COMPARISON OF INFRASOUND MEASURED AT PEOPLE'S EARS WHEN WALKING TO THAT MEASURED NEAR WIND FARMS

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Infrasound is observed in all environments at varying levels and is generated by a range of natural and anthropogenic sources. Some studies have suggested that modern wind turbines can generate a relatively low level of measurable noise at frequencies corresponding to the blade pass frequency of turbines. People walk at a variety of speeds, with typical walking frequencies similar to the blade passing frequency of modern commercial wind turbines. Measurements have been conducted of the levels of infrasound generated at the human ear when walking and compared to measured levels near wind farms. The measured level of infrasound generated at the ear at blade pass frequency when people walk can be considerably higher than the level near wind farms. In both cases, measured levels were significantly below the audibility threshold for very low frequency noise.

INTRODUCTION

Infrasound has been reported as a concern by some residents around proposed and operating wind farms and has been raised as an issue in a South Australian parliamentary inquiry [1]. Infrasound is observed in all environments, arising from a combination of natural and anthropogenic sources. A recent study conducted by the South Australian Environment Protection Authority (SA EPA) and Resonate Acoustics [2] has found infrasound levels to be no greater at houses near wind turbines than levels experienced in other urban and rural environments. Additionally, the contribution of wind turbines to the measured infrasound levels was found to be insignificant in comparison with the background level in the environment and with respect to human perception.

While the study [2] found that infrasound at houses located 1.5 kilometres from wind farms was at a level no more significant than at other locations, there were characteristics observed in the spectra at the one third octave band centre frequencies of 0.8, 1.6 and 2.5 Hz at the two locations near wind farms. These approximately correspond to the blade pass frequency and second and third harmonics of the nearby wind turbines. The highest measured $L_{eq,10min}$ levels in these one third octave bands were between 60 and 65 dB, with the highest typically occurring at 1.6 Hz. At the time the study [2] was not able to conclude whether this characteristic was a result of wind turbine operation or another source but acknowledged that it is possible that the wind turbines generated it. In light of other recent studies as discussed below, it is reasonable to conclude that these levels did result from operation of the wind turbine.

A 2012 study in Wisconsin [3] (the Shirley Wind Farm study) also measured infrasound in houses near wind turbines and found characteristics in the spectra at the blade pass frequency and related harmonics at a house located approximately 330 metres from the nearest turbine. These characteristics were not detected at two other houses located approximately 1 and 2 kilometres respectively from the nearest turbine. As for the SA EPA and Resonate Acoustics study [2], the level of the characteristics presented in the Shirley Wind Farm study [3] was well below the threshold of audibility, with a power spectrum level of approximately 60 dB measured at 1.4 Hz for a frequency resolution of 0.05 Hz.

Also of interest are recent measurement campaigns conducted by both the SA EPA [4] and the University of Adelaide [5] at Waterloo Wind Farm in response to complaints from some residents. Measurements at a number of sites were reported in the infrasonic range in both studies at sites between 1.3 and 3.5 kilometres from the nearest 3 MW wind turbines. In both reports, the blade pass signals measured in the one-third octave band 1.6 Hz were between 45 to 60 dB, including during periods of complaint. It therefore appears reasonable to use the levels measured during the SA EPA and Resonate Acoustics study [2] as a conservative basis for comparison with infrasound levels generated during walking.

Despite the measured levels of infrasound near wind farms presented in both [2] and [3] being significantly below the audibility threshold and only detectable through highly sensitive measurement equipment, the presence of infrasound that may be due to wind turbines has led to some community members expressing concern [6]. Therefore, there is interest in comparing these measured levels of infrasound to levels that people are exposed to on a daily basis.

The blade pass frequency of wind turbines is equal to the number of blades multiplied by the rotational speed of the turbine. With three blades and rotational speeds in the order of 15 to 18 rpm [7], modern commercial wind turbines of the type at the wind farms included in the SA EPA and Resonate Acoustics study [2] have a blade pass frequency of 0.8 to 0.9 Hz.

This paper investigates the hypothesis that, as people walk with a rate similar to the blade pass frequency of wind turbines, they may be exposed to infrasound with a similar characteristic and level to that measured near wind farms. This infrasound would result from the periodic change in pressure levels at the ear as people walk.

NATURE OF WALKING

When people walk there is a slight rise and fall of the head. The rate of the rise and fall (or walking pace) depends on the speed of walking, gate and stride length. There is also a side to side movement of the head at lower magnitude. There have been numerous studies of walker pace rate normally related to structural vibration assessments for building vibration response [8]. The rate of walking typically ranges from 60 paces per minute for slow walking to 120 paces per minute for fast walking [8, 9]. Using conventional engineering terminology this equates to 1 to 2 Hz. People hence commonly walk at a similar rate to the blade passing frequency and associated harmonics of modern commercial wind turbines.

Vibration testing was carried out with a test walker (walker A) at 1 Hz (60 paces per minute) and with the walker carrying a Brüel and Kjær Type 4100 head simulator. An accelerometer was attached to both the walker A (torso) and the head simulator during subsequent tests and the vertical acceleration was measured to confirm vibration levels. The measured walker vibration, measured vibration of the head simulator and a normalised sinusoidal 1 Hz signal are presented in Figure 1. The normalised sinusoidal signal has an amplitude of 0.18 g. The rms acceleration on the manikin head was 30% lower than on the test walker. Any measurements on the manikin head are hence conservative in terms of amplitude during walking.

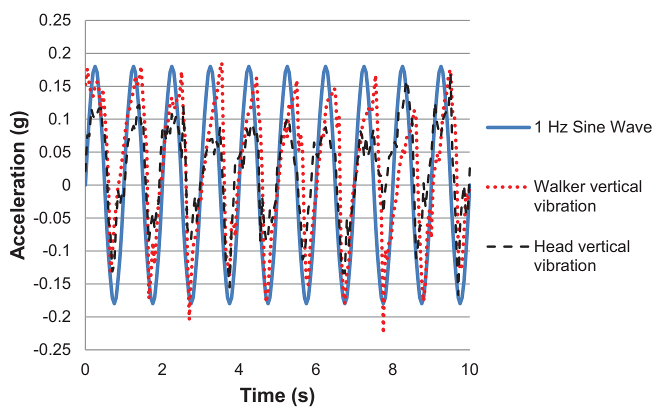

Figure 1 Measured test walker acceleration and 0.18 g amplitude normalised 1 Hz sinusoidal waveform.

To ensure that the results of the test walker are valid to the wider population a series of walking tests (an additional 6 walkers, walker B to G) was carried out where the walker was asked to walk at a comfortable pace. The measured walker vibration for a sample of each test walker is shown in Figure 2. Frequency analysis of the measured vertical vibration showed a range of walking speeds with a dominant frequency (around 100 paces per minute, with the frequency between 90 and 111 paces per minute). All test walking was inside a building, without coaching on walking style and with enough room such that their walking style was not impeded. The test walker A had similar walker vibration result (rms acceleration) to the walkers B to G and was +2% higher than the average rms acceleration at the walking speed.

The measured vibration levels for test walkers A to G show that people walk with acceleration levels similar to a sinusoidal wave (with a dominant primary frequency and harmonics) and with reasonable repeatability as demonstrated by the results for test walkers A to G. The measured levels for walker A also demonstrate that the vibration that the head simulator was subject to during the test is slightly lower than that of the walker A. This indicates that the levels of infrasound measured in the ear of the head simulator will provide a reasonable, if slightly conservative, representation of the infrasound levels at the ear of the walker.

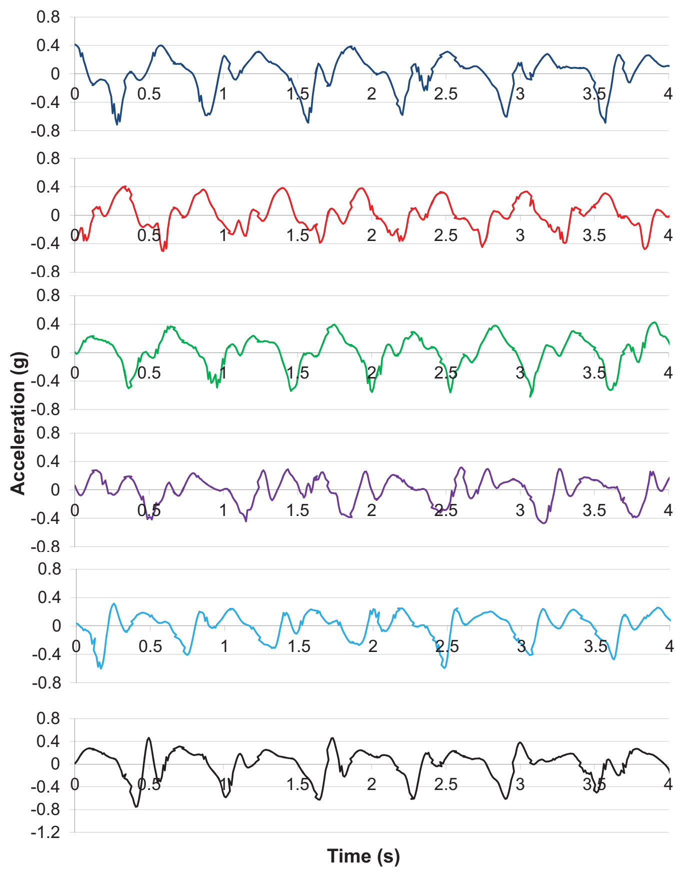

Figure 2 Measured walker acceleration for walker B (top of image) to G (bottom of image).

MEASUREMENT METHODOLOGY

The measurement of infrasound that walkers are exposed to requires a carefully considered experimental methodology. The key considerations for the measurement methodology were:

- Test walker
- Realistic head and ear interaction to represent the level of infrasound generated at the human ear
- Signal processing and low frequency system response

- Reference level to be measured within the space to identify any extraneous noise effects
- Isolation of extraneous vibration effects and other potential sources of error

It is noted that accurate measurement of environmental infrasound from anthropogenic sources requires the use of appropriate techniques to remove the effect of wind-induced noise at the microphone [2]. This is not considered to be a significant concern to this investigation as the human ear would also be subject to wind-induced infrasound when people walk. However, additional measurements were undertaken to determine whether wind-induced noise had affected the measurement results at the ear. In comparing wind farm infrasound to walker infrasound, another consideration is the indoor vs outdoor infrasound measurements. For the purpose of this comparison only the indoor levels were compared, as the variable of wind induced noise was able to be controlled. The level of infrasound measured while walking outdoors may be greater due to additional wind induced noise. As this study compares exposure infrasound levels (that humans might be exposed to) the indoor levels are taken for comparison purposes. The conclusions in this paper are taken on the basis of indoor infrasound levels during walking.

Test walker

The selected test walker (walker A) is experienced in walking at fixed frequencies with a natural gait primarily for the testing of structural vibration resulting from walker-generated vibration levels. A metronome was used to synchronise the walking frequency with a visual rather than audible beat, so that the frequency of all tests was consistent. The walker is approximately 90 kg and 180 cm tall. All walking was on a suspended timber structure floor with carpet covering. The test walker walked in a large circuit for over two minutes for each test condition to ensure sufficient data was obtained to obtain an accurate measured sound pressure level at very low frequencies.

Head and ear

Walker infrasound levels were measured with a Brüel and Kjær Type 4100 Sound Quality Head Simulator manikin designed for sound quality testing. Only the head was used for testing. A single microphone, positioned at the entrance to the ear canal on the manikin's head, was used to simulate the signal that includes the interference patterns caused by the head. The ears are moulded-silicone pinna simulator which sit around the microphones to provide directivity patterns similar to the human ear and are designed to have a frequency response to sounds coming from all directions which closely approximates the direction-dependent human response. The Brüel and Kjær Type 4100 head simulator is designed for measuring human exposure from a range of noise sources.

The head simulator was held in front of the test walker and carefully moved with a similar vertical displacement as the walker, as previously shown in Figure 1.

Signal processing and low frequency system response

Measurement of noise levels in the infrasonic range is complicated by factors that do not affect measurements in the normal audible range of sounds, in particular the use of equipment with an accurate measured response to a low enough frequency. The majority of sound level meters and microphones are generally designed to only measure noise levels accurately at the typical audio frequencies (20 Hz – 20 kHz), and are insufficient for the accurate determination of noise levels at frequencies below 20 Hz.

Measurements were carried out using the equipment listed in Table 1. All equipment held current calibration certificates from a National Association of Testing Authorities certified laboratory or were manufacturer calibrated in the case of the microphones.

Table 1. Measurement and analysis equipment

Analyser	Integrated microphone and preamplifier set	Frequency range [1]
Sinus Soundbook Quadro+ (S/N 06364)	Brüel & Kjær Type 4193-L-004 (S/N 2774943)[2]	0.2 Hz - 20 kHz
	Brüel & Kjær Type 4193-L-004 (S/N 2774944)[2]	0.2 Hz - 20 kHz

1. Frequency range determined based on the minimum of the analyser or microphone.

2. Fitted with a Brüel and Kjær Type UC-0211 low frequency noise adaptor.

Two matched Brüel & Kjær Type 4193-L-004 microphone and preamplifier sets have been used for simultaneous two-channel measurements with the Soundbook data acquisition system. One microphone was located in an ear of the Brüel and Kjær Type 4100 test head while the second microphone was located on a tripod pole within the space. The calibration chart for the data acquisition system shows negligible deviation of the instrument frequency response to frequencies as low as 0.1 Hz. The microphone calibration charts (dated 11 December 2012) also show 3 dB deviation of the frequency response to less than 28 mHz.

The equipment was setup to store linear (unweighted) 1/3rd octave band sound pressure levels from 0.2 Hz to 20 kHz over the duration of each test. The overall linear sound pressure level was also stored in 120 ms intervals during each test to allow the amplitude modulation corresponding to the walker frequency to be visualised.

Test location

All measurements described in this paper were undertaken indoors. By undertaking the measurements indoors, it was possible to minimise the influence of wind-generated turbulence on the measured infrasound levels. The stationary reference microphone was fitted with a 90 mm windshield and located approximately 2 m from two walls. For all measurement periods windows and doors were kept closed. The test walker microphone did not have a windshield as this represents the case of human exposure as discussed previously.

The approximate dimensions of the test room were 5 m (L) x 12 m (W) x 3 m (H). It is known that low frequency noise levels can vary within a room due to the modal response of rooms to noise at wavelengths on a similar scale to the physical dimensions of the room. However, studies have shown that there are negligible room effects within the infrasonic range of 20 Hz and below [2, 10].

Assessment of potential sources of error

Additional tests were carried out to identify potential sources of error in the measurements, namely:

- Extraneous vibration effects on the microphone
- Variation in measured sound pressure levels between the test head and reference microphone
- Noise generated by walking on the carpeted timber floor
- Wind-induced noise effects on the ear microphone when walking.

The results of the additional tests to assess these sources of error are discussed following the presentation of the measurement results.

MEASUREMENT RESULTS

Figure 3 presents the measured linear sound pressure levels over the infrasonic frequency range (0.2 Hz to 20 Hz) for both the microphone in the test head ear and the reference microphone within the room. It can be seen that there is a distinct characteristic peak at approximately 76 dB at the ear at the walker frequency of 1 Hz. The measured sound pressure levels are assumed to be as a result of change in static air pressure or as a result of dynamic pressure variation from side to side movement.

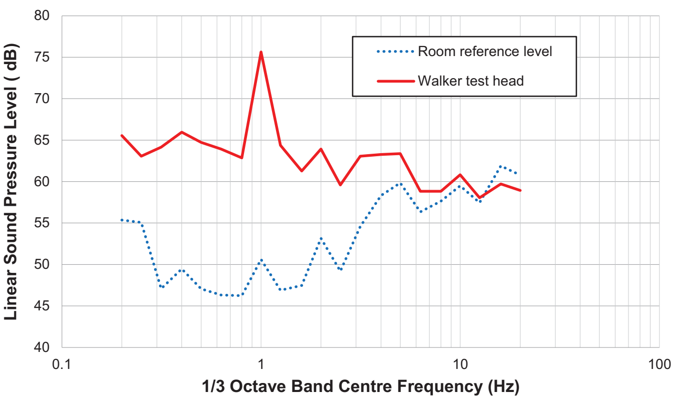

Figure 3 Walker and reference linear sound pressure levels over infrasonic range

The peak is also present in the room reference level but at a significantly lower level. This peak in room reference level is due to the repetitive noise generated by the walker on the carpeted timber floor. As the levels are significantly lower at the reference location than at the ear, despite the walking occurring very close to the reference measurement location, it demonstrates that airborne noise generated by walking on the floor did not significantly contribute to the measured levels at the ear.

It can also be seen that the levels at the ear are elevated in comparison to the room reference level across the frequency range from 0.2 Hz to approximately 5 Hz. This is most significant at the walker frequency of 1 Hz but, as it is elevated across the entire frequency range, it is believed to be the result of variations in pressure at these frequencies at a lower level than at the primary walking frequency.

Isolation of extraneous vibration effects

An obvious concern when measuring the infrasound levels walkers are exposed to is the potential influence of vibration on the microphone system. Condenser microphones have a metal diaphragm, which could be susceptible to vibration causing an elevated measured infrasound level generated by vibration rather than variation in static air pressure or as a result of dynamic pressure variation from side to side movement.

The Brüel & Kjær Type 4193 microphone has a published vibration sensitivity (<1000 Hz) of 65.5 dB equivalent SPL for 1 m/s^2 axial acceleration. The measured vibration levels with a walker at 1 Hz pace rate is nominally 0.18 g or 1.8 m/s2 amplitude in the vertical direction. This is the transverse direction for the in-ear microphone and is the less sensitive direction. The measured sound pressure level at the ear was 76 dB at the walker frequency, significantly above the microphone vibration generated level that would be expected for the vibration based on manufacturer data. Hence, vibration was considered unlikely to be the cause of measured infrasound levels at the walker frequency.

However, given the need to ensure that vibration was not the source of the induced infrasound, additional testing was carried out with the head rotated 90 degrees such that the microphone was orientated vertically. This corresponds to the most sensitive microphone direction relative to the direction of the vibration and, if vibration of the diaphragm was the cause of the measured infrasound levels, higher measured sound pressure levels would be expected.

Figure 4 presents the measured infrasound levels with the test head microphone rotated 90 degrees and in the standard orientation. Both measurements were undertaken with the test head stationary (no forwards motion) but moved up and down in the appropriate orientation. It can be seen that infrasound levels were no higher in the rotated orientation where higher vibration levels would be expected. This confirmed the measured infrasound levels were not generated through microphone vibration. It is noted that there was a change in the frequency of the motion between the two measurements, with the low vibration measurement having a greater range of motion at approximately 0.8 Hz whereas the frequency of the higher vibration measurement was more consistently 1 Hz. However, review of the measured vibration levels during both measurements indicated that there was only a minor change in the amplitude of the motion and that the two results can be compared.

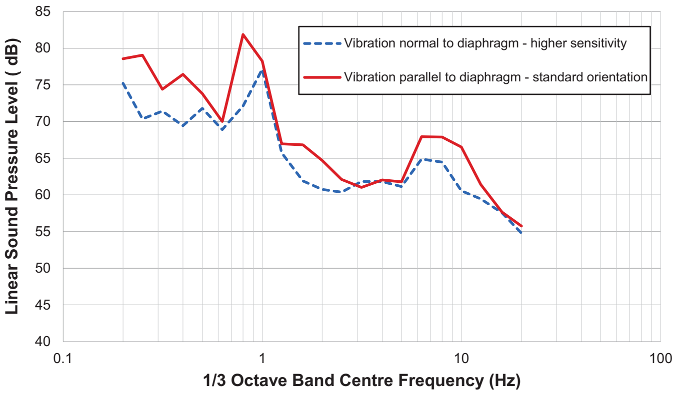

Figure 4 Walker infrasound levels with head in different orientations – rotated 90° (normal to microphone diaphragm, high vibration induced level expected) and standard (parallel to microphone diaphragm, low vibration induced level expected).

Response of test head compared to reference microphone

A stationary test was carried out to compare the measured infrasound level at the ear of the stationary test head to that measured at the reference microphone on the tripod. The measured infrasound levels were found to be within 1 dB of each other within each one-third octave band. This provided confidence that the reference microphone and test head observe the same infrasound levels and that the measured infrasound levels can be directly compared between microphones.

Wind-induced noise

It is necessary to check whether the measurement results were as a result of wind-induced noise (resulting from the walking motion) on the microphones, although this did appear unlikely given the distinct characteristic at the walker frequency.

The comparison of measurement results while walking shown in Figure 3, to measurement results with the head moved vertically with no forward motion (Figure 4) indicates the levels of the 1 Hz peaks are similar, when the vertical displacement is similar. The measurement of the same level of infrasound during both the stationary vibration tests as those in the walking tests supports the hypothesis that the primary source of measured infrasound is the change in pressure with height, rather than wind induced noise due to forwards movement through the air.

ANALYSIS

Pressure change at ear

The pressure change at the ear of the test head when walking can be approximately determined assuming a 1 Hz sine wave with amplitude of approximately 0.08g (Figure 1). This converts to a peak to peak displacement of 25 mm. The approximate rms sound pressure level at 1 Hz can then be determined for a standard air density (ρ = 1.2 kg/m^3) as:

$$p = \frac{\rho g h}{2\sqrt{2}} = \frac{1.2 \times 9.81 \times 0.025}{2\sqrt{2}} = 0.1Pa$$

$$SPL = 20\log\left(\frac{p}{p_{ref}}\right) = 20\log\left(\frac{0.1}{2\times 10^{-5}}\right) = 74dB$$

This compares well to the measured SPL of 76 dB at 1 Hz as shown in Figure 3, particularly given the relatively simplistic approximation. In reality, the measured acceleration signal on the head does not represent a perfect sine wave and the typical peak amplitude may be slightly higher than the assumed 0.08g. However, it helps to confirm that the measured infrasound signal at 1 Hz is representative of the change in pressure at the ear and not due to extraneous sources. It should also be noted that there is side to side movement of the head with reduced magnitude compared to the vertical movement and some sound pressure fluctuation may be generated by this mechanism.

Comparison of walker infrasound levels to measured levels at wind farm locations

Indoor infrasound levels were measured at one house near the Bluff Wind Farm and another near the Clements Gap Wind Farm as part of the recent SA EPA and Resonate Acoustics study [2]. The houses were located 1.4 and 1.5 kilometres from the nearest wind turbine respectively. The measured indoor infrasound levels at the houses were reviewed to identify periods where potential characteristics at the blade pass frequency (0.8 Hz) and harmonics (1.6 Hz and 2.5 Hz) were identified.

Figure 5 compares two measurements of the test walker (walker A) to measured 10-minute averaged infrasound levels at the two houses. The 10-minute period at each house was selected such that it was representative of the highest sound pressure levels at the blade pass frequency and associated harmonics for which a potential characteristic could be identified. The corresponding hub height wind speed at the wind farm was 14 m/s for the Bluff Wind Farm and 12 m/s for Clements Gap Wind Farm. For reference, rated power of the wind turbine model installed at each wind farm occurs at a hub height wind speed of 14 m/s. The cause of the apparent lower frequency characteristic at 0.5 Hz during the second walker measurement was not obvious, but it is suspected that it may be due to a difference in the walkers step on the left and right foot during that measurement.

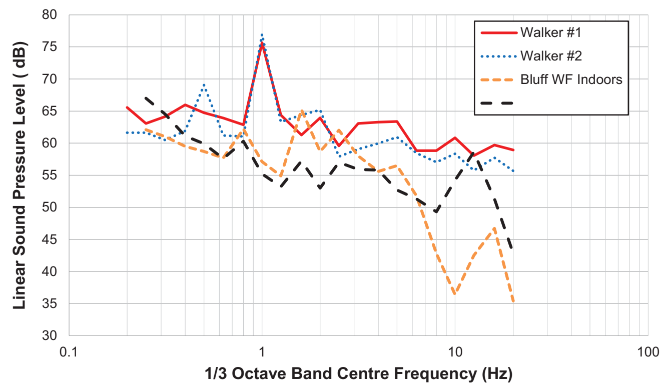

Figure 5 Comparison of measured walker infrasound levels to measured indoor infrasound levels at houses near wind farms

It is clear that, although the measured walker infrasound characteristic occurs at a slightly different frequency to the characteristics that may potentially arise from wind turbine operations, the measured sound pressure level is at least 10 dB higher for the relevant one-third octave band. The shape of the characteristic (or peak in the spectrum) is also significantly more pronounced for the test walker than for the wind farms, with a peak of approximately 12 dB above the adjoining one-third octave bands.

This comparison indicates that the human ear is regularly exposed to pressure variations at these very low frequencies (less than 2 Hz) that are significantly higher than that potentially resulting at houses from operation of a wind farm. It also demonstrates that the infrasound characteristic that may result from wind turbines at the blade passing frequency is not unique and is considerably less pronounced than that which walkers experience at similar frequencies.

The recent Shirley Wind Farm study [3] measured a power spectral level of approximately 60 dB (0.05 Hz bandwidth) at 1.4 Hz at a house approximately 330 metres from the nearest wind turbine. While difficult to directly compare the power spectrum level to 1/3rd octave band results, the level measured in the Shirley Wind Farm Study appears similar to the results measured in the SA EPA and Resonate Acoustics study [2] and measured sound pressure level at the ear when walking at a specific frequency would also be higher than that measured in the Shirley study. Note that 330 metres is significantly closer than the nearest residences to wind farms in Australia, with the nearest non-financially involved houses typically located about one kilometre away.

The SA EPA [4] and University of Adelaide [5] studies at Waterloo Wind Farm reported one-third octave band levels at 1.6 Hz of between 45 and 60 dB depending on location, including during times of complaints. The levels reported by these studies therefore appear lower than those measured in the SA EPA and Resonate Acoustics study [2] and significantly lower than those measured during walking and presented in Figure 5.

It is noted that the measured infrasound levels near wind farms in the various studies ([2], [3], [4] and [5]) include harmonics of the blade pass signal evident up to a maximum frequency of approximately 10 Hz. By contrast, the infrasonic signal generated at this test ear when walking does not exhibit as many obvious harmonics. The potential for multiple harmonics does however exist given the patterns in acceleration measured for the various test walkers which are included in Figure 2. In terms of absolute level, the blade pass signal at locations near wind farms is often measured to be highest below 2 Hz, and in this region the levels generated at the ear when walking have been measured to be higher than those measured at a typical residential distance from wind farms in Australia.

Comparison to the human hearing threshold

Møller and Pedersen [11] provide a summary of investigations into the human hearing threshold at infrasonic frequencies, presented here as Figure 6. The threshold is denoted a hearing threshold and it is noted that investigations indicate non-auditory perception occurs at levels approximately 20 to 25 dB above the hearing threshold [11].

While there is no information on the threshold at frequencies of 1 Hz and lower in Figure 6, the mean threshold at 1.5 to 2 Hz appears to be in the order of 110 to 130 dB. It is therefore clear that the measured walker infrasound levels are well below the mean hearing threshold, and the measured infrasound levels near wind farms even more so.

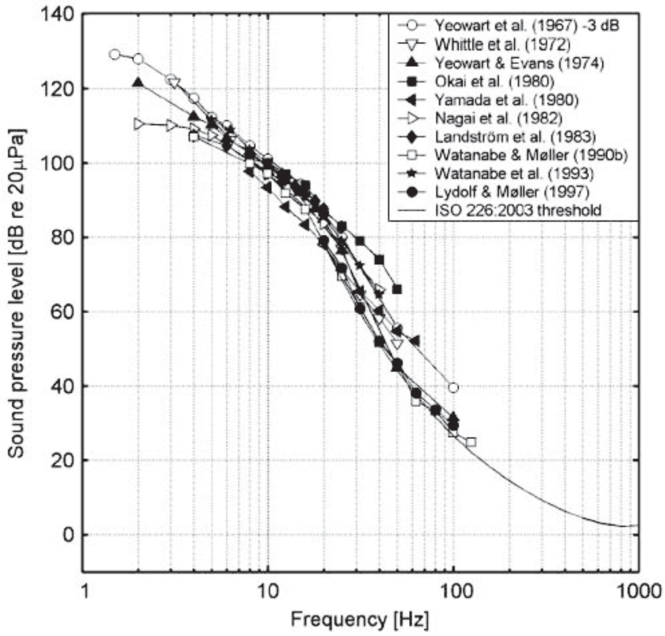

Figure 6 Summary of investigations into human hearing threshold covering frequency range at and below 20 Hz, from Møller and Pedersen [11]

CONCLUSIONS

A study has been undertaken into the infrasound levels generated at the human ear when walking. This investigation arose from findings as part of a recent study into infrasound levels measured at houses adjacent to wind farms [2] at approximately 1.5 km, where a characteristic was measured at frequencies corresponding to the wind turbine blade pass frequency and associated harmonics.

It has been found that the human ear is subject to sound pressure levels in the order of 75 dB at the one-third octave band centre frequency corresponding to the walking frequency. The characteristic that occurs at the ear during walking is similar in dominant frequency to that measured at the houses near wind farms (when walking at the same pace). However, it is significantly higher in level, with levels measured to be 10 dB higher than the highest levels measured near wind farms at 1.5 km away where residences may be located. This paper has not attempted to nor makes any conclusion on the human perception of infrasound.

ACKNOWLEDGEMENTS

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