Indoor Infrasound and low-frequency noise monitoring in a rural environment

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ABSTRACT

This paper presents the results of recent indoor noise monitoring test that was conducted in a room of a home near a wind farm whose resident claims to be annoyed by wind farm noise. The testing uses low-frequency microphones that can resolve noise below 0.5 Hz. The aim of the study is to examine the relationship(s) between the sound pressure level, weather conditions, resident rated annoyance to sound and wind farm output power data. The study concentrates on sound in the low and infrasonic frequency ranges. Additionally, the methodology records two-minutes of audio data at the same time a resident claim to be annoyed by noise from wind turbines. Annoyance was found to have some correlation with the overall noise level; however, noise levels are also correlated with local wind speed.

INTRODUCTION

Various studies have examined the relationship between wind farm noise and annoyance, where the latter can be related not only to acoustical factors but also to visual, emotional and economical ones (Doolan, 2013). In comparison with other environmental noise sources such as road, rail and aircraft, annoyance due to wind turbines are thought to occur at lower sound pressure levels (Pedersen and Waye, 2004); however, the reasons for this are still unclear. There is much controversy surrounding annoyance due to wind farm noise inside people's homes, which is affecting the social cohesion of rural communities as well as the implementation of wind power. Anecdotal evidence regarding the effect of noise on residents usually dominates most discussions on the topic. To provide clarity in these debates, simultaneous noise and annoyance data are needed, yet it is rarely available. As the noise signal may include important characteristics (related to annoyance) that are averaged out during normal statistical processing methods (such as the creation of 1/3 octave band spectra), it is important to record the audio signal to allow the application of a variety of post processing techniques.

A system that is able to record noise in a home at the precise time that the resident claims to be annoyed was recently developed by Doolan and Moreau (2013). This system was able to successfully relate the noise level in a home to personal annoyance level; however, the system was preliminary and a number of improvements were required to increase its usefulness. Specifically, it was desirable to understand the role of local wind speed and direction on noise level and annoyance. Also, it is important to understand how the noise level varies over long periods of time (when the resident is annoyed and not annoyed) to see if certain weather or other conditions are related to noise level and annoyance.

The aim of this paper is to present preliminary results from an upgraded noise and annoyance recording system that includes the improvements discussed above. Preliminary data is presented that shows simultaneous self reported degree of annoyance, weather conditions, sound power spectral density and un-weighted $L_{eq,\ 2min}$.

MEASUREMENT METHODOLOGY

Instrumentation

The recording system consisted of 4 GRAS low frequency microphones (type 40AZ) together with GRAS preamplifiers (type 26CG) and GRAS CC power supplies (type 12AL), with flat frequency response down to 0.5 Hz. A National Instruments 9234 data acquisition module with the sampling frequency of 51,200 Hz and 24 bit resolution was used to acquire the data. Prior to commencing on-site testing, the microphones were calibrated in the frequency range from 0.1 to 100 Hz using a GRAS low frequency calibrator type 42AE aswell as at 1 kHz and 94 dB with a piston-phone. The microphone sensitivity values from both calibrations were in agreement.

Continuous 1/3 octave band noise levels (linear) were recorded every two minutes and saved to the hard drive of a computer. The 1/3 octave bands were calculated using the entire two minute sample length, ensuring low levels of statistical uncertainty. When a resident reported their personal annoyance level using the computer program (described below), the 2 minute audio sample was not converted to 1/3 octave bands but saved directly to the hard drive of the computer for further analysis.

Software for annoyance logging

Self reported annoyance was obtained via the *GUI* (graphical user interface) shown in Figure 1, running on the computer that was placed outside of the room containing the microphones. The resident was asked to rate their annoyance as *'Not Annoyed'*, *'Slightly Annoyed'*, *'Moderately Annoyed'* or *'Very Annoyed'*. They were also encouraged to leave a comment regarding weather conditions, noise characteristics etc..

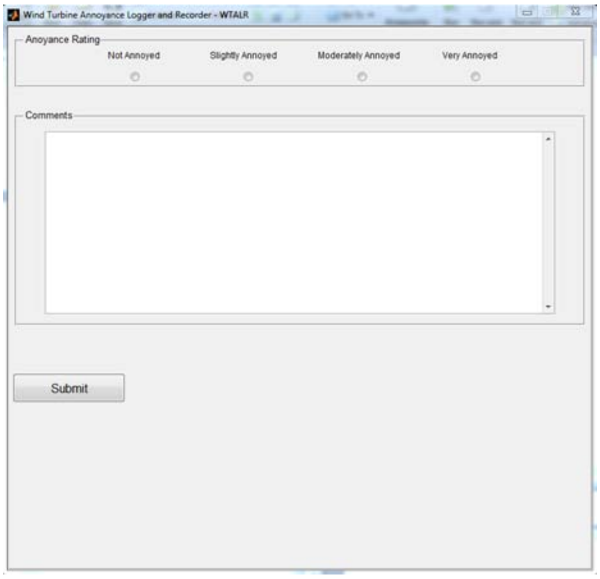


Figure 1. GUI for collecting annoyance ratings and comments

Measurement location

Measurements were undertaken at a household located approximately 2.5 km west of a wind farm (capacity of 111 MW) in South Australia from which the wind farm is visible.

Figure 2. Residence location (red dot) in comparison to the wind farm (blue line)

Microphone set-up

All four microphones were placed in an unoccupied room with dimensions of 3.9 m × 3.5 m × 3 m, on the side of the house facing the wind farm and were covered with 90 mm spherical foam wind caps. In particular, one microphone was positioned close to the window (location M4, see Figure 3) and one 10 cm from the ground in the corner of the room (location M1, see Figure 3).

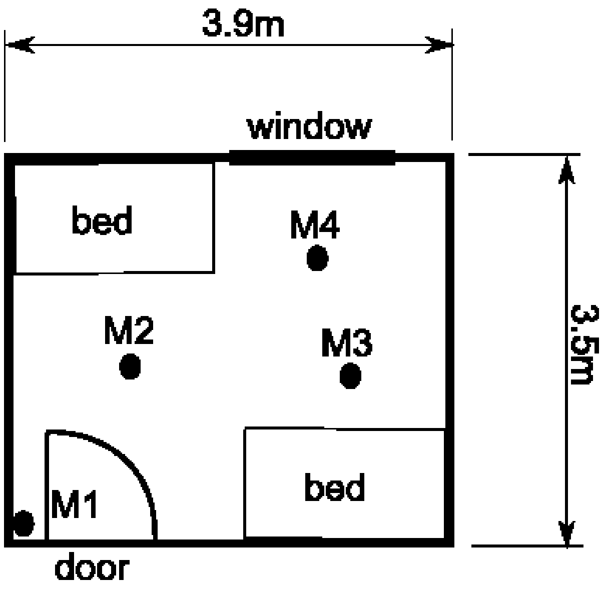


Figure 3. Microphone positions in the household

The reason for using four microphones was to establish the effect of room geometry and standing waves on the results. Apart from the microphone located in the corner (which showed an increase in amplitude compared with the others), the remaining signals were equivalent as can be seen in Figure 4.

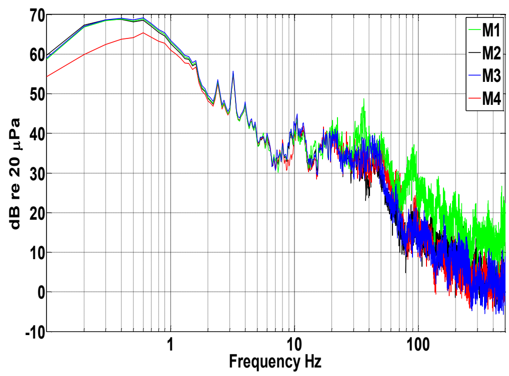


Figure 4. Comparison between 4 microphones positions. Positions are indicated in Figure 3

Weather monitoring

The weather conditions were monitored using a weather station located 5 m from the house, on the side facing wind turbines, at 1.5 m height from the ground. Wind speed and wind direction were recorded every 5 min.

The complete operational state and wind speed and direction at hub height of the wind farm during testing was not made available to the authors at the time of writing, but there is a good possibility of this data being made available at a future date. In this study, only the power output data was available for the analysis.

PRELIMINARY RESULTS

The results from the household were taken during the period from 2/5/2013 to 7/5/2013. During that time, 20 self reported annoyance measurements were collected. Three were rated as *'Very Annoyed'*, six as *'Moderately Annoyed'*, seven as

'Slightly Annoyed' and four as *'Not Annoyed'*. The comments accompanying each annoyance rating are presented in Table 1.

Table 1. Annoyance ratings and corresponding comments. Repeated comments are listed once only

Annoyance rating	***Comments***
'Very Annoyed'	• Loud rumbling noise
'Moderately Annoyed'	• Thumping, roaring noise • Rumbling noise • Weird dreams and slight headache
'Slightly Annoyed'	• Bad night sleep, not much noise • Weird dreams, hardly any noise • Rumbling • Felt pressure in ears • Mild whirring noise

In Figures 5-7, the annoyance levels together with wind speed, wind direction and $L_{eq,\ 2mim}$ (no weighting) are presented. The $L_{eq,\ 2min}$ is the average sound pressure of the four microphones within the room. In general, data reveal high correlation between local wind speed and $L_{eq,\ 2min}$. The data from 2/5/2013 to 7/5/2013 are divided into three figures for increased clarity.

The wind speed in Figure 5 ranges from 0-5 m/s. The dominant wind direction from around the evening on 2/5/2013 until the early morning of the next day is *N/NE*. For the rest of the measurement period in Figure 5, the wind direction is scattered. During this period, the resident rated themselves as '*Not Annoyed*' to '*Moderately Annoyed*'.

Figure 6 shows the largest portion of the measurement time during which the resident was most annoyed. The wind speed during that time reached levels of up to 8 m/s and the dominant wind direction was *NE*. Of the three times that the resident was *'Very Annoyed'*, two occurences correspond to the relatively high $L_{eq,\ 2min}$; '*Very annoyed @ 5/5 0.55AM*' and '*Very Annoyed @ 5/5 7.25AM*' are both in the region of 75-80 dB. However, the remaining '*Very Annoyed*' rating doesn't follow this trend and falls into the 65-70 dB region.

During the last part of the measurement period, Figure 7 shows that the wind speed is 0 m/s half of the time and that the wind direction is mostly scattered. During this period, the resident rated themselves as '*Not Annoyed*' to '*Moderately Annoyed*'

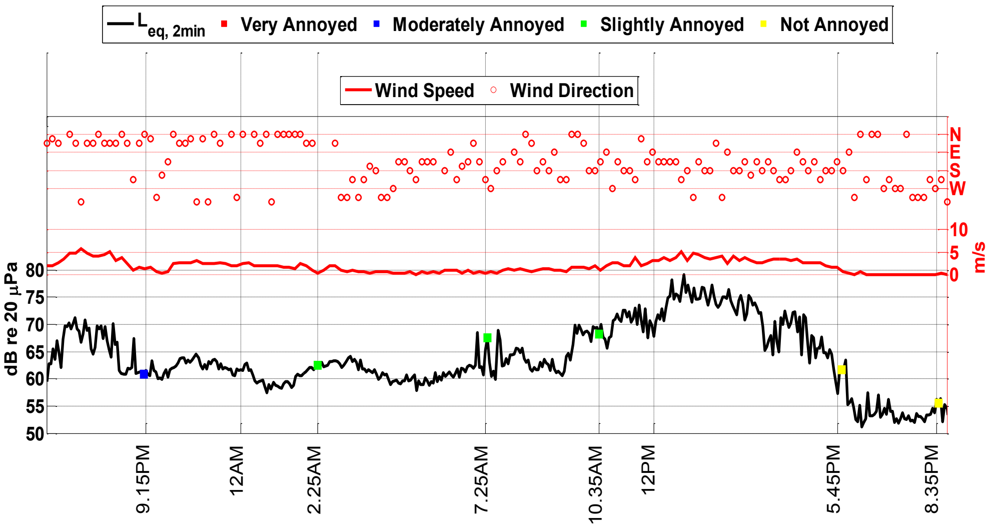


Figure 5. Top: wind direction and wind speed from 2/5 6.25PM to 3/5 8.25PM. Bottom: $L_{eq,2min}$ level with annoyance ratings. From left to right the annoyance symbols are spaced as follows: 2/5 9.15PM, 3/5 2.25AM, 3/5 7.25AM, 3/5 10.35AM, 3/5 5.45PM, 3/5 8.35PM

The time of a day might have a significant influence on the annoyance rating. For the two annoyance cases in Figure 6, namely *'Very Annoyed @ 5/5 8.25PM'* and *'Moderately Annoyed @ 6/5 2.25PM'*, there is no apparent evidence as to why they have been ranked differently, apart from the different time of day.

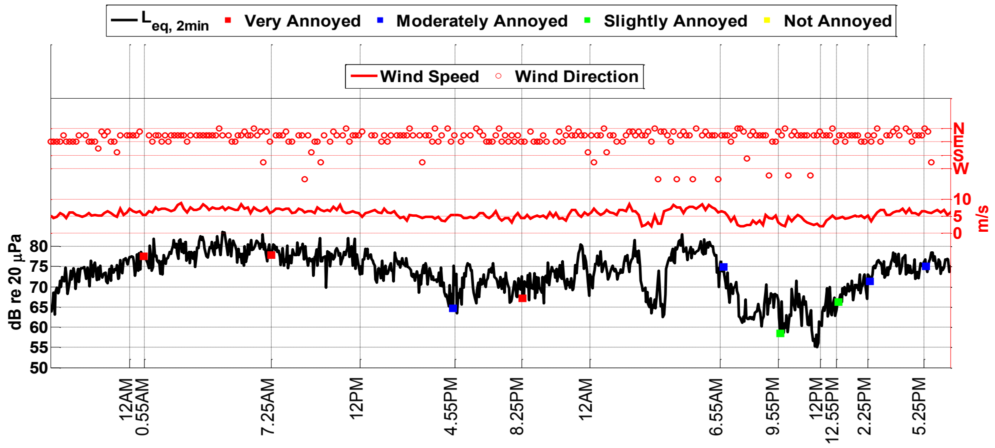


Figure 6. Top: wind direction and wind speed from 5/5 7.55PM to 6/5 7.06PM. Bottom: $L_{eq,2min}$ level with annoyance ratings. From left to right the annoyance ticks are spaced as follows: 5/5 0.55AM, 5/5 7.25AM, 5/5 4.55PM, 5/5 8.25PM, 6/5 6.55AM, 6/5 9.55PM, 6/5 12.55PM, 6/5 2.25PM, 6/5 5.25PM

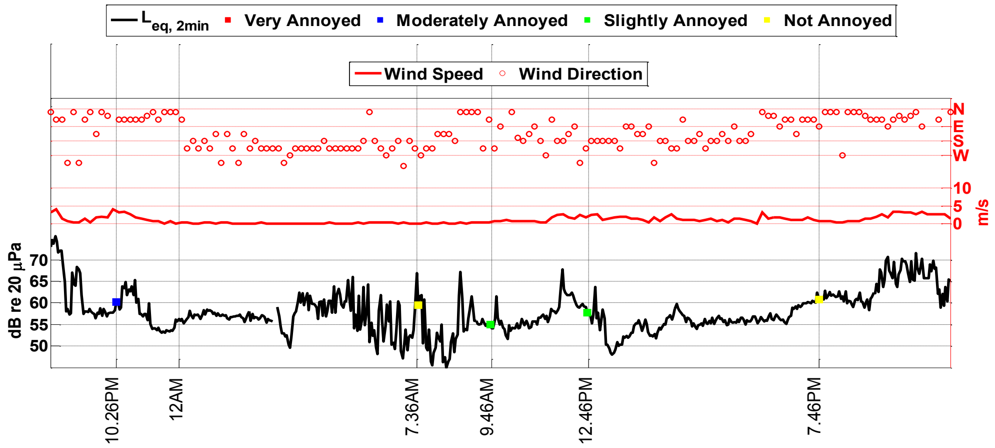


Figure 7. Top: wind direction and wind speed from 6/5 8.16PM to7/5 10.46PM. Bottom: $L_{eq,\ 2min}$ level with annoyance ratings. From left to right the annoyance ticks are spaced as follows: 6/5 10.26PM, 7/5 7.36AM, 7/5 9.46AM, 7/5 12.46PM, 7/5 7.46PM

Figure 8 shows the single sided power spectral density versus frequency at the various annoyance ratings. Welch's averaged modified periodogram method of spectral estimation was used to calculate the power spectral density (PSD) with the following settings: Hanning window of length 512000 points, 50% overlap and 512000 FFT points. The PSD was corrected by dividing by the bandwith in order to compensate for the use of a Hanning window (Randall, 1977).

Figure 9 shows the noise spectra for all annoyance ratings presented in one-third-octave bands compared with the curve representing the ISO:226 (2003) median hearing threshold.

The narrow band spectral analysis in Figure 8 reveals tonal components during nearly all annoyance ratings. The most distinct tones can be observed for *'Not Annoyed @ 3/5 8.35PM'*. Frequency peaks occur at 1.6 Hz, 2.4 Hz and 3.2 Hz and appear to coincide with the upper harmonic components of the blade pass frequency of 0.8 Hz. The amplitude of these tones (relative to the broadband level) is around 15 dB. The reason they can be observed in the power spectral density is most likely is the reduction in background noise due to very low wind speed. It is interesting to note that at that time, the wind farm output was around 55% of its full capacity, (as can be seen in Figure 10(a)).

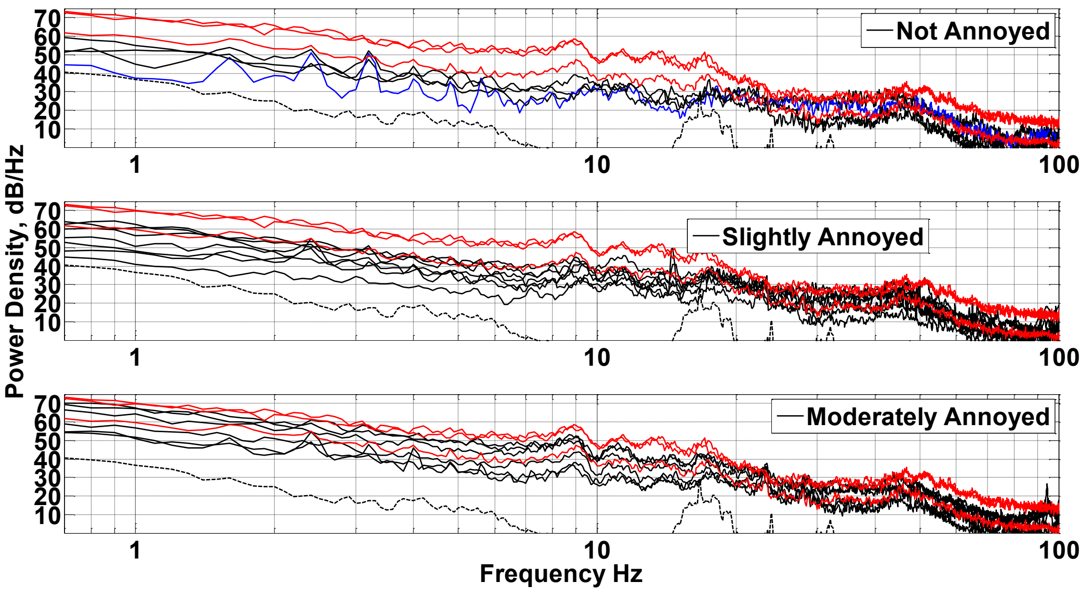


Figure 8. Narrow band single sided power spectral density comparison between '*Very Annoyed*', '*Moderately Annoyed*', '*Slightly Annoyed*' and '*Not Annoyed*'. The blue line represents *'Not Annoyed @ 3/5 8.35PM'*. In each subfigure, the red curves represent '*Very Annoyed*' cases and the dashed black line shows the measurement system noise floor. Frequency resolution is 0.1 Hz.

A distinction between *'Very Annoyed'*, *'Not Annoyed'* and *'Slightly Annoyed'* can be seen in Figure 8 in terms of sound level; *'Not Annoyed'* and *'Slightly Annoyed'* are always below the *'Very Annoyed' SPL*, while the level difference between *'Moderately Annoyed'* and *'Very Annoyed'* is not as clear.

The *'Very Annoyed'* narrow band spectra in Figure 8 display some weak tonal components at 8.9 Hz, 11.3 Hz, 17.1 Hz and 28 Hz. These components also occur at other annoyance ratings but they are less distinct. However, as shown in Figure 9 the levels associated with all annoyance ratings are well below perceptional threshold (below about 50 Hz).

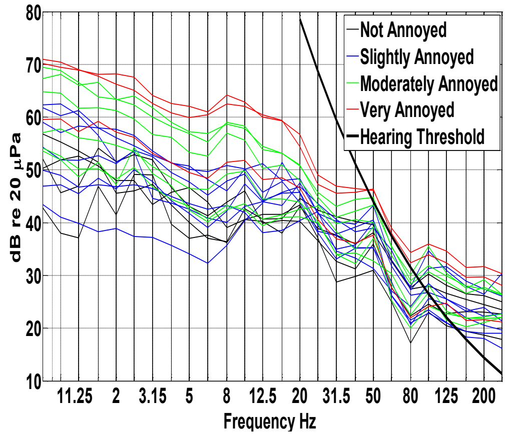
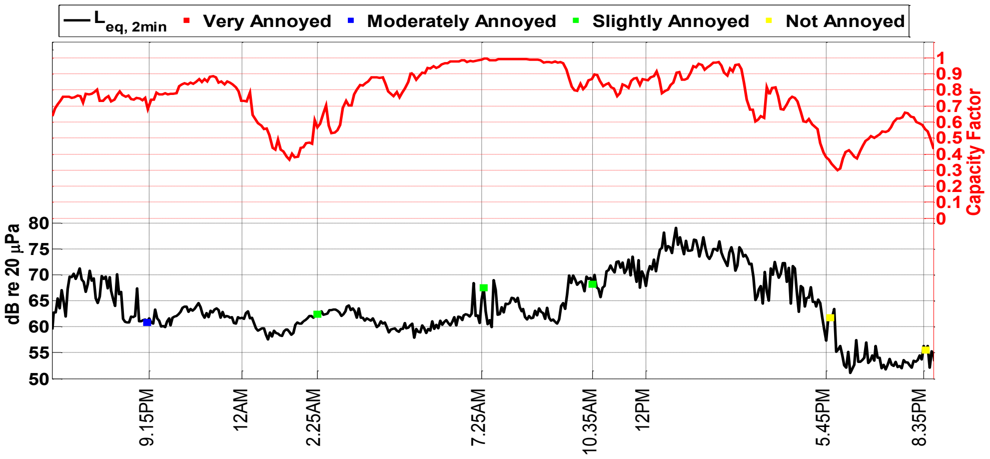
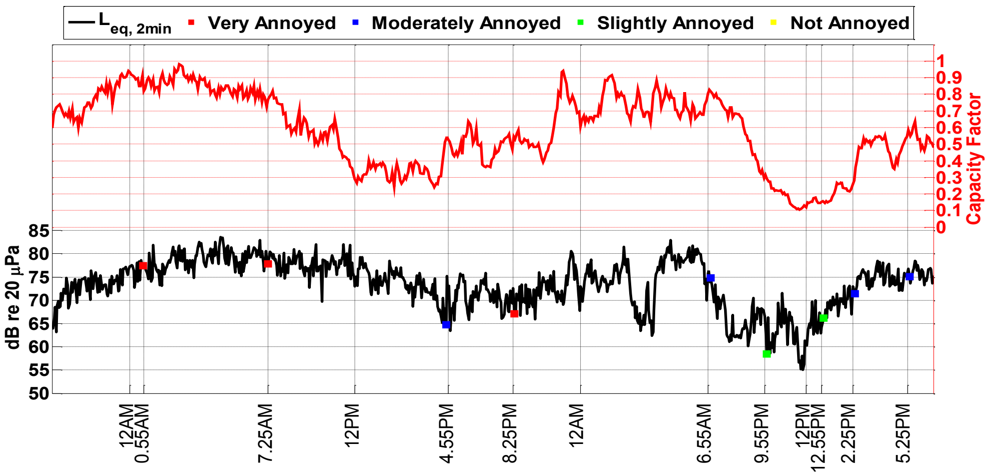


Figure 9. 1/3 octave bands annoyance in comparison to the median hearing threshold as listed in ISO:226 (2003)

Figure 10 shows the wind farm capacity factor over the measurement period together with the resident's annoyance ratings and $L_{eq,\ 2\ min}$. This figure shows that when the wind farm output power was close to its maximum, the resident was *'Slightly Annoyed'* (Figure 10(a)) or *'Very Annoyed'* (Figure 10(b)). The wind speed at the residence at that time was between 0-2 m/s and 5-8 m/s respectively. The wind direction in the first case was scattered while in the second case was *NE* with the corresponding $L_{eq,\ 2min}$ of 65-70 dB and 75-80 dB respectively.



(a)



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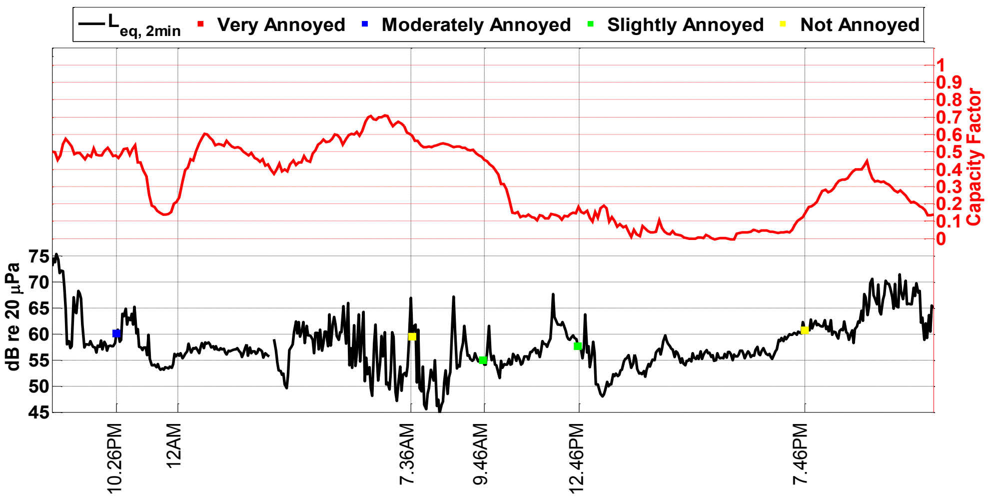

(c)

Figure 10. Wind farm capacity factor, together with the $L_{eq,\ 2min}$ and the annoyance rating, for the following time periods: from 2/5 6.25PM to 3/5 8.25PM (a), from 5/5 7.55PM to 6/5 7.06PM (b) and from 6/5 8.16PM to 7/5 10.46PM (c). Capacity factor of 1 represents 111 MW.

DISCUSSION

The results presented are interesting and require careful interpretation. They constitute a limited sample size, so general application of the conclusions needs to wait until a larger number of recordings have been obtained. In this study, the resident reports that they are annoyed, attributes the annoying noise to a wind farm and provide descriptors of that noise. The resident also claims to have some kind of sleep disturbance at various times.

The recorded noise levels show some increase with annoyance, but there is also close correlation of the noise level with local wind speed. Narrowband spectral density analysis shows that there are some infrasonic “tones”, but only when the resident was not annoyed and the local wind speed was low.

If the wind farm were the source of annoying noise, then we would expect the strongest annoyance to be reported when local wind speed was low (minimising masking noise) and when the wind farm output was high. However, for these results, it appears that annoyance is most likely related to local wind speed rather than another factor.

High annoyance was recorded when the local wind speed was high, when local masking noise would be at its greatest. Indeed, when interesting features of the narrowband spectrum are recorded that are quite likely attributable to the wind farm, the local wind speed is low and the resident rates themselves as not annoyed.

The authors do not doubt the sincerity of the resident, therefore there must be significant non-acoustical moderating factors (Doolan, 2013) influencing the perception and self-reported annoyance of noise in this case.

CONCLUSIONS

Noise levels and personal annoyance ratings were recorded for a resident who lived near a wind farm in South Australia. The major conclusions from this study are:

1. The $L_{eq,2min}$ is well-correlated with the local wind speed.

2. Noise levels in the infrasound and low-frequency bands (below 50 Hz) are well below the *ISO226-2003* median perception threshold, making them unlikely to be audible by a person with normal hearing.

3. Annoyance ratings do partially correlate with the high $L_{eq, 2min}$ noise levels.

4. The resident was not annoyed when the local wind speed was low and its direction was scattered.

5. Some measurements show peaks in the infrasonic and low-frequency bands. In one case, these peaks are revealed when the local wind speed drops to a low value.

The dataset collected in this preliminary study is small and in the future, measurements should be carried out with a larger population and the methodology should preferably take into account the hearing conditions of the participants, their view on wind farms and health aspects. It is likely that non-acoustical moderating factors play a role in the perceived annoyance of the resident to wind farm noise (Doolan, 2013).

ACKNOWLEDGEMENTS

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