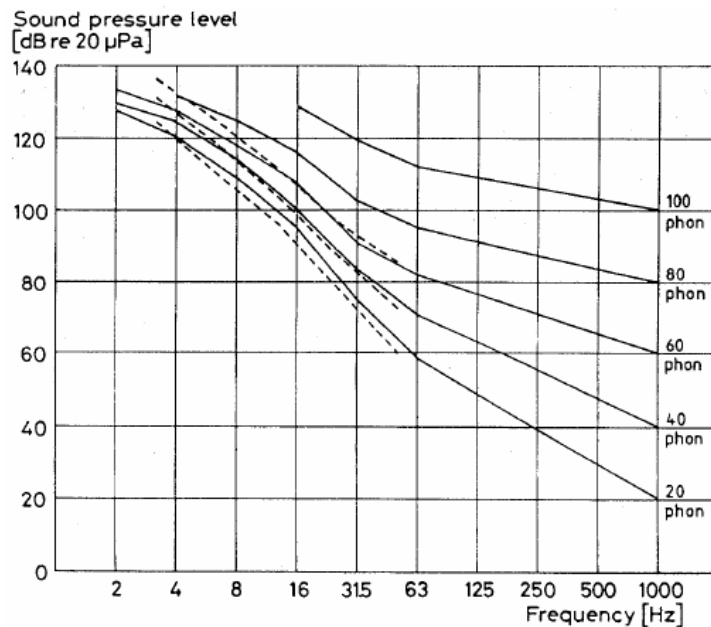
INDIVIDUAL THRESHOLDS — The threshold levels are averaged over groups of subjects. The threshold of an individual may differ from the average. Investigations at higher frequencies have shown that an individual threshold exhibits a microstructure, in which there are fluctuations in sensitivity of up to 12dB at specific tones (Cohen, 1982). Further investigations of this effect were made at both low and high frequencies (Benton, 1984;

Frost, 1980; Frost, 1987). For example, Frost (1987) measured thresholds at 5Hz intervals over the range 20Hz to 120Hz with results which compares two subjects, one of whom is about 15dB more sensitive than the other at 40Hz. Both subjects had similar audiograms at 250, 500 and 1000Hz.

People vary greatly in looks, height, size etc and their sensitivity to sounds also varies greatly. In addition, though individuals when tested for hearing acuity appear to have the same sensitivity to a range of sounds, their hearing can actually vary significantly in the fine detail, so to speak.

Some threshold investigations at low frequencies have also included measurement of equal loudness contours (Lydolf and Møller, 1997a; Watanabe and Møller, 1990a; Whittle et al., 1972; Yeowart, 1976). Equal loudness contours above 20Hz illustrate the trend that, as the frequency reduces, the contours come closer together. Thus the 80 phon range of loudness at 1,000Hz, from 10dB to 90dB, spanning 80dB, is compressed into 40dB at 20Hz. The mid-frequency rule of thumb that a 10dB increase in level represents a doubling of loudness, fails at low frequencies. At 20Hz a doubling of loudness occurs for a level change about 5dB, and requires a smaller change at lower frequencies.

The main loudness level measurements at very low frequencies have been by (Møller and Andresen, 1984; Møller and Andresen, 1984; Whittle et al., 1972). Figure 9, from Møller and Andresen, compares the results. Møller and Andresen made measurements at octave frequencies from 2Hz up to 63Hz. Whittle's measurement frequencies were at octaves between 3.15Hz and 25Hz, followed by third octave frequencies to 50Hz. There is good agreement over the main range with the continuing tendency for the contours to become closer as the frequency reduces. The more rapid growth in loudness at low frequencies is an important factor in its subjective effects.



Loudness Measurements: ——— Møller and Andresen - - - - Whittle

The curves are intended to illustrate that as the frequency reduces the curves come closer together illustrating the fact that the “dynamic range” (from threshold to discomfort) of human hearing at lower and lower frequencies becomes smaller. The result is that a doubling of subjective loudness occurs with a smaller increase in the sound pressure level at lower frequencies (5dB compared with 10dB at higher frequencies).

FALSE PERCEPTIONS — There is always low frequency noise present in an ambient “quiet” background. Origins are often from transportation or industrial sources, which are too far away to be clearly identified. However, depending on the type of location, typical levels might rise rapidly below 50Hz and reach 40-50dB at frequencies below 20Hz. An investigator may conclude that this rise in low frequency levels is the source of the complaint, neglecting that the threshold at 20Hz is higher than 70dB. As a general rule, broadband noise which is more than 20dB below the average threshold is unlikely to be a problem, as it lies below the threshold of the most sensitive persons.

The instances when a noise is heard by a complainant, but cannot be measured or detected by instruments at significant levels, make it necessary to consider the possibility that a mechanism other than an airborne sound is responsible, leading to a false perception of noise. Potential origins of false perceptions include tinnitus, electromagnetic waves, synaesthesia, hypnagogic effects and the “cognitive itch”.

The source of low frequency sounds can be hard to locate. The frequency and hence the wavelength of the sound determines how fine the localisation of the sound can be. Because of the long wavelengths involved, infrasound when audible will appear to be everywhere and not be coming from any particular direction. This effect is the reason why, in home stereo systems, only one sub-woofer loudspeaker is necessary – a stereo effect does not occur at low frequencies.

It can be difficult and dangerous to attribute a particular “sound” or effect to a particular potential source where low frequencies of sound are concerned. There are many instances in New Zealand where people have alleged noises are present and objective measurement simply cannot detect anything present. Even if it were detected but was at a very low level, based on any reasonable objective criterion the level would probably be deemed to be reasonable.

In any event, audibility of a sound should not be a criterion when assessing low frequency or infrasound. It is not a criterion that is used in any other type of noise assessment. It cannot be confirmed objectively (with measurements). Other environment noise is assessed on reasonableness of the level. Noise limits placed on most industrial activities allow for some increase in the level of the emission over the background level of noise. There is no reason why the same approach should not apply in the case of infrasound.

dBC — dBA WEIGHTING — The difference between C and A-weightings has also been considered as a predictor of annoyance (Broner, 1979; Kjellberg et al., 1997), as this difference is an indication of the amount of low frequency energy in the noise. If the difference is greater than 20dB, there is the potential for a low frequency noise problem. Kjellberg et al used existing noise in work places (offices, laboratories, industry etc) with 508 subjects. Three sub-groups were obtained with a maximum difference in low and

high frequency exposure. The conclusions on correlations of (dBC - dBA) difference and annoyance were that the difference is of limited value, but, when the difference exceeds 15dB, an addition of 6dB to the A-weighted level is a simple procedure. However, the difference breaks down when the levels are low, since the low frequencies may then be below threshold. The difference cannot be used as an annoyance predictor, but is a simple indicator of when further investigations may be necessary.

Disturbance from noise of industrial plants was investigated by Cocchi (Cocchi et al., 1992). Comparisons were made of loudness evaluations and various weighted levels and it was suggested that the difference between linear and A-weighting could be used as an assessment. For the spectra investigated, lower values of dBA (20 - 35dBA) correlated with higher (dBLIN - dBA) differences of 20 to 30dB. For high values of dBA (60 - 70dBA), the difference varied from 10-30dB, but mainly clustered in the 10 - 20dB range. This is possibly because noise with low dBA values might be associated with a higher proportion of low frequencies. Advantages of (dBLIN - dBA) over (dBC - dBA) were not discussed.

The use of A-weighted measurements in conjunction with either C-weighted or Linear measurements seems to be an unnecessary complicated procedure. If there is a suspected high level of low frequency or infrasound emission it would be preferable to measure the frequency spectrum directly. Frequency analysers are commonly used these days for day to day analysis so the dBC – dBA procedure is an unnecessary step.

LOW FREQUENCY NOISE AND SLEEP — Although exposure to low frequency noise in the home at night causes loss of sleep, there is evidence that low frequency noise under other conditions induces short sleep periods (Fecci et al., 1971; Landström and Byström, 1984; Landström et al., 1985; Landström et al., 1991; Landström et al., 1982; Landström et al., 1983). Fecci et al monitored workers exposed to noise from air conditioning in a laboratory. The noise peaked at 8Hz with a level of 80dB, but also included broadband noise at higher frequencies. It was found, by EEG recording, that subjects exposed to the noise exhibited a much higher percentage of drowsiness than that found in a non-exposed population. Landström and his colleagues carried out a series of laboratory evaluations of physiological effects of low frequency sound, with particular reference to sleep periods, as detected by EEG recordings. The main conclusions from this work are:

- *Exposure to intermittent noise at 16Hz and a level of 125dB was an effective stimulus of reduced wakefulness*
- *When stimuli at 6Hz and 16Hz were at 10dB below and 10dB above the hearing threshold, the levels above threshold led to a reduced wakefulness. The levels below threshold did not have this effect.*
- *When 10 deaf and 10 hearing subjects were exposed to 6Hz at 115dB for 20 minutes, reduced wakefulness was found amongst the hearing subjects, but not the deaf ones. This indicates that the effects depend on cochlear stimulation, since the noise was above threshold level.*

- *A reduction in wakefulness occurred during a repeating 42Hz signal at 70dB, whilst an increase in wakefulness occurred for a repeating 1,000Hz signal at 30dB.*
- *Exposure to ventilation noise with and without tones indicated greater fatigue in the presence of the tone. A masking noise (pink noise) added to the ventilation noise tended to counteract this effect.*

The work by Landström and colleagues shows that low frequency noise above the threshold of hearing leads to reduction in wakefulness. This does not contradict Fecci, although the spectrum for the workers investigated by him was below threshold at the peak of 8Hz, as the spectrum was above the threshold at frequencies greater than 20Hz. Fecci may have been mistaken in attributing the effects he observed to the frequencies below 20Hz.

Any effect requires the stimulus of the cochlear (the hearing organ in the inner ear) and requires the level of the sound to be above the hearing threshold. This work appears to indicate that levels of infrasound just above the hearing threshold tend to help with sleep whereas higher frequency sound results in the opposite effect.

LOW FREQUENCY NOISE AND STRESS — Stresses may be grouped into three broad types: cataclysmic stress, personal stress and background stress. Cataclysmic stress includes widespread and devastating physical events. Personal stress includes bereavements and similar personal tragedies. Cataclysmic and personal stresses are evident occurrences, which are met with sympathy and support, whilst their impacts normally reduce with time. Background stresses are persistent events, which may become routine elements of our life. Constant low frequency noise has been classified as a background stressor (Benton, 1997b; Benton and Leventhall, 1994). Whilst it is acceptable, under the effects of cataclysmic and personal stress, to withdraw from coping with normal daily demands, this is not permitted for low level background stresses. Inadequate reserves of coping ability then leads to the development of stress symptoms. In this way, chronic psychophysiological damage may result from long-term exposure to low-level low frequency noise.

Changes in behaviour also follow from long-term exposure to low frequency noise. Those exposed may adopt protective strategies, such as sleeping in their garage if the noise is less disturbing there. Or they may sleep elsewhere, returning to their own homes only during the day. Others tense into the noise and, over time, may undergo character changes, particularly in relation to social orientation, consistent with their failure to recruit support and consent that they do have a genuine noise problem. Their families and the investigating EHO may also become part of their problem. The claim that their "lives have been ruined" by the noise is not an exaggeration, although their reaction to the noise might have been modifiable at an earlier stage.

Since there are no effects in people where the level of sound is inaudible, the described effects relate to levels of sound above the threshold of audibility. In the case of infrasound this means a level of at least 90dBG. Any effects will be dependent on the level of the sound above the threshold of audibility, and will probably be more likely to occur as the level of sound increases.

AUDITORY SENSITIVITY — Special difficulties arise when, despite persistent complaints, there is no "measurable" noise, or the noise levels at low frequencies are in the 40 - 50dB range, well below threshold. Van den Berg supports tinnitus as an explanation in these circumstances (van den Berg, 2001). With respect to audibility, the average threshold levels must be interpreted carefully. Van den Berg's choice of a limit criterion is the low frequency binaural hearing threshold level for 10% of the 50 - 60 year old population, which is 10-12 dB below their average hearing level (van den Berg and Passchier-Vermeer, 1999a). This may be too strict, since 10% of the age group has more sensitive hearing. For example, in England, which has a population of about 49 million, there are nearly 5 million in the 50 - 59 year age group. Thus, 500,000 of this age group in England will be more sensitive than the suggested cut-off for perception of low frequency noise. Yamada et al (1980) found one subject to be 15dB more sensitive than the average, whilst recent work (Kitamura and Yamada, 2002), gives two standard deviations from the average threshold as about 12dB. However, the average threshold of the complainants in this work is somewhat higher than the ISO 226 threshold. A range of two standard deviations covers 95% of people. Based on Kitamura and Yamada, three standard deviations, assuming a random distribution, is given by 18dB from the average threshold and covers 99% of the population. The remaining 1% includes 0.5% who are more sensitive than the three standard deviation limit and 0.5% less sensitive than this limit, at the opposite side of the average threshold. 0.5% of the population of England is about 245,000 persons, whilst 0.5% of the 50 - 60 year age group is about 25,000 people, who might have very sensitive low frequency hearing. A "rule of thumb" may be to take 15 - 20dB below the ISO 226 threshold as the cut off for perception, but this is a very generous level, depending on the complainants hearing level at low frequencies.

The threshold of hearing for a population of people varies greatly. Some people have a threshold of hearing at a particular frequency that is 15dB lower than the average, and similarly some people have hearing that is less sensitive. The spread of sensitivities at a particular frequency is measured by a value called a Standard Deviation. This is a mathematical measure of the variability of the numbers involved – the greater the spread of sensitivities the bigger the standard deviation. In a population of people, by deducting one, two or three Standard Deviation values from the mean threshold value results in what percentage of that population will still be able to hear a sound at a particular level below the mean threshold level. The question of what threshold should be used depends on the spread of hearing acuity.

The sensitivities referred to are related to low-frequency sound rather than infrasound. The ISO 226 Standard deals with normal threshold of hearing at frequencies above 20Hz and therefore cannot be used in the assessment of the infrasound situation.

SURVEYS OF OCCURRENCE AND EFFECTS — In a catalogue of 521 social surveys (Fields, 2001), there are four which are specific to low frequency noise. Two of these are for clearly identified transport sources - air and rail - two are for noise from other sources (Mirowska and Mroz, 2000; Persson and Rylander, 1988). However, a number of additional surveys, either not listed by Fields or too recent for inclusion, have also been

carried out (Møller and Lydolf, 2002; Persson-Waye and Bengtsson, 2002; Persson-Waye and Rylander, 2001; Tempest, 1989; Yamada et al., 1987).

A database of low frequency noise problems has been established in Japan by collecting the results of published work (Yamada et al., 1987). 206 datasets were obtained giving personal details, including individual threshold measurements, the type of complaint and measured levels. Some main points from the survey are: At the lower frequencies, below 16Hz, the levels which cause complaints of rattling of light-weight building components are below the hearing threshold; and the minimum measured threshold (of hearing) is 10-15dB below the average threshold.

This data indicates that levels of frequencies below 16Hz and below the hearing threshold can cause lightweight building elements (unspecified) to rattle. How this relates to New Zealand building materials is unknown. The threshold level at frequencies below 16Hz is in excess of 90dB.

NOISE ON HEALTH — The results of a recent survey of complaints about infrasound and low frequency noise on 198 persons in Denmark (Møller and Lydolf, 2002) revealed that nearly all reported a sensory perception of sound. They perceived the sound with their ears, but many mentioned also the perception of vibration, either in their body or in external objects. The sound disturbs and irritates during most activities, and many considered its presence as a torment to them. Many reported secondary effects, such as insomnia, headache and palpitation. These findings support earlier reports in the published literature.

At very high sound pressure levels (greater than 140dB), ear pain and pressure become the limiting factors. Direct evidence of adverse effects of exposure to low-intensity signals (less than 90dB) is lacking.

The primary effect of infrasound in humans appears to be annoyance. (Andresen and Møller, 1984; Broner, 1978a; Møller, 1984). To achieve a given amount of annoyance, low frequencies were found to require greater sound pressure than with higher frequencies; small changes in sound pressure could then possibly cause significantly large changes in annoyance in the infrasonic region (Andresen and Møller, 1984). Beginning at 127 to 133dB, pressure sensation is experienced in the middle ear (Broner 1978a). Regarding potential hearing damage Johnson (Johnson, 1982) concluded that short periods of continuous exposure to infrasound below 150dB are safe and that continuous exposures up to 24 hours are safe if the levels are below 118dB.

There are no known links to wind turbine generators of the population base referred to here. It is noted that there is a lack of any evidence of adverse effects at levels of infrasound less than 90dB. Where there is an effect when the level is high enough, it seems to be one of annoyance rather than other effects. The levels quoted are in the range of 118dB to 133dB. This level of sound in the infrasound region of the frequency spectrum at distances of several hundreds of metres from the source of the sound would require a sound power level at the source in the region of 175dB to 190dB – an overpressure of almost one atmosphere. Though interesting, this level of emission does not relate in any practical way to wind turbine generators.

BIOLOGICAL EFFECTS ON HUMANS — In the numerous published studies there is little or no agreement about the biological activity following exposure to infrasound. Reported effects include those on the inner ear, vertigo, imbalance etc.; intolerable sensations, incapacitation, disorientation, nausea, vomiting, bowel spasm; and resonances in inner organs, such as the abdomen and heart. Workers exposed to simulated industrial infrasound of 5 and 10Hz and levels of 100 and 135dB for 15 minutes reported feelings of fatigue, apathy and depression, pressure in the ears, loss of concentration, drowsiness, and vibration of internal organs. In addition, effects were found in the central nervous system, cardiovascular and respiratory systems (Karpova et al., 1970). In contrast, a study of drivers of long distance transport trucks exposed to infrasound at 115dB found no statistically significant incidence of such symptoms (e.g. fatigue, subdued sensation, abdominal symptoms, and hypertension (Kawano et al., 1991).

Although the effects of lower intensities are difficult to establish for methodological reasons, evidence suggests that a number of adverse effects of noise in general arise from exposure to low frequency noise: loudness judgements and annoyance reactions are sometimes reported to be greater for low frequency noise than other noises for equal sound pressure level; annoyance is exacerbated by rattle or vibration induced by low frequency noise; and speech intelligibility may be reduced more by low frequency noise than other noises except those in the frequency range of speech itself, because of the upward spread of masking. Intense low frequency noise appears to produce clear symptoms including respiratory impairment and aural pain. On the other hand it is also possible that low frequency noise provides some protection against the effects of simultaneous higher frequency noise on hearing (Berglund et al., 1996).

The effects relate to high levels of exposure, for example, in the working environment. In relation to the lower levels of intensity, it is recognised that the effects, if any, are difficult to establish with any degree of certainty. They are unlikely to relate in any real way to emissions from wind turbine generators at the distances where people are likely to live.

GENERAL REVIEW OF EFFECTS OF LOW FREQUENCY NOISE ON HEALTH - CONCLUSION — There is no doubt that some humans exposed to infrasound experience abnormal ear, central nervous system, and resonance induced symptoms that are real and stressful. If this is not recognised by investigators or their treating physicians, and properly addressed with understanding and sympathy, a psychological reaction will follow and the patient's problems will be compounded. Most subjects may be reassured that there will be no serious consequences to their health from infrasound exposure and if further exposure is avoided they may expect to become symptom free.

The conclusions of the general review relate to all levels of exposure to low frequency sound with an emphasis on the high levels in a working environment. They should be read in this context. They will not be applicable to the relatively low levels of low frequency emissions from wind turbine generators, especially those emissions below the threshold of hearing.

9 ADDITIONAL MATERIAL

There is an abundance of material available through the Internet concerning noise relating to wind farms and wind turbine generators but the majority is anecdotal in nature. There is no scientific material available concerning wind turbine generators that is suitable for this report, other than that cited in this report.

ENVIRONMENTAL NOISE GUIDELINES: WIND FARMS: ENVIRONMENTAL PROTECTION AGENCY, SOUTH AUSTRALIA: PUBLISHED FEBRUARY 2003

The Noise Criteria and conditions relating to tone and infrasound are stated as:

The predicted equivalent noise level ($L_{Aeq,10m}$), adjusted for tonality in accordance with these guidelines, should not exceed 35dB(A), or the background noise ($L_{A90,10}$) by more than 5dB(A) whichever is the greater, at all relevant receivers for each integer wind speed from cut-in to rated power of the wind turbine generator.

The sound power level data at each integer wind speed from cut-in speed to the speed of rated power should be specified in the development application as determined in accordance with International Electrotechnical Standard IEC 61400-11.

Tonality is a characteristic that can increase the adverse impact of a given noise source and it can be determined by breaking the noise signature down into discrete frequency bands. If tonality is a characteristic of the wind turbine generator noise, 5dB(A) should be added to the predicted or measured noise level from the wind farm. To help determine whether there is tonality, the method and results of testing (such as in accordance with IEC 61400-11) carried out on the proposed wind turbine generator model to determine the presence of tonality should also be specified in the development application.

With regard to annoying characteristics:

These guidelines have been developed with the fundamental characteristics of noise from a wind farm taken into account. These include the aerodynamic noise from the passing blades (commonly termed swish) and the infrequent and short-term braking noise. However, annoying characteristics that are not fundamental to a typical wind farm should be rectified. Such characteristics may include infrasound (low frequency noise below the audible frequency range that manifests as a rattle in lightweight materials such as glass) or adverse mechanical noise (perhaps generated as a failure of a component).

Infrasound was a characteristic of some early wind turbine models that has been attributed to early designs in which turbine blades were downwind of the main tower - the turbulence generated around the tower was cut through by the blades, generating this effect. Modern designs generally have the blades upwind of the tower. Wind conditions onto the blades and improved blade design minimise the generation of the effect. The EPA has consulted the working group and completed an extensive literature search but is not aware of infrasound being present at any modern wind farm site.

REPORT: LOW FREQUENCY NOISE: TECHNICAL RESEARCH SUPPORT FOR DEFRA NOISE PROGRAMME CONDUCTED BY CASELLA STANGER IN 2001

Reiterates the information in the WHO guidelines and the DEFRA report.

NOISE ANNOYANCE FROM WIND TURBINES - A REVIEW

SWEDISH ENVIRONMENTAL PROTECTION AGENCY

By Eja Pedersen, Högskolan i Halmstad

Report #5308: August 2003

The study summarises present knowledge on noise perception and annoyances from wind turbines in areas where people live or spend recreation time. There are two main types of noise from a wind turbine: mechanical noise and aerodynamic noise. The aerodynamic noise emits from the rotor blades passing the air. It has a swishing character with a modulation that makes it noticeable from the background noise. The swishing character with a modulation that makes it noticeable from the background noise part of the wind turbine noise was found to be the most annoying.

Field studies performed among people living in the vicinity of wind turbines showed that there was a correlation between sound pressure level and noise annoyance, but annoyance was also influenced by visual factors such as the attitude to wind turbines' impact on the landscape. Noise annoyance was found at lower sound pressure levels than in studies of annoyance from traffic noise. There is no scientific evidence that noise at levels created by wind turbines could cause health problems other than annoyance.

WIND TURBINE NOISE ISSUES

A white paper prepared by the Renewable Energy Research Laboratory: Center for Energy Efficiency and Renewable Energy: Department of Mechanical and Industrial Engineering: University of Massachusetts at Amherst, MA

Published in June 2002 and Amended March 2004

Reiterates the information in the WHO guidelines and the DEFRA report.

THE ASSESSMENT AND RATING OF NOISE FROM WIND FARMS

The Working Group on Noise from Wind Turbines: Final Report September 1996 ETSU-R-97 for: The Department of Trade and Industry, UK

A detailed and complex document dealing with the assessment and rating of noise from wind farms but it does not deal with the issue of concern relating to this work.

10 INTERNATIONAL AND NATIONAL STANDARDS

ISO 7196: 1995 ACOUSTICS — FREQUENCY-WEIGHTING CHARACTERISTIC FOR INFRASOUND MEASUREMENTS

In the Introduction the standard makes the point that in practice, some noises consist of, or contain components at, frequencies below 20 Hz. At present, there are no standardized methods for sound pressure measurements of these noises, nor for their description and assessment with respect to human response. Although research in this field is comparatively sparse, there is evidence of infrasonic effects which are potentially harmful or unpleasant to human subjects and some authorities may desire to extend their regulations or codes of practice governing noise emissions to cover sources of infrasound. For this reason, it is considered to be highly desirable to standardize measurement and description methods in order to facilitate the exchange of information and to avoid proliferation of incompatible procedures.

The method described in the Standard corresponds to the direct perception of infrasound. At present, this is the only human response for which there is an ample research base.

The perception of infrasound, although apparently achieved through the auditory mechanism, differs in some respects from that usually understood by hearing. The normal threshold of perception is considerably higher than at audio frequencies (about 100dB relative to 20 μ Pa at 10Hz), whilst toleration for high levels is not raised correspondingly, that is, the dynamic range is smaller and the rate of growth of sensation with sound pressure level is much more rapid. In the frequency range 1Hz to 20Hz, sounds that are just perceptible to an average listener will yield weighted sound pressure levels close to 100dB(G) when measured in accordance with ISO7196. A very loud noise will yield a weighted level in the order of 120dB, only 20dB above the threshold of perception. G-weighted sound pressure levels which fall below about 90dB will not normally be significant for human perception.

Attention should be paid to the fact that, due to the combined effect of individual differences in perception threshold and the steep rise in sensation above the threshold, the same infrasonic noise may appear loud and annoying to some people while others can hardly perceive it.

The Standard specifies a frequency-weighting characteristic, designated G, for the determination of weighted sound pressure levels of sound or noise whose spectrum lies partly or wholly within the frequency band from 1Hz to 20Hz.

The G-weighting characteristic is illustrated below in Figure 1 below.

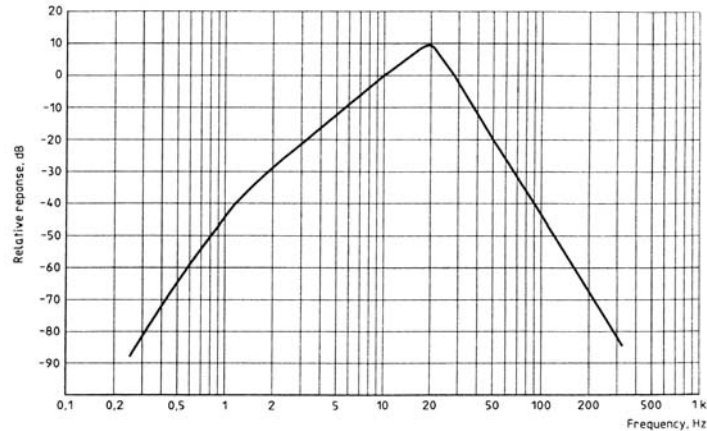


Figure 1: G-weighting characteristic

The G-weighting curve is so defined that it has a gain of 0dB at 10Hz, ie, the G-weighted sound pressure level of a pure tone at 10Hz is equal to the un-weighted sound pressure level. Between 1Hz and 20Hz the curve approximates a straight line with a slope of 12dB per octave. In this way, each frequency is weighted in accordance with its relative contribution to the perception of the sound.

DRAFT AUSTRALIAN STANDARD ACOUSTICS — MEASUREMENT, PREDICTION AND ASSESSMENT OF NOISE AND WIND TURBINE GENERATORS

The draft Australian Standard DR 04173 has been recently publicly notified for comment and comments closed on 2nd June 2004. The draft appears to be very largely based on the NZS6808:1998 Standard with minor modifications to suit Australian conditions. Like the NZ Standard it specifically does not include the methodology for the measurement of other characteristics that may be present in the noise emission of wind turbines such as infrasound, low frequency noise (noise outside the normal auditory range of the human ear), impulsivity, and low frequency modulation of broad band or tonal noise. For these types of assessment the Standard refers to the International Standard IEC 61400-11. The second edition of this International Standard was published in December 2002 as *Wind turbine generator systems – Part 11: Acoustic noise measurement techniques*

IEC 61400-11: WIND TURBINE GENERATOR SYSTEMS – PART 11: ACOUSTIC NOISE MEASUREMENT TECHNIQUES

The purpose of this part of IEC 61400 is to provide a uniform methodology that will ensure consistency and accuracy in the measurement and analysis of acoustical emissions by wind turbine generator systems. The standard has been prepared with the anticipation that it would be applied by:

- *the wind turbine manufacturer striving to meet well defined acoustic emission performance requirements and/or a possible declaration system;*
- *the wind turbine purchaser in specifying such performance requirements;*

- *the wind turbine operator who may be required to verify that stated, or required, acoustic performance specifications are met for new or refurbished units;*
- *the wind turbine planner or regulator who must be able to accurately and fairly define acoustical emission characteristics of a wind turbine in response to environmental regulations or permit requirements for new or modified installations.*

This standard provides guidance in the measurement, analysis and reporting of complex acoustic emissions from wind turbine generator systems. The standard will benefit those parties involved in the manufacture, installation, planning and permitting, operation, utilization, and regulation of wind turbines. The measurement and analysis techniques recommended in this document should be applied by all parties to insure that continuing development and operation of wind turbines is carried out in an atmosphere of consistent and accurate communication relative to environmental concerns. This standard presents measurement and reporting procedures expected to provide accurate results that can be replicated by others.

A standardised measurement procedure is essential for the determination of sound levels relating to relatively large sources of sound such as wind turbines. Non-standardised measurement procedures would be likely to result in unacceptable variations in the results from different approaches.

It is noted that optional measurements may include directivity, infrasound, low-frequency noise and impulsivity.

It is recommended that additional measurements be taken to quantify noise emissions that have definite character that is not described by the measurement procedures detailed in the standard. Such character might be the emission of infrasound, low-frequency noise, low-frequency modulation of broadband noise, impulses, or unusual sounds (such as a whine, hiss, screech or hum), distinct impulses in the noise (for example bangs, clatters, clicks, or thumps), or noise that is irregular enough in character to attract attention. These areas are discussed, and possible quantitative measures outlined in the Annex A. It is noted that these measures are not universally accepted and are given for guidance only.

The whole of Annex A is an informative part of the Standard and so in effect it is not part of the Standard itself.

In this Annex of the Standard it is noted that certain aspects of infrasound, low frequency noise, impulsivity and amplitude modulation are not fully understood at present. Thus it may prove that measurement positions farther away from the wind turbine than those specified in the standard may be preferable for the determination of these characteristics. Recommendations on how to deal with any issues relating to infrasound, low-frequency noise, impulsivity, amplitude modulation and other noise characteristics are stated in brief.

INFRASOUND — Sound at frequencies below 20Hz is called infrasound. Although such sound is barely audible to the human ear, it can still cause problems such as vibration in buildings and, in extreme cases, can cause annoyance. If infrasound is thought to be

emitted, an appropriate measure to use is the G-weighted sound pressure level according to ISO 7196.

LOW FREQUENCY NOISE — A disturbance can be caused by low-frequency noise with frequencies in the range from 20 to 100Hz. The annoyance caused by noise dominated by low frequencies is often not adequately described by the A-weighted sound pressure level, with the result that nuisance of such a noise may be underestimated if assessed using only an L_{Aeq} value.

It may be possible to decide whether the noise emission can be characterised as having a low-frequency component. This is likely to be the case if the difference between the A and C-weighted sound pressure levels exceeds approximately 20dB.

In these circumstances, low-frequency noise may be quantified by extending the one-third octave band measurements in a specified way.

This Standard deals reasonably effectively with the areas of concern around the infrasound and low-frequency sound issue that are not covered by NZS6808. It should therefore be used in conjunction with NZS6808 where necessary and appropriate.

11 LOW-FREQUENCY SOUND/INFRASOUND FROM WIND TURBINE GENERATORS

There is little data available concerning the level of sound emission in the infrasound range of frequencies from modern wind turbine generators. The limited information available indicates that the level of emission of these frequencies is little or no more than at the higher frequencies in the octave above 20Hz.

This level of infrasound emission is so low that it would be inaudible even at reasonably close distances to a wind turbine generator.

The typical range of sound power level for wind turbine generators is in the range of 100 to 105dBA – a much lower sound power level (10dB or more) than the majority of construction machinery such as dozers. In order for infrasound to be audible even to a person with the most sensitive hearing at a distance of, say, 300metres would require a sound power level of at least 140dB at 10Hz and even higher emission levels than this at lower frequencies and at greater distances. There is no information available to indicate that wind turbine generators emit infrasound anywhere near this intensity.

The information available from manufacturers on wind turbines indicates that the sound power level of a typical wind turbine in the 16Hz one third octave band is around 105dB at a wind speed of 10m/s. It is unlikely that the sound power level in the lower frequency bands than this would be substantially any higher than 105dB. This means that the sound pressure level at only 100 metres distance will be in the approximate range of 50dB to 55dB and this is far lower than the audibility threshold of around 85dB for this low frequency sound. Frequencies lower than 16Hz have an even higher threshold level than this and the level of emission is not likely to be any higher. Therefore the sound pressure level of very low frequency infrasound (<16Hz) will be even lower relative to the audibility threshold for those frequencies.

ISO 7196 indicates that infrasound at a level of 90dBG or less will not normally be significant for human perception.

There is simply insufficient emission in the infrasound region of the sound spectrum for it to be audible at distances from the wind turbine generator where people would normally be located.

For people working close to an operating turbine, where the noise level exceeds 85dBA, they should be wearing suitable hearing protectors. However it should be appreciated that at frequencies below 100Hz hearing protectors give little or no reduction in the sound level. The level of exposure is unlikely to be greater than 85dBA at ground level.

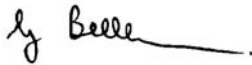
12 REVIEW OF NEW ZEALAND STANDARD: NZS6808:1998

The need to review the current standard may be appropriate. It is now 6 years since first publication and an Australian standard based on this original document is now under development. It may be appropriate and timely for a review but this is not considered as necessary on the basis of the need for the standard to include consideration of low-frequency sound or infrasound. If infrasound is a consideration in a particular project with wind turbine generators the appropriate standard to use in its evaluation is IEC 61400-11.

The current Standard refers to this document as a Draft International Standard IEC DIS 1400-11 with respect to Special Audible Characteristics. It may be appropriate to update that reference at the time of any review. Any review should also take account of the content of the new Australian Standard when published.

13 CONCLUSIONS

1. The lack of technical material other than that included within this report, to some extent is to be expected since all relevant material is likely to have been picked up and included within the World Health Organisation and Department of Environment, Food, and Rural Affairs (DEFRA) review documents.
2. The information available concerning infrasound frequency emission from wind turbine generators indicates that the level of emission at frequencies below 20Hz is little more or no more than at frequencies in the octave above 20Hz. Typical sound power levels at infrasound frequencies are no higher than between 100 and 105dB.
3. This level of infrasound emission is so low that it would be inaudible even at reasonably close distances to a wind turbine generator.
4. There is no information available to indicate that wind turbine generators emit infrasound anywhere near the intensity in the infrasound region for the sound to be audible even to a person with the most sensitive hearing acuity at a distance where houses are generally located relative to wind farms.
5. It is important to realise that there is no reliable evidence that would indicate any effects on people when infrasound is present at a level below the hearing threshold.
6. The information available seems to indicate that it is possible for a modulation or throbbing sound to be associated with wind turbine generators. If this is the case in any particular situation, it should be addressed by reference to clause 5.3.1 in NZS6808. Any tonality should be determined by reference to IEC61400-11 and assessed in accordance with clause 5.3.1 in NZS6808.
7. The South Australian Environmental Protection Agency in its Environmental Noise Guidelines on Wind Farms states that *"the EPA has consulted the working group and completed an extensive literature search but is not aware of infrasound being present at any modern wind farm site"*. This concurs with the work carried out in the preparation of this report.
8. There is no evidence to indicate that low-frequency sound or infrasound from current models of wind turbine generators should cause concern to anyone living close to a wind turbine generator or a wind farm.



G Bellhouse

14 ACRONYMS

AS	Australian Standard
dB	Decibel
DEFRA	Department of Environment, Food, and Rural Affairs, United Kingdom
EHO	Environmental Health Officer
EPA	Environmental Protection Agency
Hz	Hertz, the unit of frequency
IEC	International Electrotechnical Commission
ISO	International Standards Organization
L_{10}	10 percentile of sound pressure level
L_{50}	Median sound pressure level
L_{90}	90 percentile of sound pressure level
$L_{Aeq,T}$	A-weighted equivalent sound pressure level for period T
L_{Amax}	Maximum A-weighted sound pressure level in a stated interval
$L_{eq,T}$	Equivalent sound pressure level for period T
L_p	Sound pressure level
NZS	New Zealand Standard
Pa	Pascal, the unit of pressure
PNL	Perceived Noise Level
SEL	Sound Exposure Level
SPL	Sound pressure level
SWL	Sound power level
UK	United Kingdom
USA	United States of America
WHO	World Health Organization

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