Comparison of the noise levels measured in the vicinity of a wind farm for shutdown and operational conditions

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

[1] University of Adelaide, Australia

ABSTRACT

Outdoor and indoor microphone measurements have been taken in the vicinity of the Waterloo wind farm at a number of locations during periods when the nearby wind farm was operational as well as when it was shutdown. The majority of the shutdowns were of short duration and 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 several days as it was related to a cable fault. Comparisons are made between both the third-octave spectra and narrowband spectra measured during the shutdown and operational periods. Operational times immediately adjacent to the shutdown times, as well as at other times when the wind conditions at hub height and at the residence matched the conditions recorded during a shutdown time, are considered in the analysis. It is shown that there are consistent and significant differences in noise spectra at the residence for the shutdown and operational cases, particularly for frequencies below 100 Hz. These differences can be observed at distances up to 8.7 km from the wind farm.

Keywords: Wind farm noise, amplitude modulation, shutdown I-INCE Classification of Subjects Number(s): 14.5.4

1. INTRODUCTION

Rural areas in South Australia are characterised by low ambient noise levels, particularly during nighttime hours. The operation of a large industrial wind farm can present a significant contrast to these ambient conditions, particularly at a downwind location when there is high wind shear. Under such conditions, the low frequency and infrasonic components of wind farm noise can travel large distances due to a combination of refraction, which causes sound waves to bend towards the ground, small atmospheric absorption and insignificant losses on reflection from the ground. This phenomenon has been investigated for a single wind turbine under downwind conditions, where it was found that the attenuation rate of noise in the frequency range of 2 Hz to 20 Hz is 3 dB/doubling of distance, rather than the 6 dB/doubling of distance which occurs due to spherical spreading (1).

Several residents who live in close proximity to wind farms report annoyance even when the measured noise levels are relatively low. The noise is often described as “thumping” or “rumbling” in character, which suggests that the amplitude of the noise varies with time and that it is low-frequency in nature. A periodic variation of the amplitude with time is referred to as amplitude modulation and listening tests have shown that for a given noise level, the presence of amplitude modulation significantly contributes to perceived annoyance (2). Annoyance by low frequency noise often occurs in the range of an individual’s hearing threshold (3) and therefore if a low frequency noise is audible to the individual and is amplitude modulated, it is likely to be annoying.

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 *et al.* (4), 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, or have no sensation (4). The pressure fluctuations or cyclic variations in local barometric pressure caused by wind turbine noise have also been compared to similar fluctuations which are experienced by an individual on a ship in high seas (5). The

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

pressure fluctuations experienced by the individual on the ship occur due to changes in the elevation which cause the barometric pressure to vary relative to the individual. Dooley (5) proposed that this cyclic pressure variation may be the cause of motion sickness on ships as well as nausea in the vicinity of wind farms.

Previous measurements recorded in the vicinity of wind farms have shown evidence of infrasound and low frequency noise, where the latter is modulated at the blade-pass frequency. Ambrose *et al*. (6) investigated noise at a residence that was approximately 500 m from a "NOTUS" wind turbine and recorded peaks at the blade-pass frequency and harmonics as well as a 22.9 Hz tone indoors that was modulated at the blade-pass frequency of 0.7 Hz. The sound pressure level of this tone varied significantly above and below the associated outer hair cell threshold of 45 dB. Metelka (2013) conducted measurements at distances of 400 m and 500 m from the Kincardine wind farm in Ontario during the nighttime. The measured spectra showed distinct peaks at the blade-pass frequency and harmonics as well as peaks at 20.1 Hz and 40.2 Hz, which were amplitude modulated at the blade-pass frequency.

Recently, the South Australian Environmental Protection Authority (SA EPA) conducted a series of measurements in the vicinity of the Waterloo wind farm in rural South Australia. In their report (7), the EPA notes the presence of a "rumbling" noise but they asserted "low frequency content was not discernible subjectively when replaying audio records at actual levels." The EPA report (7) also included an analysis of the noise levels when the wind farm was shutdown and operational. Noise in the 50 Hz third-octave band was found to increase by as much as 30 dB when the wind farm was operational compared to when it was shutdown. Further analysis was not carried out however, since the noise in the 50 Hz third-octave band did not meet the definition of a tone according to standards such as NZ 6808:2012 (8) and ANSI S12.9 - Part 4 which require a 15dB difference between the possible tone and adjacent third-octave components, for a frequency range from 25 to 125Hz. During wind farm operation, the noise level in adjacent third-octave bands was also up to 20 dB higher than for shutdown conditions.

The aims of the study reported on here were to quantify the wind farm contribution to the measured noise level through comparison between shutdown and operational conditions and to investigate the character of the noise signature that is associated with wind farm operation. Data were collected near the Waterloo wind farm, at three different residences, which are located at distances between 3 km and 8 km from the nearest wind turbine. The wind farm was both operational and entirely shutdown during the measurement period at each residence and the local weather conditions during shutdown and operation were matched to account for the contribution of wind-induced noise. Where possible, measurements were selected for nighttime hours between 12 am and 5 am, where the local wind speed at the microphone was negligible, to maximise the signal-to-noise ratio between wind turbine noise and ambient noise.

2. INSTRUMENTATION/FIELD MEASUREMENT LAYOUT

Continuous indoor and outdoor measurements were carried out for periods of approximately one week at three residences located near the Waterloo 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. For the indoor acoustic measurements, three B&K 4955 microphones 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 (9). The microphones were connected to LAN-XI hardware and continuous 10-minute recordings were made using Pulse software. The average sound pressure level of the three microphones was calculated in accordance with the Danish guidelines for indoor low-frequency noise measurements (10). This average includes one microphone positioned in the room corner. Results recorded with this microphone were used in the narrow-band analysis. In this corner position, the maximum sound pressure level would be measured since this is an anti-node for all room response modes.

The outdoor third-octave measurements were made using G.R.A.S. 40AZ / SV 12L microphones connected to a SVAN 958 sound level meter, which measured continuously over 10-minute intervals. The microphones have a noise floor of 17 dB(A) and a flat frequency response down to 0.8 Hz. The time data used in the narrow-band analyses were measured using a G.R.A.S. type 40AZ microphone with 26CG preamplifier with 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. Hemispherical secondary windshields were used to minimise wind-induced noise experienced by the outdoor microphones, and they were designed to be consistent with the IEC 61400-11 standard (11), which specifies the use of these secondary windshields 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. The weather measurements were collected in 5-minute intervals and then the 10-minute average was calculated during post-processing.

The location of the residences relative to the wind farm is shown in Figure 1. 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 and 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.

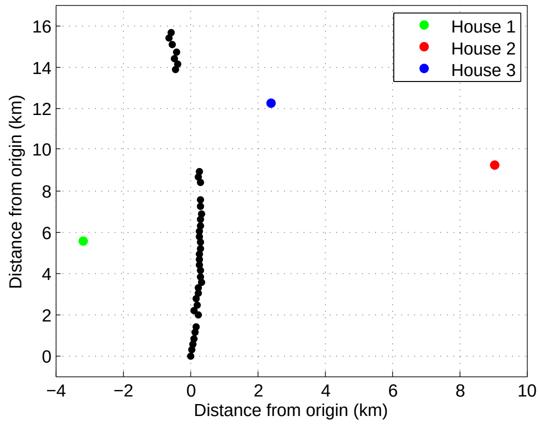


Figure 1 – Layout of residences relative to the Waterloo wind farm.

3. RESULTS

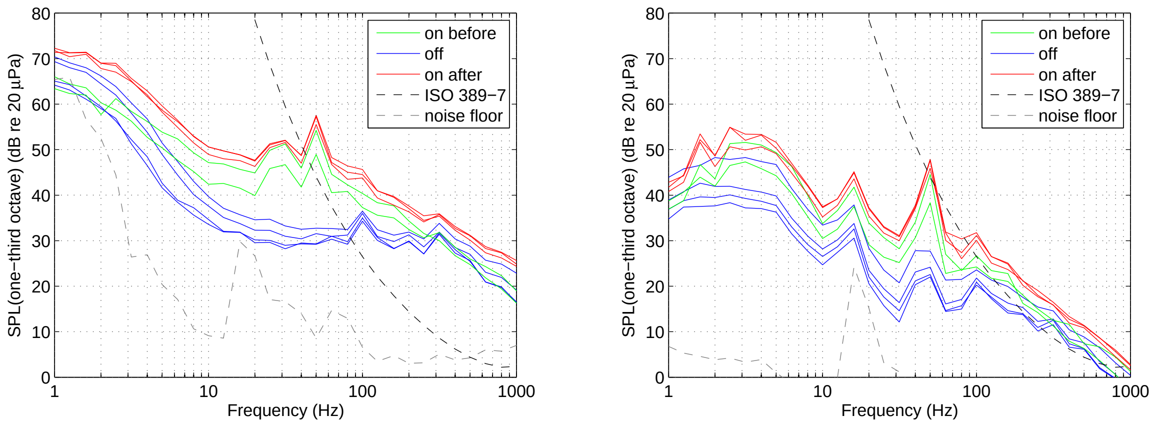
3.1 Third-octave acoustic spectra

In this section the third-octave spectra measured at the three residences described in Section 2 are presented for shutdown and operational conditions. The following plots show the unweighted sound pressure level for times related to when the wind farm was shut down. Comparisons are made between measurements that were taken before the shutdown (three 10-minute averages), during the shutdown and after the shutdown (three 10-minute averages) as well as for other measurement times where the wind conditions at hub height and at the residence were similar to those that occurred during shutdown. The conditions were matched based on the criteria that the wind speed at hub height should be within +/-10%, the wind speed at 1.5 m should be within +/-10% and the wind direction at hub height should be within +/-22.5°. These tolerances were reduced in some cases, where there were a large number of operational conditions that matched the shutdown conditions.

3.1.1 House 1

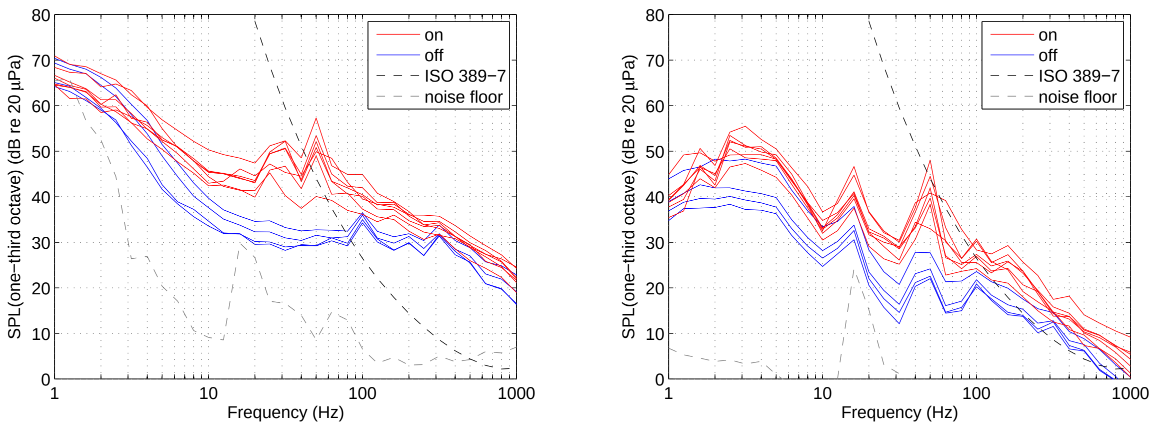
The unweighted 10-minute averaged third-octave spectra for the shutdown and operational cases are shown in Figure 2 and Figure 3. The curve labelled "ISO 389-7" corresponds to the generally accepted threshold of hearing for normal ears subjected to steady tonal noise. The outdoor and indoor noise levels measured during the shutdown cases were consistently lower than those measured when the wind farm was operating. This can be observed for the entire frequency range from 1 Hz to 1000 Hz. Comparison between Figure 2 (a) and (b) and Figure 3 (a) and (b) reveals that the increased noise levels can also be observed for operational conditions selected based on matching wind speed conditions.

The most significant difference in the spectra occurs for the 50 Hz third-octave band, where the sound pressure level difference between shutdown and operational cases can be more than 25 dB for both outdoor and indoor measurements. The high sound pressure level in this third-octave band observed during operational conditions cannot be attributed to electrical noise as it is not present when the wind farm is shut down. In comparison to the SA EPA study (7) results, the difference between shutdown and operational levels in this third-octave band is much larger, where the outdoor operational levels in the 50 Hz third-octave band, measured at the same residence by the EPA, were closer to 45 dB (instead of the 58 dB shown in Figure 2 (a)) and the shutdown levels are similar to those shown in Figure 2 (a) and Figure 3 (a) giving a difference of approximately 15 dB. The indoor levels for this residence reported by the SA EPA (7) were also much lower than those presented in Figure 2 (b) and Figure 3 (b) and were close to 30 dB. Contrary to the EPA report (7) findings, the data in Figure 2 and Figure 3 shows that the noise in the 50 Hz third-octave band, associated with operational conditions, would be audible both indoors and outdoors to a person with normal hearing according to ISO 389-7 (12). In addition, the peak in the 50 Hz third-octave band is more than 15 dB higher than the level in the adjacent third-octave bands for the indoor results. According to guidelines specified in standards such as NZS 6808:2010 (8) and ANSI S12.9 - Part 4 (13), this would be classified as a tone and hence an adjustment to the allowable wind farm noise limits would be required. According to the SA EPA standard (14), a penalty of 5 dB(A) would need to be added to the measured noise level in the case of identified tonality. The results in this report suggest that this would lead to non-compliance at the Township residence but the EPA study (7) results indicate that the wind farm would still be compliant.



(a) Outside third-octave - 1/5 (shutdown, 20:10 - 21:00). (b) Inside third-octave - 1/5 (shutdown, 20:10 - 21:00).

Figure 2 – Comparison of third-octave spectra for House 1 before/during/after shutdown.



(a) Outside - shutdown vs. operational (shutdown, 1/5 20:10 - 21:00). (b) Inside - shutdown vs. operational (shutdown, 1/5 20:10 - 21:00).

Figure 3 – Comparison of third-octave spectra for House 1 with wind conditions matching the wind farm shutdown.

The outdoor results shown in Figure 2 (a) and Figure 3 (a) also indicate that the sound pressure level in the third-octave bands from 25 Hz to 40 Hz is higher when the wind farm is operating. On the other hand, the indoor results shown in Figure 2 (b) and Figure 3 (b) do not show peaks in the sound pressure level at these frequencies. It is possible that the noise level in this third-octave band varies with room position due to the presence of room resonances and thus the average results would not reflect the worst case scenario for indoor noise. The large difference in the sound pressure level indoors relative to outdoors was also shown in the SA EPA report (7) for these third-octave bands. Another characteristic that can be attributed to wind farm operation are the peaks in the infrasonic frequency range which appear to correspond to harmonics of the blade-pass frequency. Additionally, a significant peak is evident in the 16 Hz third-octave band for the indoor results. While this peak is present for both operational and shutdown conditions, the level is consistently higher when the wind farm is operating, by as much as 15 dB. It is believed that there is a structural resonance of the residence in this frequency range which is excited by both wind induced noise and wind farm noise. It has been found previously that structural resonances occur in the range of 12-30 Hz, according to data measured for several different housing structures (15).

Given that the nearest wind turbine is located in the direction of 88° from the Township residence, it was established that the residence was downwind from the wind farm for all measurements which are presented for the shutdown and operational cases, as shown in Table 1. The wind speed measured at a height of 1.5 m in the vicinity of the residence was relatively low and did not exceed 2.7 m/s. The wind speed at hub height was above the cut-in speed of 3.5 m/s (16) but did not reach the rated speed of 15 m/s (16). The maximum power output for the entire wind farm was 72% but there were some 10-minute samples for which the power output was as low as 25%. This explains the variations in sound pressure level observed for the third-octave spectra associated with wind farm operation, particularly in the 50 Hz third-octave band where the level varied by up to 15 dB.

Table 1 – Wind conditions for shutdown vs. operational (House 1).

	Wind speed (m/s)			Wind direction (°)			Power Output (%)
Description	1.5 m	10 m	hub height	1.5 m	10 m	hub height	
Shutdown	1.6 - 2	3.4 - 4.3	9.7 - 11.7	135	135	125.5 - 129.4	0
Adjacent	1.6 - 2.7	3.6 - 4.7	9.8 - 14.2	135	135	124.7 - 131	26 - 72
Condition match	1.6 - 2	3.1 - 4.3	8.8 - 12.7	135	135 - 146.3	122.6 - 134.1	25 - 69

3.1.2 House 2

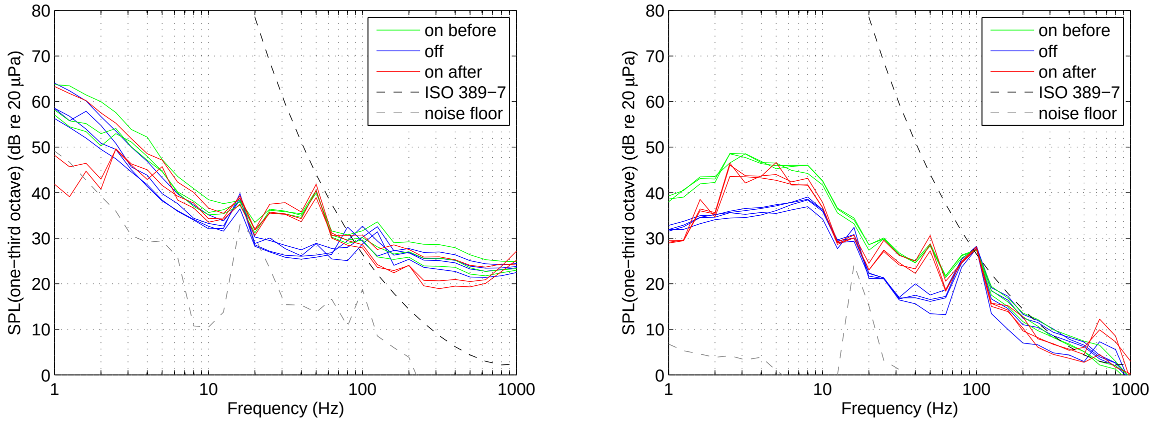
The unweighted 10-minute averaged third-octave spectra for the shutdown and operational cases are shown in Figure 4 (a) and Figure 4 (b) for the residence which is 8.7 km from the wind nearest wind turbine. The outdoor noise levels measured during the shutdown cases were consistently lower than those measured when the wind farm was operating for all the third-octave bands between 20 Hz and 63 Hz. For the indoor results, the noise levels were lower during shutdown for almost all third-octave bands below 80 Hz. The increased noise levels can also be observed for operational conditions selected based on matching wind speed conditions but the corresponding results are not shown here.

Consistent with Section 3.1.1, the most significant difference in the spectra occurs for the 50 Hz third-octave band, where the sound pressure level difference between shutdown and operational cases can be higher than 15 dB for both outdoor and indoor measurements. The plots shown in Figure 4 indicate that the outdoor noise in the 50 Hz third-octave band is close to the audibility threshold for a person with normal hearing, which is defined in ISO 389-7 (12). However, as discussed in Section 1, wind turbine noise is highly variable with time and therefore it is expected that peak noise levels would be much higher than the 10-minute average levels. Hence, noise in the 50 Hz third-octave band is likely to be be audible outside and possibly inside to a person with normal hearing according to ISO 389-7 (12).

The outdoor and indoor results shown in Figure 4 (a) and Figure 4 (b) also indicate that the sound pressure levels in the third-octave bands from 25 Hz to 40 Hz are higher when the wind farm is operating as was observed in Section 3.1.1. This unduly influences the tonality assessment outlined in the NZS 6808:2010 (8) and ANSI S12.9 - Part 4 (13) standards. Another characteristic noted in Section 3.1.1 that can be attributed to wind farm operation are the peaks in the infrasonic frequency range, which appear to correspond to harmonics of the blade-pass frequency of 0.8 Hz. These peaks are more noticeable indoors where the contribution from wind-induced noise would be expected to be much lower.

The peak in the 100 Hz third-octave band is most likely attributable to a transformer, which was located nearby the residence and this explains why it was present when the wind farm was shutdown.

Since the nearest wind turbine is located in the direction of 268° from House 2, it can be seen that the residence was downwind from the wind farm for all of the measurements according to Table 2. The wind



(a) Outside third-octave - 10/6 (shutdown, 5:10 - 6:00).

(b) Inside third-octave - 10/6 (shutdown, 5:10 - 6:00).

Figure 4 – Comparison of third-octave spectra for for House 2 before/during/after shutdown.

speed measured at a height of 1.5 m in the vicinity of the residence was relatively low and did not exceed 2 m/s. The wind speed at hub height was above the cut-in speed of 3.5 m/s but was significantly lower than the rated speed of 15 m/s (16). Hence, due to the low hub height wind speeds, it is possible that the sound pressure levels plotted in Figure 4 are lower than the maximum levels that would occur at this residence. The maximum power output for the entire wind farm was 68 % but there were some 10-minute samples for which the power output was as low as 32%. As a result, there is some variability in the sound pressure level for the third-octave spectra measured during operational conditions. This is most evident in the infrasonic frequency range but there is also a variation of up to 3 dB in the 50 Hz third-octave band.

Table 2 – Wind conditions for shutdown vs. operational (House 2).

	Wind speed (m/s)			Wind direction (°)			Power Output (%)
Description	1.5 m	10 m	hub height	1.5 m	10 m	hub height	max
Shutdown	1.1 - 1.3	3.1 - 4.3	9.8 - 10.5	168.8 - 337.5	281.3 - 326.3	306 - 308	0
Adjacent	0.2 - 2	1.3 - 4.1	8.7 - 12.8	247.5 - 292.5	270 - 303.8	303.5 - 307.2	32 - 68
Condition match	1.1 - 1.3	2.2 - 3.8	9.4 - 10.9	292.5 - 315	292.5 - 315	295.2 - 306.5	46 - 68

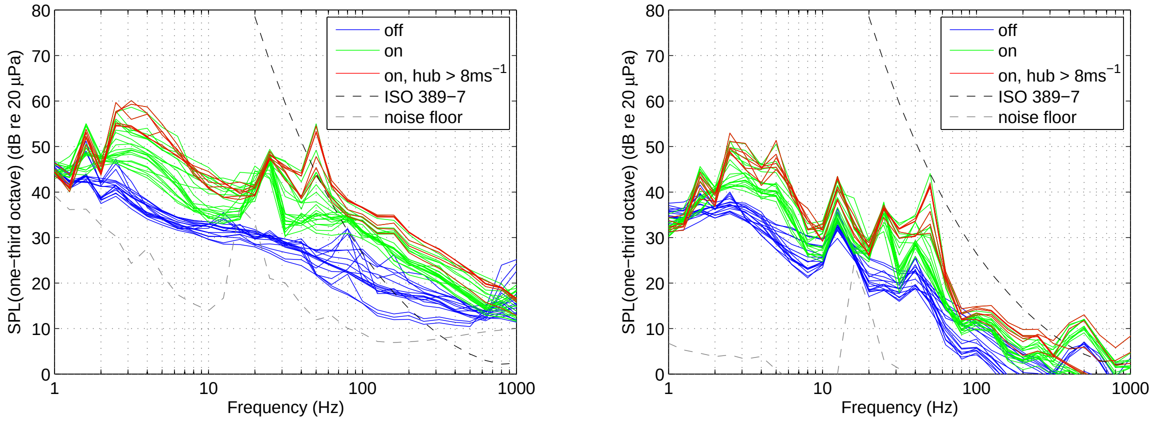
3.1.3 House 3

Unweighted third-octave spectra corresponding to a period during which the entire wind farm shut down due to the presence of a cable fault are shown in Figure 5 (a) and Figure 5 (b). To minimise interference from wind-induced noise and other extraneous noise sources, the measurements for comparison were selected during nighttime hours between 12 am and 5 am when the wind speed measured at 1.5 m in the vicinity of the microphones was 0 m/s. Due to wind shear, the wind speed at hub height was non-zero and for all results shown in Figure 5 (a) and Figure 5 (b), it was greater than 6.5 m/s.

The outdoor and indoor noise levels measured during the shutdown cases were consistently lower than those measured when the wind farm was operating for the majority of third-octave bands between 1 Hz and 1000 Hz. Moreover, the noise levels measured when the hub height wind speed was greater than 8 m/s were in general, the highest noise levels recorded, as shown by the red-coloured plots in Figure 5 (a) and Figure 5 (b). This provides evidence of a strong correlation between significant increases in low frequency noise and infrasound, and wind farm operation.

As was noted in Section 3.1.1 and Section 3.1.2, the largest difference in the spectra occurs for the 50 Hz third-octave band, where the sound pressure level difference between shutdown and operational cases can be higher than 30 dB for both outdoor and indoor measurements. The plots shown in Figure 5 (a) indicate that the outdoor noise in the 50 Hz third-octave band is at least 10 dB higher than the audibility threshold for a person with normal hearing, which is defined in ISO 389-7 (12). The corresponding indoor results shown in Figure 5 (b) indicate that the noise in the 50 Hz third-octave band was extremely close to the audibility threshold (12). However, since wind turbine noise is highly variable with time, it is expected that peak noise levels would be much higher than the 10-minute average levels. Therefore, it is highly likely that noise in the 50 Hz third-octave band is audible outside and possibly inside to a person with normal hearing according to ISO 389-7 (12).

Comparison between the outdoor results presented in Section 3.1.1 indicates that the level of broadband infrasound shown in Figure 5 (a) is significantly lower for House 3 than for Houses 1 and 2 when the wind farm is switched off, due to the absence of wind-induced noise. As a result, peaks at blade-pass harmonics are much more distinct and the sound pressure level measured in adjacent third-octave bands is as much as 15 dB lower. As was observed in Section 3.1.1 and 3.1.2, higher sound pressure levels are also associated with the third-octave bands from 25 Hz to 40 Hz when the wind farm is operational, particularly when the wind speed at hub height is greater than 8 m/s. Furthermore, a distinct peak at 12.5 Hz can be identified for the indoor results only, although the associated wavelength is too large to indicate room resonance effects. Therefore, it is likely that this is a structural resonance which is related to the construction properties of this residence.



(a) Outside third-octave - 24/7 to 1/8 (shutdown, 24/7 to 26/7). (b) Inside third-octave - 24/7 to 1/8 (shutdown, 24/7 to 26/7).

Figure 5 – Comparison of third-octave spectra for House 3 during/after cable fault.

The closest wind turbine to House 3 is located in the direction of 300° and therefore, the residence was downwind from the wind farm for the majority of the operational measurements according to Table 3. The wind speed at hub height was above the cut-in speed of 3.5 m/s (16) but was significantly lower than the rated speed of 15 m/s (16). Hence, due to the low hub height wind speeds, the sound pressure levels plotted in Figure 4 could be lower than the maximum levels that would occur at this residence. The maximum power output for the entire wind farm was 57 % but there were some 10-minute samples for which the power output was as low as 12%. Therefore there are some significant variations in the third-octave spectra measured during operational conditions, particularly in the 50 Hz third-octave band and below.

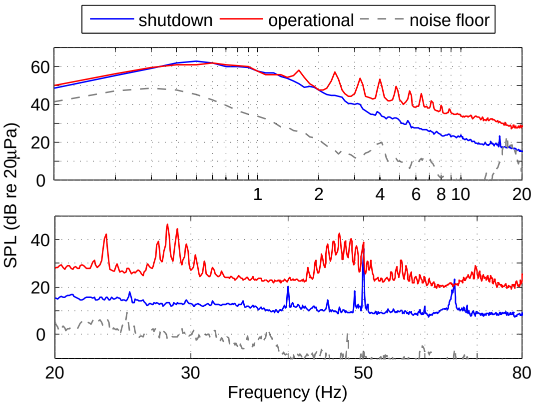
Table 3 – Wind conditions for shutdown vs. operational (House 3).

	Wind speed (m/s)		Wind direction (°)		Power Output (%)
Description	10 m	hub height	10 m	hub height	max
Shutdown	0 - 1.6	8.8 - 12.5	22.5 - 337.5	286.5 - 316.5	0
Operational	2.2 - 3.8	6.5 - 10.4	0 - 337.5	242.3 - 351.7	12 - 57

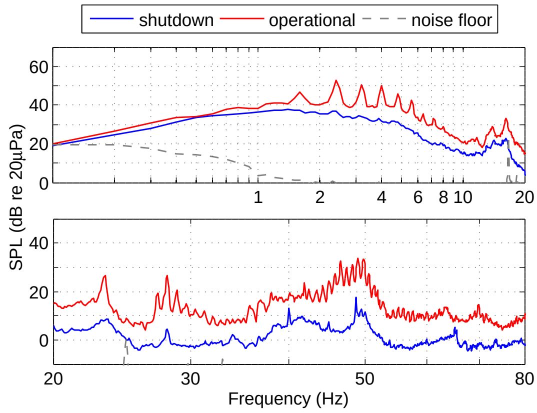
3.2 Narrow-band spectra

A narrow-band analysis with a fine resolution can provide more detail about the tonal components of the noise source as well as side-bands associated with amplitude modulation. On the other hand, the amplitude of spectral peaks is dependent on the chosen frequency resolution and hence, comparison to standards such as IS0 389-7 (12), which is relevant for third-octave band levels, is meaningless. Hence, the emphasis of this analysis was to choose an appropriate frequency resolution which would enable identification of the peaks spaced at the blade-pass peaks frequency of 0.8 Hz. The chosen resolution was 0.1 Hz and the narrow-band plots have been divided into two frequency ranges to improve resolution.

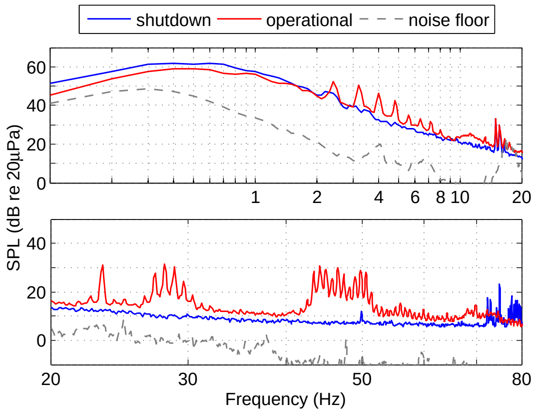
The narrow-band spectra depicted in Figure 6 show results for one 10-minute average measured during wind farm shutdown and another 10-minute average measured during wind farm operation. Identical analysis periods have been selected for the outdoor and indoor results and therefore the spectra are shown in adjacent figures. Selection of the operational periods was based on the prominence of tonal peaks and amplitude modulation for the 10-minute periods of analysis that were presented in Section 3.1. The shutdown measurements depicted in Figure 6 correspond to the lowest 10-minute sound pressure levels that were measured when the wind farm was shut down.



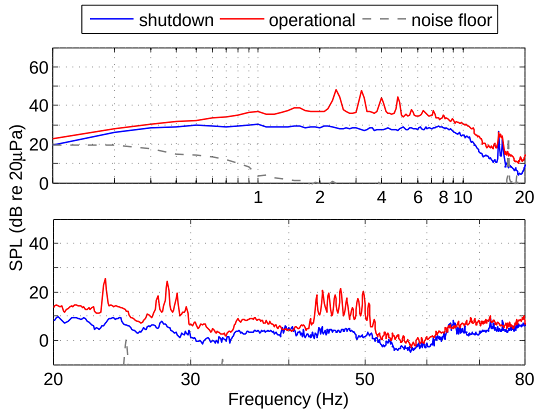
(a) Outdoor spectra - House 1 (ON 1/5, 19:40; OFF 1/5, 20:40)



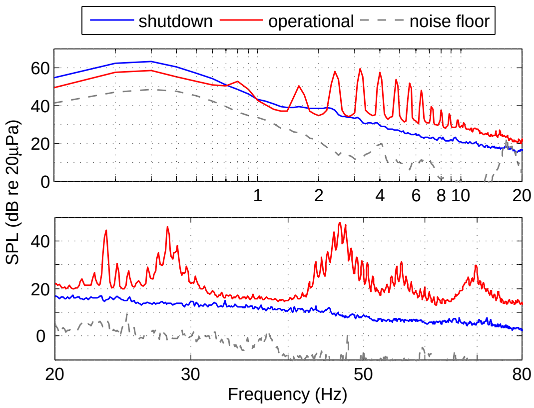
(b) Indoor spectra - House 1 (ON 1/5, 19:40; OFF 1/5, 20:40)



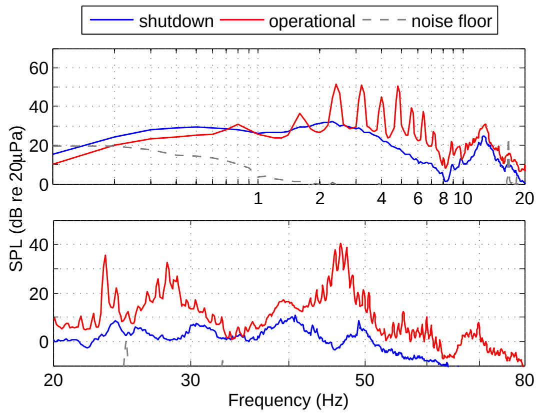
(c) Outdoor spectra - House 2 (ON 10/6, 4:40; OFF 10/6, 5:40)



(d) Indoor spectra - House 2 (ON 10/6, 4:40; OFF 10/6, 5:40)



(e) Outdoor spectra - House 3 (ON 29/7, 3:25; OFF 26/7, 1:55)



(f) Indoor spectra - House 3 (ON 29/7, 3:25; OFF 26/7, 1:55)

Figure 6 – Comparison of outdoor and indoor narrow-band spectra with local wind conditions similar to wind farm shutdown conditions

The aim was to identify the maximum possible contrast between shutdown and operational conditions. It was found that the 10-minute measurement results that show the most significant peaks at the blade-pass frequency and harmonics, do not necessarily correspond to cases where the wind farm power output was highest.

The most significant difference between the narrow-band plots associated with shutdown and operational conditions is the general absence of tonal peaks and broadband peaks for the shutdown cases as shown in Figure 6. The 50 Hz narrowband peak in Figure 6a shows an obvious exception, but this peak is related to electrical noise associated with some aspect of the NI data acquisition system, which is confirmed by its absence in the third-octave spectra measured with the SVAN 958 sound level meter, which was presented in Figures 2a and 3a.

The infrasonic peaks that appear in the spectra exclusively during operational conditions are consistently harmonics of the blade-pass frequency of 0.8 Hz. This blade-pass frequency is expected for Vestas V90-3MW wind turbines, which have a nominal speed of 16.1 rpm (16). The first set of harmonics begins either at the fundamental frequency of 0.8 Hz, as shown in Figure 6e and 6f, or the second harmonic of 1.6 Hz, as indicated in Figures 6a to Figure 6d. The detectability of the fundamental peak at 0.8 Hz appears to be directly related to the amplitude of broadband infrasound present below 1 Hz. The harmonics extend to the 11th harmonic of 8.8 Hz and sometimes slightly higher.

Another consistent feature of the narrow-band spectra for operational conditions is the presence of low frequency peaks at 23.3 Hz, 28 Hz, 46.6 Hz, 56 Hz and 69.9 Hz, which are most evident in the outdoor spectra shown in Figures 6a, 6c and 6e. It appears that the fundamental frequencies of these peaks are 23.3 Hz and 28 Hz and that the other peaks are harmonics. Each of these low frequency peaks has side-bands, which are spaced at the blade-pass frequency and appear to be most numerous around the peak at 46.6 Hz, where there can be up to seven peaks on either side of the main peak. Further insight into the origin of these peaks and side-bands can be gained through determining if they are exact multiples of the blade-pass frequency. In this case it is possible that some harmonics of the blade-pass frequency are selectively amplified, perhaps as a consequence of cavity resonance between the turbine blade and tower (17). On the other hand, if the peaks and side-bands are not exact multiples of the blade-pass frequency then it is probable that the tonal peaks represent tonal noise that is amplitude modulated at the blade-pass frequency.

To determine whether the peaks and side-bands are harmonics of the blade-pass frequency, the frequency resolution of the narrow-band analysis for the measurement shown in Figure 6e was increased to 0.0017 Hz, enabling more accurate calculation of the blade-pass frequency to give 0.8033 Hz. Selected peaks are shown as well as adjacent side-bands, where applicable, in Table 4. The frequencies that correspond to an exact multiple of the blade-pass frequency are highlighted in grey. The results indicate that all except one infrasonic peak is an exact multiple of the blade-pass frequency. On the other hand, only four peaks in the low frequency range above 20 Hz appear to be exact multiples of the blade-pass frequency. Nevertheless, if the peak at 27.993 Hz is considered to be the 35^{th} harmonic then the associated blade-pass frequency would be 0.7998 Hz, a variation of only 0.0035 Hz, which is in the same order of magnitude as the frequency resolution of the narrow-band analysis. These results indicate that the tonal peaks and sidebands could either be related to selective amplification of the blade-pass frequency harmonics which are generated according to spinning mode theory (17) or they could be associated with gearbox vibration which is transmitted to the tower and blades and re-radiated as sound. The tower and blades provide large surface areas for radiating sound and variation in gearbox loading due to changes in aerodynamic forces on the blades could account for the amplitude modulation.

Table 4 – Exact frequencies of tonal peaks and sidebands

Infrasonic spectral peaks													
Exact frequency, f	0.803 (f_0)	1.607	2.410	3.213	4.017	4.820	5.623	6.427	7.230	8.033	8.837	9.638	10.440
f/f_0	1	2	3	4	5	6	7	8	9	10	11	11.998	12.996
Low frequency spectral peaks													
Exact frequency, f	23.295	24.100	24.905	27.198	27.993	28.803	45.793	46.603	47.423	55.197	56.082	56.785	69.768
f/f_0	28.998	30	31.002	33.857	34.846	35.855	57.004	58.012	59.033	68.710	69.811	70.687	86.849

The data presented for the indoor results below 6 Hz is uncalibrated and hence does not reflect the true sound pressure level for these frequencies. However, peaks at the blade-pass frequency and harmonics shown in Figures 6b to 6f indicate that the microphone is still capable of measuring (albeit with decreased accuracy) below 6 Hz.

The results show that there is little attenuation of the signal from outdoors to indoors below a frequency of 80 Hz. The tonal peaks and side-bands corresponding to operating conditions, which were observed for the outdoor measurements, are still clearly distinguishable for the indoor results. The spectra corresponding to shutdown conditions contain some small peaks that did not exist in the outdoor results. These peaks can be attributed to room modes and structural resonances which are excited by wind-induced noise. Nevertheless, these peaks are insignificant when compared to the contribution of wind farm noise.

4. CONCLUSIONS

There is a significant difference in the unweighted third-octave spectra when the Waterloo wind farm is shut down compared to when it is operational for each of the three residences investigated in this study. The most prominent difference occurs in the 50 Hz third-octave band and it has been shown that operational levels can be as much as 30 dB higher than shutdown levels. The peak in this third-octave band is also higher than the audibility threshold defined in ISO 389-7 (12) by as much as 10 dB for the outdoor measurements. This peak was also measured indoors when the wind farm was operational but the magnitude is slightly lower and the rms level averaged over 10 minutes is at the same level as the audibility threshold defined in ISO 389-7 (12), although the variability in the noise results in the peak levels being much higher than the rms audibility threshold.

Outdoor infrasonic noise levels associated with wind farm operation vary depending on the local wind speed at the microphone. During periods of negligible wind at the microphone, distinct peaks corresponding to blade-pass harmonic frequencies are clearly distinguishable. The outdoor results presented for House 3, where the wind speed at the microphone was zero, showed the most distinct peaks in the infrasonic frequency range out of the three residences investigated. For Houses 1 and 2, these peaks in the outdoor spectra were evidently masked by wind-induced noise and this is further confirmed by their presence in the indoor spectra for measurements at these locations, as shown in Section 3.1.1 and 3.1.2. The wind-induced noise is caused by pressure fluctuations and vortex shedding, which are sensed by the microphone but bear no relation to acoustic disturbances. Therefore, to adequately portray the levels of infrasound outdoors, it is imperative that there is negligible wind in the vicinity of the microphone. The shutdown times selected by the wind farm operator gave few opportunities to record such conditions. Hence, it is suggested that in future studies, times between 12 am and 5 am with negligible wind at the measurement locations are selected for shutdown/operational comparisons.

The narrow-band spectra associated with wind farm operation show a consistent occurrence of peaks at specific frequencies in the infrasonic and low frequency ranges. The frequencies of these peaks are the same at each residence and they are not present when the wind farm is shut down, which indicates that they are the result of wind farm noise. The low frequency peaks at 23.3 Hz, 28 Hz, 46.6 Hz and 56 Hz are surrounded by side-bands spaced at the blade-pass frequency of 0.8 Hz. Results obtained by increasing the frequency resolution indicate that it is quite feasible that the low frequency peaks are harmonics of the blade-pass frequency. Thus their presence can either be attributed to selected amplification of blade-pass frequency harmonics or amplitude modulation of a turbine associated noise source at the blade-pass frequency. Further investigation into the source of the noise is currently being undertaken.

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