Investigation of the time dependent nature of infrasound measured near a wind farm

Branko ZAJAMŠEK[1]; Kristy HANSEN[1]; Colin HANSEN[1]

[1] University of Adelaide, Australia

ABSTRACT

It is well-known that wind farm noise is dominated by low-frequency energy at large distances from the wind farm, where the high frequency noise has been more attenuated than low-frequency noise. It has also been found that wind farm noise is highly variable with time due to the influence of atmospheric factors such as atmospheric turbulence, wake turbulence from upstream turbines and wind shear, as well as effects that can be attributed to blade rotation. Nevertheless, many standards that are used to determine wind farm compliance are based on overall A-weighted levels which have been averaged over a period of time. Therefore the aim of the work described in this paper is to investigate the time dependent nature of unweighted wind farm noise and its perceptibility, with a focus on infrasound. Measurements were carried out during shutdown and operational conditions and results show that wind farm infrasound could be detectable by the human ear although not perceived as sound.

Keywords: wind farm noise, on and off wind farm, infrasound, OHC threshold, crest factor
I-INCE Classification of Subjects Number(s): 14.5.4

1. INTRODUCTION

Wind turbine noise is influenced by atmospheric effects, which cause significant variations in the sound pressure level magnitude over time. In particular, factors causing amplitude variations include wind shear (1), directivity (2) and variations in the wind speed and direction. Wind shear, wind speed variations and yaw error (deviation of the turbine blade angle from optimum with respect to wind direction) cause changes in the blade loading and in the worst case, can lead to dynamic stall (3). With regards to propagation, the wind speed and direction between the source and receiver as well as wind shear and temperature inversions can vary significantly over time as well as location. Also, wind farm noise arriving at a receptor location several kilometers away can be heavily weighted to lower frequencies due to a combination of refraction, which causes sound waves to bend towards the ground, small atmospheric absorption at low frequencies and insignificant losses on reflection from the ground at low frequencies.

When evaluating the impact of wind turbine noise on residents living near a wind farm, it is important to consider the time variability of the noise for a number of reasons. The periodic variation in the amplitude of the sound, which is known as amplitude modulation, is perceived as more annoying according to listening tests conducted by Lee *et al.*(4). Moreover, compliance assessment procedures often overlook peak noise levels by averaging over large sample periods and ignoring the highest 90% of the measured signal. According to Bray and James (5), wind turbine noise is characterised by high crest factor, which means that wind turbine noise is highly time variant and thus more likely to perceived as annoying. As a direct consequence, wind-turbine infrasonic and low-frequency noise can be readily audible at much lower rms levels than has been acknowledged in the literature (6).

The perceived loudness of low frequency noise can increase significantly for a corresponding small increase in the acoustic energy, which is reflected in reduced spacing of equal loudness contours at lower frequencies (7). The implication of this observation is that low frequency sounds which are only slightly above the threshold of hearing can be perceived as loud (8). Since hearing thresholds can vary between individuals, it is possible that a sound that is inaudible to some people could be perceived as loud to others (9). Thresholds of audibility provided in the ISO 389-7 (10) standard cover the frequency range from 20 Hz to 18,000 Hz but below 20 Hz,

[1]kristy.hansen@adelaide.edu.au
[2]branko.zajamsek@adelaide.edu.au
[3]colin.hansen@adelaide.edu.au

no such international standard has been developed. Nevertheless, a considerable number of research studies have focused on human perception of low frequency noise and infrasound and a comprehensive review of this literature was conducted by Møller and Pedersen (9). Their investigation led to the development of a normal threshold of audibility curve, which is based on existing data derived from listening tests. The listening tests involved exposure to sinusoidal tones in a free-field listening environment (9). It was observed that the resulting threshold of audibility curve follows a 12 dB/octave slope. Moorhouse *et al*. (8) also conducted listening tests on three listening groups, namely, low frequency noise sufferers, eldery people (55-70 years old) and people of a younger age. This gives testing a more general validity. Listening tests were conducted using three sound samples, namely, real sounds (source unspecified), pure tones and beating tones. It was observed that low frequency noise sufferers are the least sensitive in absolute[1] terms and the most sensitive for beating tones and real sounds relative to the absolute hearing threshold. The main outcome of the study done by Moorhouse *et al*. (8) is the development of a criterion curve for the assessment of low frequency noise complaints. The curve covers the frequency range from 10 Hz to 160 Hz and is used by the Department for Environment, Food and Rural Affairs (DEFRA) in the United Kingdom for low frequency noise assessments. A somewhat different approach for assessing hearing threshold was used by Salt and Huller *et al*. (11) who focused on the response to noise of the outer hair cells (OHC). The cochlea, which is the inner part of the ear, consists of inner hair cells (IHC) and the above-mentioned OHC. However, hearing threshold measurements, as mentioned above (references (8), (9)) commonly measure the response of IHC, which are more sensitive at higher frequencies, since their response is perceived as sound (11). On the other hand, the OHC are more sensitive at lower frequencies (at levels far below the hearing threshold). Salt and Huller *et al*. (11) outline a sound pressure level threshold at which the OHCs respond to airborne sound stimuli. It should be noted, that the understanding of how human ear responds to low frequency sounds is based on measurements performed on animals. The comparison between “Møller”, “Moorhouse” and OHC threshold curves can be seen in Figure 1, where a large differences in noise perceptibility thresholds can be observed. . As can be seen, the difference is up to 40 dB at 10 Hz between the “Møller” and OHC threshold. The “Moorhouse” threshold, on the other hand, lies ∼32 dB above the OHC threshold. The threshold curves obtained by Moorhouse *et al*. (8) for pure tones, beating tones and real sounds (source unspecified) are not shown since they only extend down to the 31.5 Hz one-third octave band center frequency.

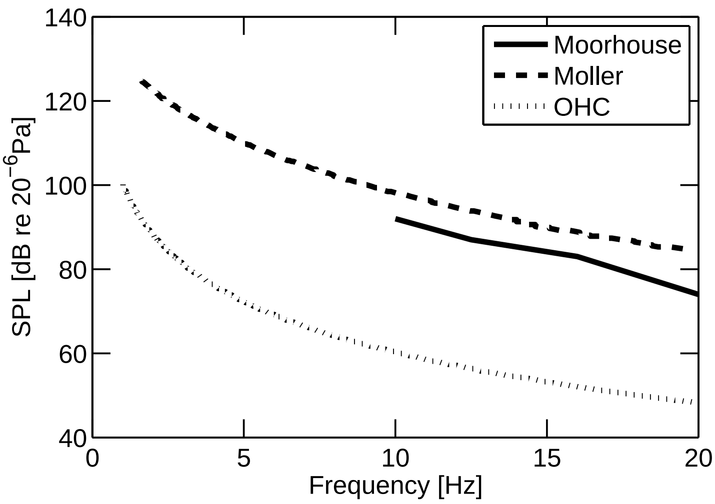

Figure 1 – Comparison of threshold curves.

Some residents have reported annoyance when the wind farm is inaudible to them. They describe such symptoms as dizziness and nausea as well as unfamiliar sensations in their ears. According to Salt and Huller *et al*. (11), these symptoms may be related to infrasound, which stimulates the outer hair cells of the human ear at levels below the audibility threshold. This results in information transfer via pathways that do not involve conscious hearing, which may lead to sensations of fullness, pressure or tinnitus, but also may not lead to any sensation (11). The pressure fluctuations or cyclic variations in local barometric pressure caused by wind turbine noise have also been compared to similar pressure fluctuations that are experienced by an individual on a ship in high seas (12) as a result of the up and down motion of the ship changing the atmospheric pressure experienced by people’s ears. Dooley (12) proposed that this cyclic pressure variation may be the cause of

[1]Absolute in this context refers to the hearing threshold determined according to a conventional audiometric test.

motion sickness on ships as well as nausea in the vicinity of wind farms.

This study investigates the contribution of a wind farm to measured levels of infrasound through consideration of shutdown and operational conditions with comparable wind conditions at outdoor microphones. The measured levels are compared to established audibility thresholds for infrasound outlined by Møller and Pedersen (9) and response curves for the outer hair cells within the ear which have been discussed by Salt and Huller (11). The time variant nature of the sound is also investigated via the crest factor.

2. FIELD MEASUREMENTS

Continuous indoor and outdoor measurements were carried out for periods of approximately one week at three residences located near a wind farm, which is made up of 37 operational turbines. During each measurement period, the wind farm was shutdown for at least 50 minutes, which allowed collection of data corresponding to shutdown and operational conditions. The first two shutdowns were deliberate on the part of the wind farm operator, as they were associated with the recent EPA noise impact study; however, one of the shutdowns lasted for 54 continuous hours as it was related to a cable fault. The wind farm shutdowns provided a unique opportunity for measuring ambient noise levels, thus enabling comparison of shutdown and operational conditions.

The indoor acoustic measurements were recorded using three B&K 4955 microphones that were located at various positions around an unoccupied room. These microphones have a low noise floor of 6.5 dB(A) and a flat frequency response down to 6 Hz. While these microphones do not have a flat frequency response below 6 Hz, they are still capable of measuring the blade-pass frequency and harmonics (13). The microphones were connected to LAN-XI hardware and continuous 10-minute recordings were made using Pulse software. One of the indoor microphones was positioned in a corner, since this is an anti-node for all room response modes and thus the measured amplitude represents the maximum level. Nevertheless, there was good agreement between the spectra measured by the three microphones for frequencies below 20 Hz. This is expected since standing waves would not occur in an average-sized room at such low frequencies; therefore results are presented for the corner microphone only in this paper.

The outdoor acoustic measurements were made using a G.R.A.S. type 40AZ microphone with 26CG preamplifier, which has a noise floor of 16dB(A) and a low frequency linear response down to 0.5 Hz. The microphone was connected to a National Instruments data acquisition device, which measured continuously over 10-minute intervals. A hemispherical secondary windshield was used to minimise wind-induced noise experienced by the outdoor microphone, and it was designed to be consistent with the IEC 61400-11 standard (14), which specifies the use of this secondary windshield for sound power measurements close to a wind turbine. Wind speed and direction were measured at heights of 1.5 m and 10 m using Davis Vantage Vue and Vantage Pro weather stations, respectively. These weather measurements were collected in 5-minute intervals and then the 10-minute average was calculated during post-processing. Wind speed and direction at hub height were measured using a SODAR unit which was located on the ridge-top in the gap between the Northern and Southern wind turbine group shown in Figure 2. The wind farm operator also provided hub height wind data for the duration of the EPA study and therefore this data are referred to for House 1 and House 2 in this paper.

The location of the residences relative to the wind farm is shown in Figure 2. House 1 is situated 3.5 km from the nearest wind turbine, which is near the centre of the main turbine group. The downwind direction from the closest wind turbine to the residence is 88°. It is estimated that this residence was built in the early 1900's. The walls are constructed of 350 mm thick stone/cement brick, the windows are a small-medium, single-pane, wood-framed sash design and the roof is constructed from corrugated sheet steel. The ceiling consists of plaster panels and the ceiling space has recycled paper insulation. This house was unoccupied for the duration of the measurements. House 2 is 8.7 km from the nearest wind turbine which is the northernmost turbine of the main group. The downwind direction from the closest wind turbine to the residence is 268°. For the indoor measurements, a small cottage was used which is separated from the main residence by about 10 m. The walls of the cottage are constructed of stone without insulation. The roof consists of corrugated sheet steel. The ceiling is constructed of wooden panels and there are two medium-sized windows, one of which faces towards the wind farm. House 3 is 3.3 km from the nearest wind turbine, which is the southernmost turbine in the smaller northern group. The downwind direction from the closest wind turbine to the residence is 300°. The walls of this residence are constructed of concrete and the roof consists of corrugated sheet steel. The indoor instrumentation was located in the room closest to the wind farm, which has one medium-sized window facing the wind farm. The house was occupied during the measurement period but the results presented in this paper were collected between 12 am and 5 am for this residence, during which time indoor disturbances were expected to be minimal.

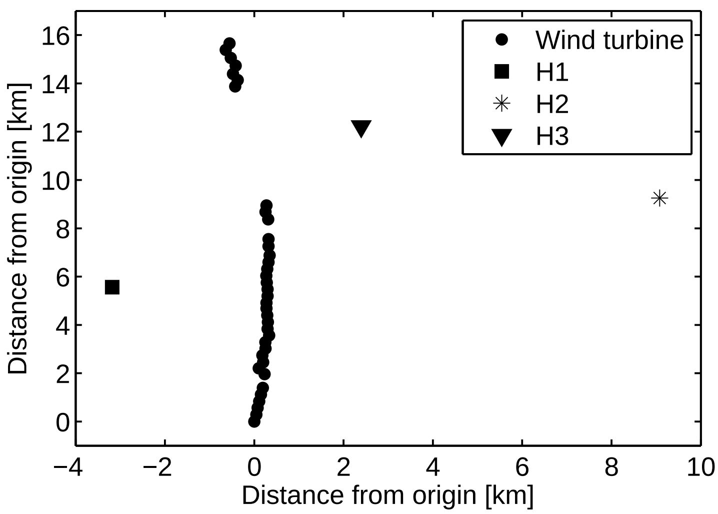

Figure 2 – Location of residences relative to the wind farm.

3. RESULTS

The following analysis pertains to the infrasonic frequency range, which comprises frequencies below 20 Hz, where the difference between operational and shutdown conditions can be up to 20 dB. Large differences in the measured noise levels for shutdown and operational conditions were also observed in the low frequency range (20 Hz - 200 Hz) but will not be discussed here. The infrasonic frequency range was compared to the Møller and Pedersen (9) and Moorhouse *et al.* (8) hearing thresholds and the Salt and Huller (11) OHC threshold.

Table 1 shows the wind conditions and wind farm power output for operational and shutdown conditions. As can be seen, the wind speed at 10 m is generally low and very similar during operational and shutdown conditions. This means that wind-induced noise is minimal and comparable between operational and shutdown conditions.

Table 1 – Wind conditions for shutdown vs. operational for all residents.

		Wind speed (m/s)		Wind direction (°)		
Residence	Description	10 m	hub height	10 m	hub height	Power Output (%)
H1	Operational	3.35	10.5	135	133	44
	Shutdown	3.35	9.7	135	129	0
H2	Operational	2.9	8.7	281	305	56
	Shutdown	3.8	10.5	315	306	0
H3	Operational	0.4	10.4	22.5	287.0	57
	Shutdown	0.9	12.4	22	291	0

The narrow-band spectra corresponding to shutdown and operational conditions are shown in Figures 3, 4 and 5. The spectra were calculated using Welch's averaged modified periodogram method of spectral estimation with a Hanning window of length 81920 (10 $\times$ the sampling frequency) points and 50% overlap which gives 0.1 Hz frequency resolution.

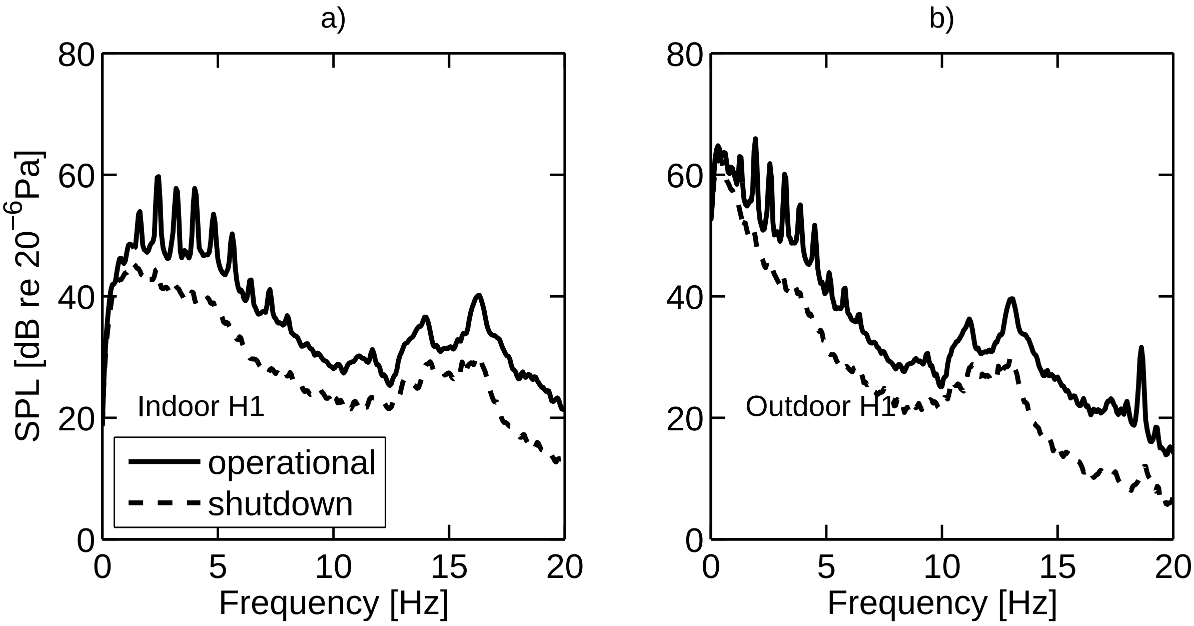

Figure 3 – Spectra comparison between operational and shutdown conditions for residence H1. The comparison is done for indoor (a) and outdoor (b).

The difference between the operational and shutdown conditions, indoor and outdoor, is clearly evident. When the wind farm is operating, the blade pass frequency ($\sim$0.8 Hz) and upper harmonics are visible in the spectrum which corresponds well with the operational speed of 16.1 rpm (15). Due to the wind induced noise in outdoor measurements, the spectra around$\sim$1Hz in Figures 3b, 4b and 5b is higher in comparison to indoor measurements.

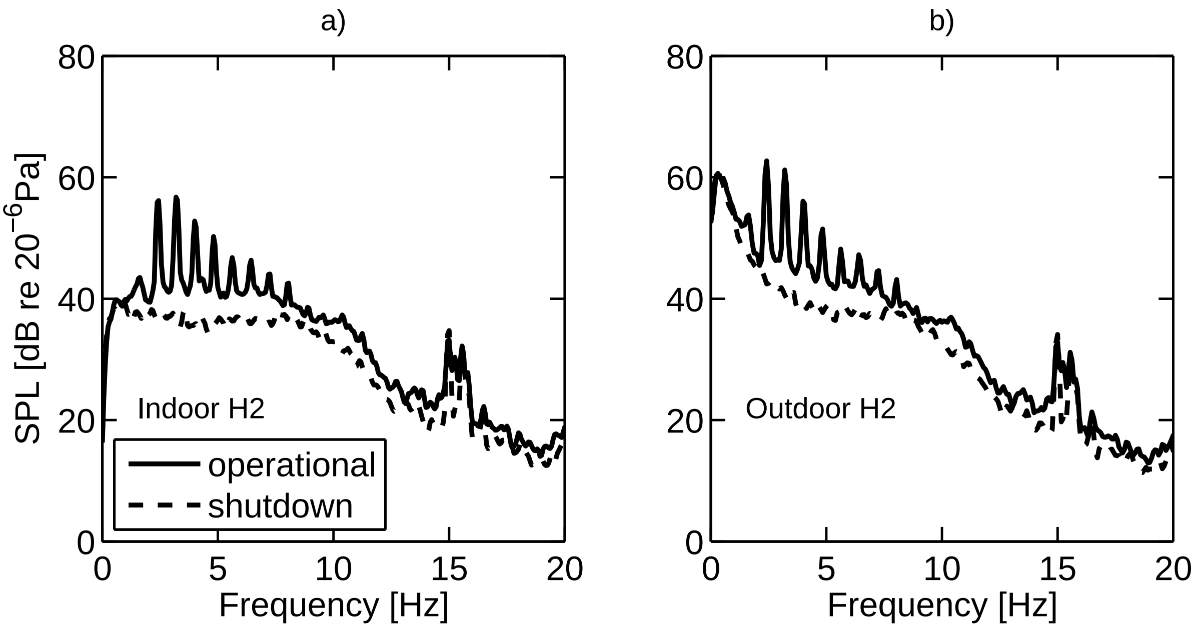

Figure 4 – Spectra comparison between operational and shutdown conditions for residence H2. The comparison is done for indoor (a) and outdoor (b).

At these tonal components, the SPL can be up to 20 dB higher in comparison to the time when the wind farm is off, as shown in Figure 5b. Furthermore, Figure 5b shows a peak at ∼13 Hz which is believed to be a house structural resonance which is excited by wind turbine noise.

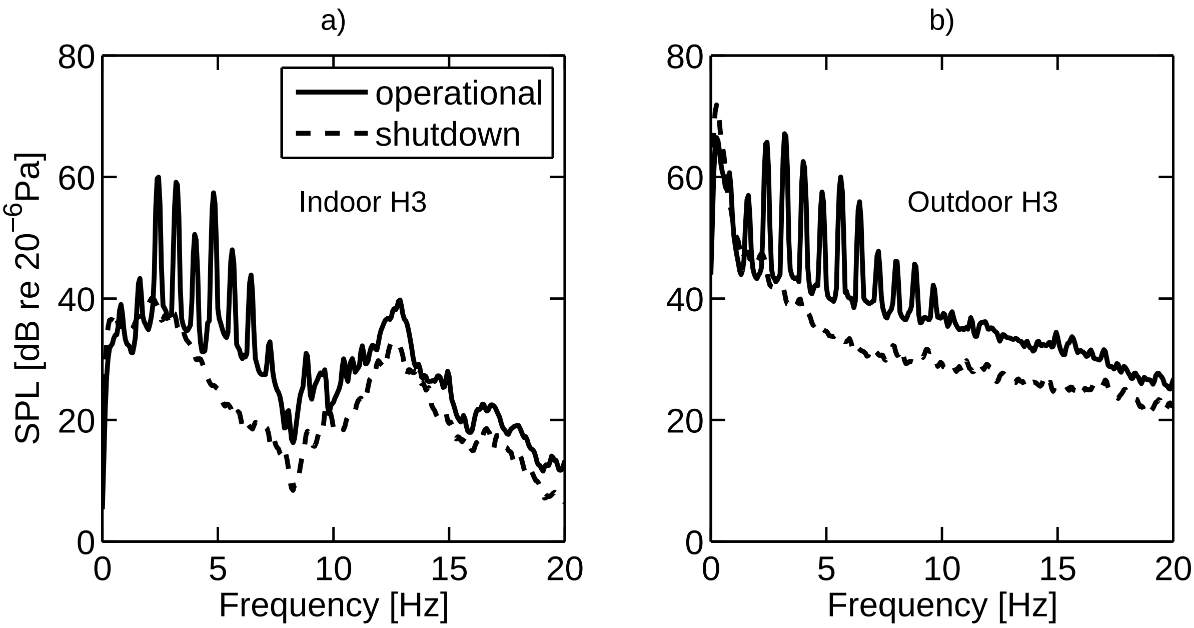

Figure 5 – Spectra comparison between operational and shutdown conditions for residence H3. The comparison is done for indoor (a) and outdoor (b).

Figure 6 shows a comparison between two hearing thresholds and wind turbine noise. The infrasonic range of wind turbine noise is not perceptible which is in agreement with previously published research (16).

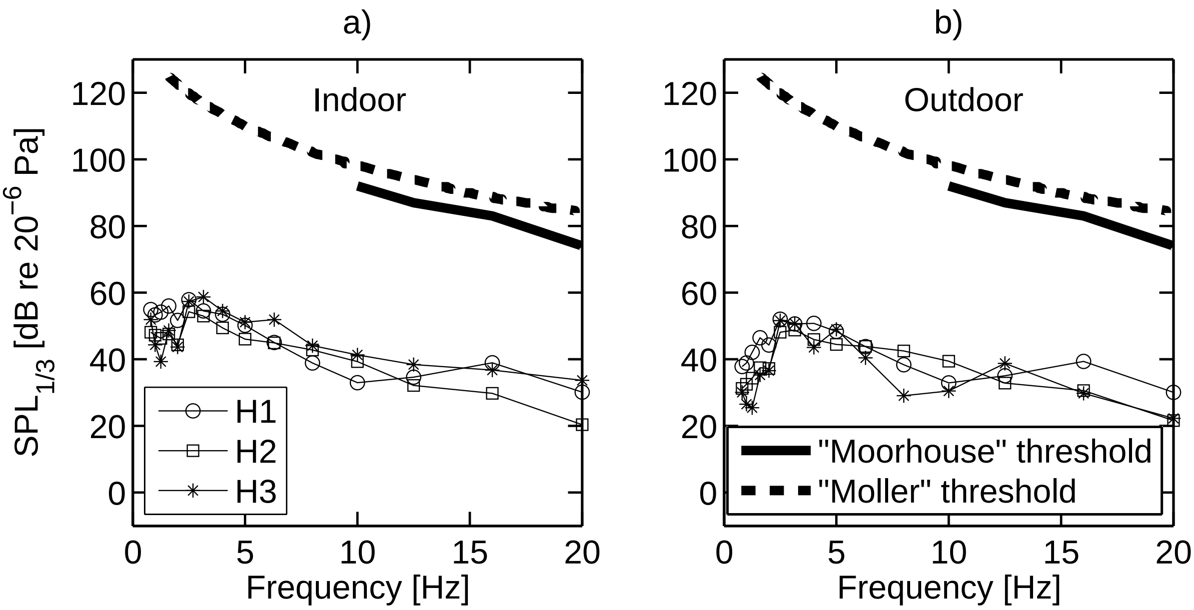

Figure 6 – One-third octave band sound pressure level at H1, H2 and H3 for operational condition, in comparison to “Moorhouse”(8) and “Møller”(9) thresholds. a) inside and b) outside.

On the other hand, the outer hair cells (OHC) in the human ear can be stimulated by sounds at levels below those that are heard (11). This stimulation can result in the firing of neurons, which results in a signal being sent to the brain. The physiological effects of this neurological process are hitherto unknown. Hence, the OHC threshold described by Salt (11) has been plotted in Figures 7, 8 and 9 for comparison with the peak levels in 1 Hz bandwidth time series.

Peak time series level, as opposed to frequency domain representation, was chosen because of the nonstationary nature of wind farm noise. Analysis in frequency domain commonly involves averaging over long periods of time and thus the peak values cannot be captured.

The time signal was filtered using 1Hz bandwidth 10^{th} order Butterworth filters, with center frequencies f_c = 2,3,4...20 Hz. For the center frequency f_c = 1 Hz a low pass 10^{th} order Butterworth filter with a cut-off frequency at 2 Hz was used. This type of filter was used because it has a flat frequency response in a pass band and thus preserves the peak level.

As can be seen in Figures 7a and 7b, the OHC threshold is exceeded when the wind farm is operational and also when it is shutdown. The difference between these two is apparent in magnitude and frequency range. The difference in magnitude between operational and shutdown conditions is in the order of ∼5 dB around 17 Hz. In terms of frequency, operational conditions exceed the threshold at ∼12 Hz while for the shutdown conditions this happens at ∼14 Hz.

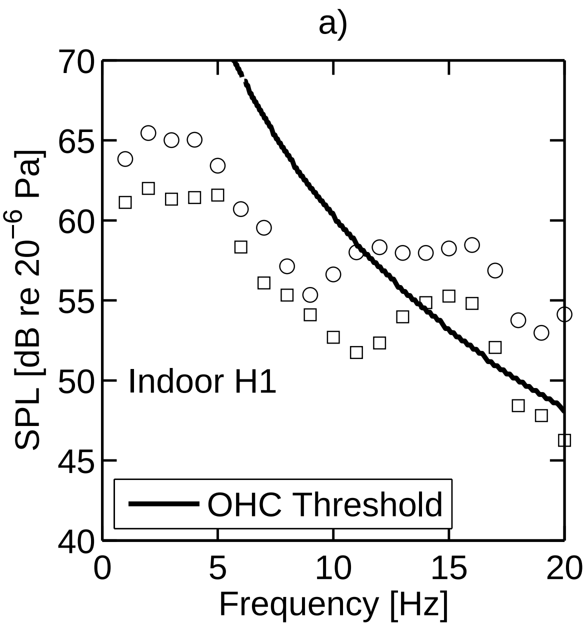

Figure 7 – Peak sound pressure level comparison at H1, for operational and shutdown conditions, indoor (a) and outdoor (b).

In Figures 8a and 8b, it can be seen that the infrasound does exceed the OHC threshold by ∼1 dB. This occurs for operational and shutdown conditions. The overall difference between the operation and shutdown conditions is not as large as in the other cases, however, a general trend of SPL being higher when the wind farm is operational can be observed.

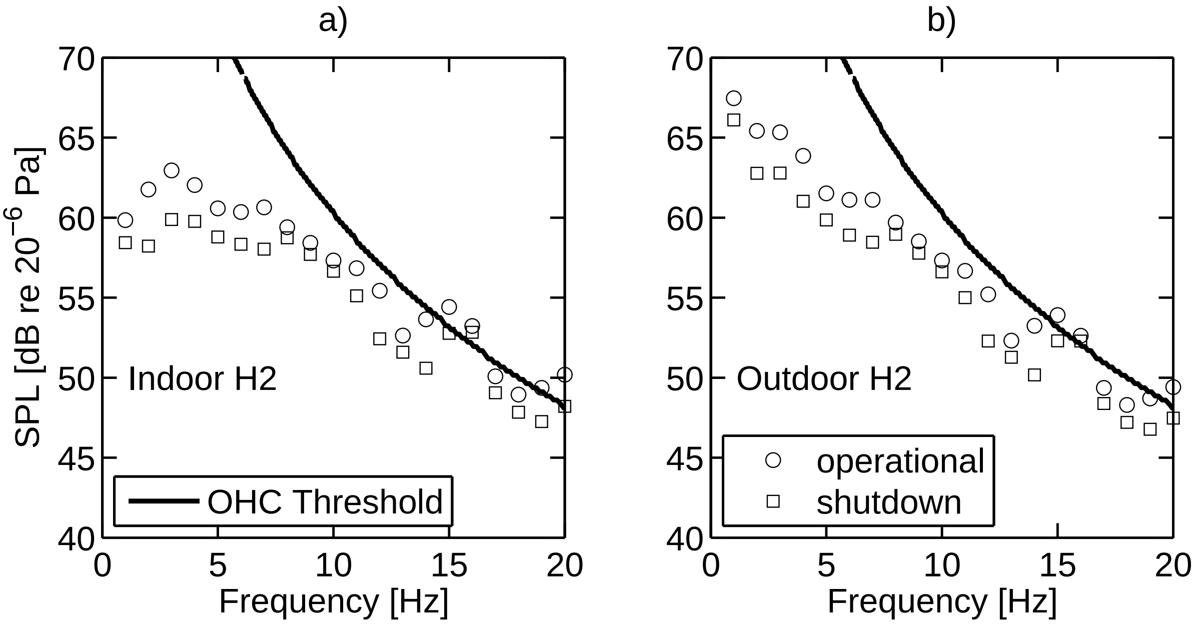

Figure 8 – Peak sound pressure level comparison at H2, for operational and shutdown conditions, indoor (a) and outdoor (b).

Figures 9a and 9b, also show a higher SPL when the wind farm is on. In Figure 9a the SPL exceeds the OHC threshold at ∼13 Hz which is believed to be the frequency associated with the house structural resonance, which gets enhanced by wind turbine noise. When the wind farm is shutdown the SPL does not exceed the OHC threshold. For the outdoor operational conditions in Figure 9b, a peak exceeding the OHC threshold by ∼4 dB at ∼16 Hz can be observed.

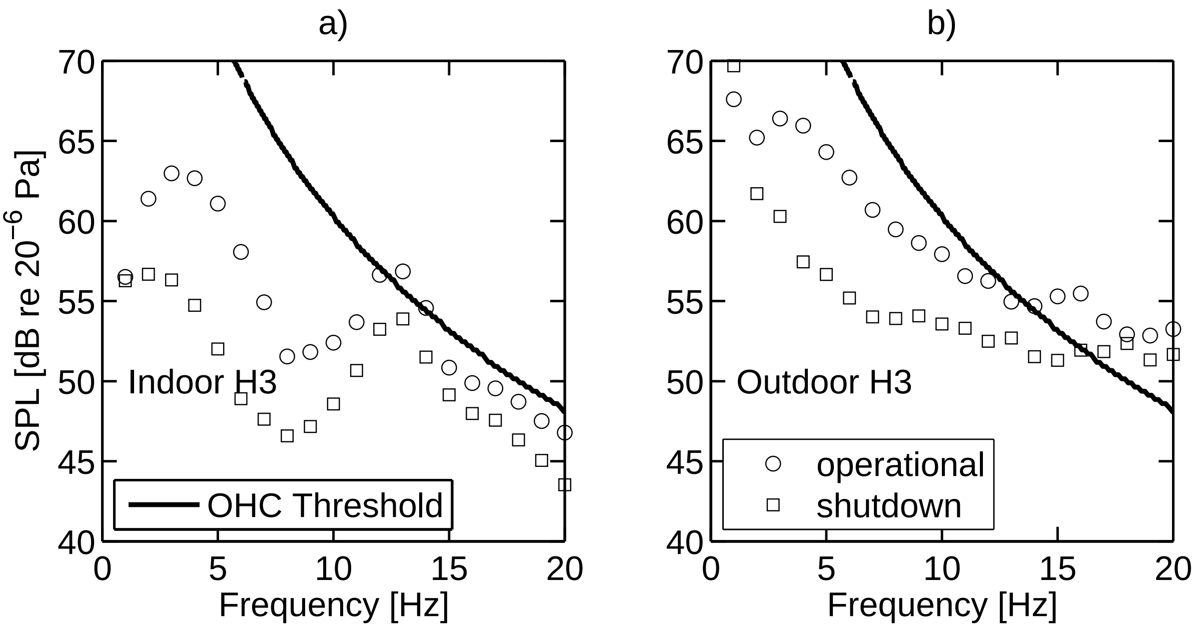

Figure 9 – Peak sound pressure level comparison at H3, for operational and shutdown conditions, indoor (a) and outdoor (b).

From the results presented in Figures 7, 8 and 9 the following can be concluded for the three residences and wind farm considered in this study: *a)* the OHC threshold can be exceeded at frequencies >12 Hz, *b)* the OHC threshold can be exceeded both when the wind farm is operating and when it is shut down, *c)* when the wind farm is operating, the OHC threshold can be exceeded by up to 5 dB. It can be therefore be concluded, that wind farm infrasonic noise can be unconsciously registered by people living in surrounding residences, even at distances of 8 km from the nearest turbine in a wind farm .

An additional effect on the physiology of the ear could be caused by the transient and tonal nature of wind turbine noise. A measure of the transient nature, or signal impulsiveness, is the crest factor which is defined as $\frac{x_{peak}}{x_{rms}}$, where x stands for a time series. Some typical values of crest factor are 1.41 for a sine wave and ∼4 for Gaussian noise (5).

The crest factor was calculated for times when the wind farm was operational and shutdown over a 10 min period. The time signal was filtered using a a low-pass 4^{th} order Butterworth filter, with a cut-off frequency of 20 Hz and the results are presented in Table 2.

Table 2 – Crest factor <20 Hz for operational and shutdown conditions.

	H1		H2		H3	
	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor
Operational	4.3	6.7	4.3	5.1	3.5	4
Shutdown	7.2	7.1	6.6	4.2	3.9	3.6

As can be seen from Table 2 the crest factor varies from 3.5 to 6.7 for when the wind farm is operational, which suggest that wind farm infrasound may be impulsive. Higher crest factor values are observed for the outdoor results, which are likely attributed attributed to the fluctuating wind induced noise.

The crest factor is also high during the wind farm shutdown periods as shown in Table 2, indicating that crest factor may not be a very good indicator of wind farm impulsiveness. For a comparison with the crest factor, *rms* values are given in Table 3.

Table 3 – rms acoustic pressure for operational and shutdown conditions.

	H1		H2		H3	
	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor
Operational	0.02	0.04	0.01	0.03	0.01	0.04
Shutdown	0.006	0.02	0.004	0.02	0.003	0.04

The *rms* values during shutdown can be up to 300% lower in comparison to when the wind farm is operational, which should be taken into account when evaluating the usefulness of crest factor for assessing wind farm noise.

The short and long term effects of the impulsiveness of the infrasound on the human subconscious response is not known at this stage and further research is needed to understand these effects.

4. SUMMARY

Outdoor and indoor measurements were carried out at three residences located in the vicinity of a wind farm. Measurements were done for both operational and shutdown conditions and significant differences between shutdown and operational conditions were found in the infrasonic range (below 20 Hz). More specifically, distinct peaks at the blade-pass frequency, associated with operational conditions, were found to be and generally more than 20 dB higher than the levels measured at equivalent frequencies when the wind farm is shutdown. These observations are consistent for both the outdoor and indoor results.

Despite the large differences in the infrasonic noise level measured during shutdown and operational conditions, the one-third octave sound pressure levels are are well below the threshold of audibility derived by Møller and Pedersen (9) and Moorhouse *et al.* (8) which suggests that the infrasonic range of wind turbine noise is not perceived as sound. However, comparison of peak sound pressure levels in bandpass filtered time signals with a 1 Hz bandwidth indicated that wind farm infrasound might be detected by the ear and thus could influence how people feel in its presence. Furthermore, the infrasound was shown to have an impulsive character, which might also be an important factor.

Results presented in this paper are of a preliminary nature and thus no firm conclusions can be drawn from it. The possibility of the ear being responsive to inaudible levels of infrasound does require further research.

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