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Simultaneous indoor low-frequency noise, annoyance and direction of arrival monitoring

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Summary

The source of annoying low-frequency noise indoors is difficult to determine or diagnose, especially if those performing an investigation cannot control potential sources that complainants attribute to it. In this paper, a methodology for monitoring indoor noise level, self-reported annoyance, noise direction of arrival (DOA) and weather data, simultaneously, is described and applied to two wind farm noise annoyance test cases. Residents/complainants were asked to rate their personal level of annoyance via a computer-interface where they could also leave a comment. The DOA was recorded using a three-microphone array that was actuated when residents rated their annoyance level on the computer. By using this methodology, personal annoyance can be related to the DOA, thus determining the direction from which the noise attributed to annoyance is coming from, aiding in the identification of its source. Measurements were performed using low-frequency microphones having flat frequency response down to 0.5 Hz. To ensure accuracy of the noise measurements for all frequencies of interest, a specialised low-frequency microphone calibrator was used.

1. 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 factors. In comparison with other environmental noise sources such as road, rail and aircraft, annoyance due to wind turbines was found at lower sound pressure levels (Pedersen and Waye, 2004; Doolan, 2013).

The wind speed and atmospheric stability have an important effect on sound generation, propagation and consequently annoyance. For example, under certain conditions during the night, the atmospheric boundary layer can become stable causing a higher wind speed at hub height than at the ground, which may lead to a situation of high sound power emission from the turbine and low masking background noise at an observer (van den Berg, 2004). Under such conditions the pitch thumping (repetition rate around 1 second which coincides with the blade passing frequency) may become noticeable and annoy residents living around the wind farm.

The subjective sensations such as 'pulsating', thumping and 'swishing' are commonly used for describing annoying wind turbine noise (Pedersen and Waye, 2004). This suggests that annoyance is not dependent on sound pressure level only but also on detailed spectral characteristics.

Positively relating annoyance with sound directly from a wind farm, or any source where direct control is impossible, is challenging. What is required is a measurement system that is able to record noise in a resident's home at the exact time that they are annoyed. As the noise signal may include important characteristics that can be 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. Such a measurement system was developed recently by Doolan and Moreau (2013). This system was able to successfully relate noise level in a home with personal annoyance level; however, the system was preliminary and many improvements are required to improve its usefulness. Specifically, it is desirable to be able to understand the role of local wind speed and direction on noise level and annoyance. Additionally, the direction from which the sound approaches a resident's home is needed so as to help identify the source location. 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 improved noise and annoyance measurement system. Two sets of measurements are presented obtained in two homes situated at different distances from a wind farm. Preliminary data are presented that shows simultaneous self reported degree of annoyance, weather conditions, power spectral density, and un-weighted $L_{eq,\ 2min}$.

2. Experimental design

2.1 Instrumentation

The measuring system consisted of 4 GRAS low frequency microphones type 40AZ together with GRAS preamplifiers type 26CG and GRAS CC supply type 12AL, with flat frequency response down to 0.5 Hz. A National instruments 9234 data acquisition module with sampling frequency of 51200 kHz and 24 bit resolution was used to acquire the data. The microphones were calibrated in the frequency range from 0.1 to 100 Hz prior to the measurements using GRAS low frequency calibrator type 42AE. Additionally, calibration was checked just prior to the measurements at 1 kHz and 94 dB with a piston-phone. 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 the computer. The 1/3 octave bands were calculated using the entire two minute sample length, ensuring low levels of 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.

2.2 Software for annoyance logging

Self reported annoyance was obtained via a GUI (graphical user interference), shown in Figure 1 below, running on a computer placed outside of the room containing the microphone. Residents were asked to rate their annoyance with 'Not Annoyed', 'Slightly Annoyed', 'Moderately Annoyed' and 'Very Annoyed'. They were also encouraged to leave a comment regarding weather conditions, noise characteristics etc.

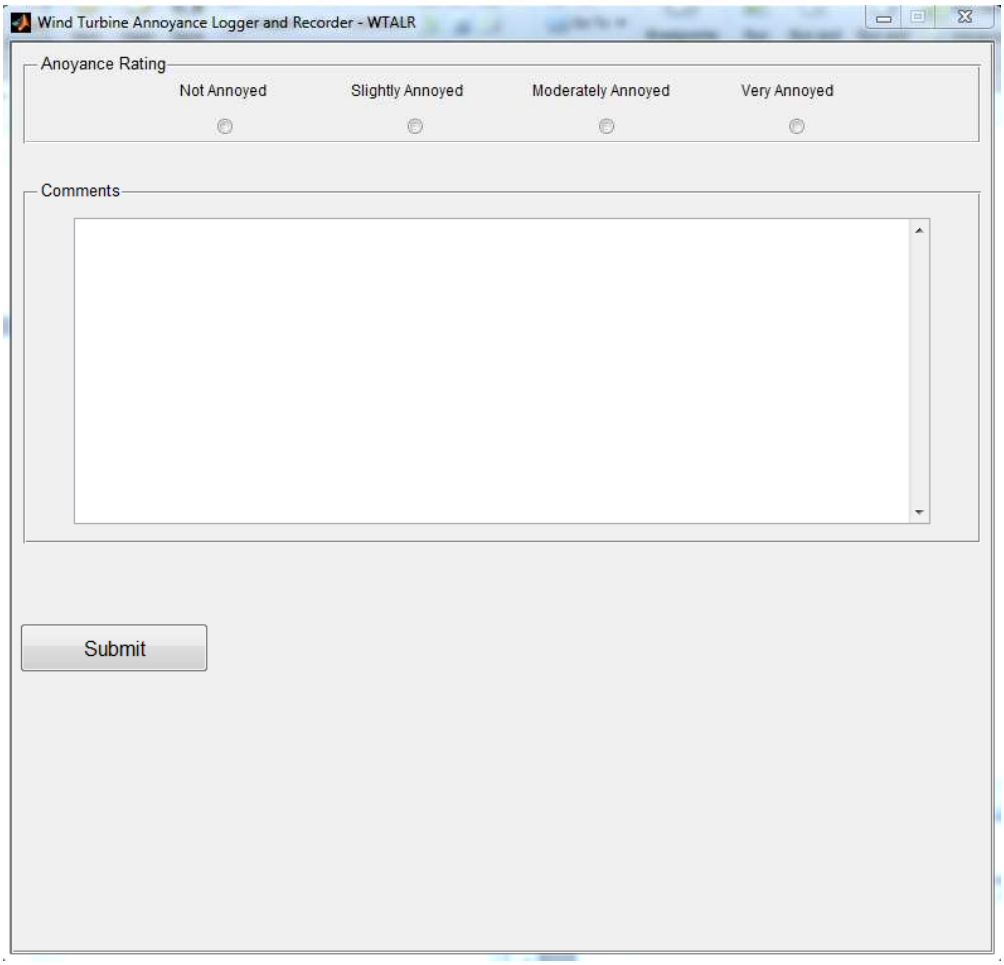

Figure 1: GUI for collecting annoyance ratings and comments.

2.3 Measurement location

Measurements were undertaken at two households; Household A is located approximately 2.5 km west of Waterloo wind farm (capacity of 129 MW) in South Australia and Household B is located approximately 8 km east of the same wind farm (see Figure 2 below). The wind farm is visible from Household A but not from Household B.

Figure 2: The households positioning relative to the wind farm indicated by blue lines. (the terrain image courtesy of Google)

2.4 Microphone set-up

In both households, one microphone was placed in an unoccupied room on the side of the house facing the wind farm. The other three microphones were arranged into an array outside of the house in order to determine direction of arrival (DOA) of noise. At Household A the microphones were placed 3.5 m apart and were covered with 90 mm spherical foam wind caps. The array was placed 5 m from the facade. At Household B the microphones were positioned 2 m apart and were covered with double layer wind caps. The first layer consisted of a 90 mm foam wind cap and second one was a 450 mm diameter spherical or hemi-spherical windcap made out of foam and fur as seen in Figure 3 below. The microphone with the spherical wind cap was positioned 1.5 m from the ground. The other two were placed on a steel plate, 1 m in diameter. The array was constructed 30 m from the facade of the house.

Figure 3: Top: microphone array at Household A (the second microphone from the right is not part of the array). Bottom: microphone array at Household B.

The arrays were situated so that its most sensitive side, the direction where the wave fronts are parallel to the array, was facing the wind farm. If the sound arrives from the direction of the wind farm, the signal on each sensor will be in phase and thus the array output is maximum.

The spacing between the sensors and frequency resolution are related via d/λ, where d is the spacing between the sensors and λ is the sound wavelength. When the ratio exceeds 1, grating lobes appear meaning that no unique direction of arrival can be determined. On the other hand, when the ratio approaches 0, the beam-width is increasing, eventually also reaching the point where no unique direction of arrival can be determined, since the array directivity pattern becomes omni-directional.

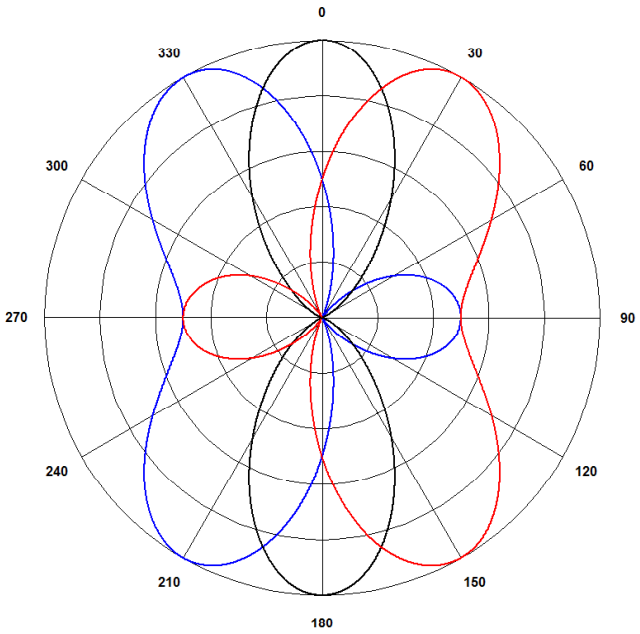

Figure 4: Directivity (linear) on a unit circle for a 3 sensor linearly spaced array with 0.5λ spacing. The black curve represents 0°, red curve 30° and blue curve 330° steering angle. The 0° is defined as the broadside i.e. the direction where the wave fronts are parallel to the array.

According to the sensor spacing (2 m and 3.5 m) the low frequency limit of the array located at Household A is 85 Hz and the low frequency limit of the array at Household B is 50 Hz. The directivity pattern at those frequencies is shown in Figure 4. The angular resolution becomes substantially worse when approaching 90° or 270° respectively due to the widening of the main lobe.

2.5 Weather monitoring

The weather conditions at Household A were monitored at 1.5 m height while at Household B they were monitored at 1.5 m as well as 10 m height. Wind speed and wind direction were recorded every 5 min.

The operational states of the wind farm during testing were 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.

3.0 Preliminary results

3.1 Household A

The results from Household A were taken during the period 8/5/2013 to 10/5/2013. During that time, 7 self reported annoyance measurements were collected. One was rated as 'Very Annoying', one as 'Moderately Annoying' and five as 'Slightly Annoying'. Comments accompanying each annoyance rating are presented in Table 1.

Table 1: ratings and corresponding comments for Household A.

Annoyance rating	Comments
'Very Annoyed'	• Thumping/rumbling noise which can be heard over television. Feel head pressure pulling the same rhythm as thumping.
'Moderately Annoyed'	• Can hear rumbling and feel pressure in ears. Wind direction north-east.
'Slightly Annoyed'	• Rumbling noise. Not much wind at the turbines but strong breeze at the house. • Feel pulsing in head and pressure in ears. Turbines are slowly turning. • Very slight rumbling. Wind direction north

Wind speed and direction as well as two minute $L_{eq,\ 2min}$ measurements are shown in Figure 5. The wind speed was in the range from 0-5 m/s. The wind direction was mainly north-east apart from on the afternoon of 9/5/2013, where the wind direction was more variable.

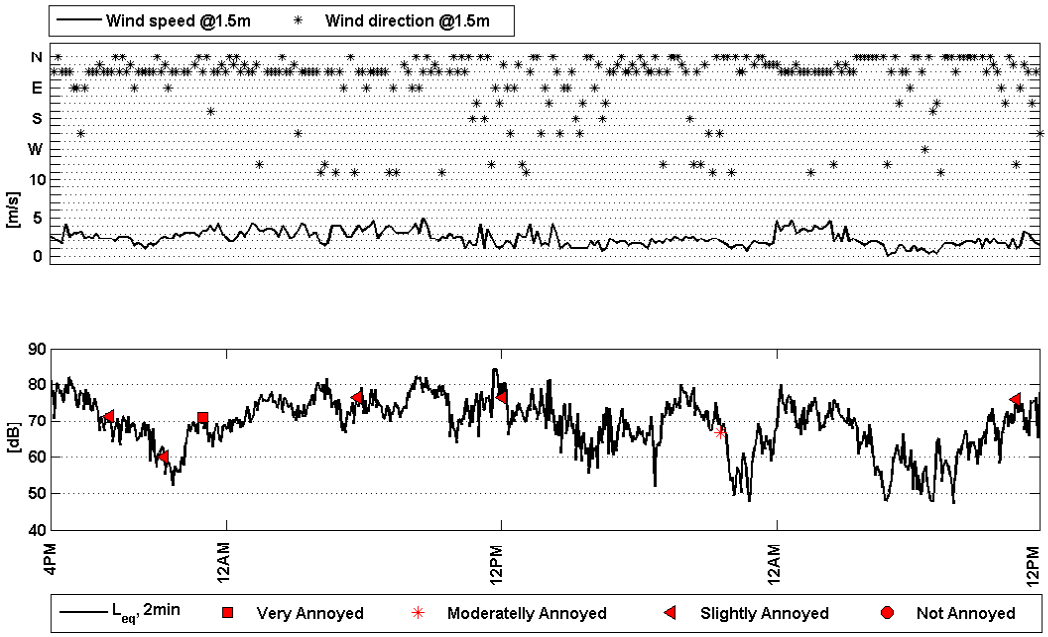

Figure 5: Top: wind direction and wind speed. Bottom: $L_{eq,\ 2\ min}$ level with annoyance rating. From left to right the annoyance ticks are spaced as follows: 8/5 6.56PM, 8/5 9.26PM, 8/5 11.06PM, 9/5 5.46AM, 9/5 12.06PM, 9/5 9.46PM, 10/5 10.46AM. Household A.

Interestingly, the times when the person was 'Very Annoyed' or 'Moderately Annoyed' do not coincide with the highest $L_{eq,2min}$ and consequently with highest wind speed. They are both in the zone of 70 dB, which is approximately 10 dB lower than the highest $L_{eq,\ 2min}$ recorded.

The highest noise levels are evident in the low-frequency and infrasonic region as can be seen in Figure 6 below, where the pressure fluctuations in those regions are highly correlated with the $L_{eq,\ 2min}$ in Figure 5. As Figure 6 and Figure 7 show, the “Very Annoyed” signals contain very weak tonal components whereas the other signals do not contain tones or have much weaker

ones. The level of the “Very Annoyed” signas are variable, sometimes higher, sometimes lower than the “Slightly” or “Moderately” annoyed signals.

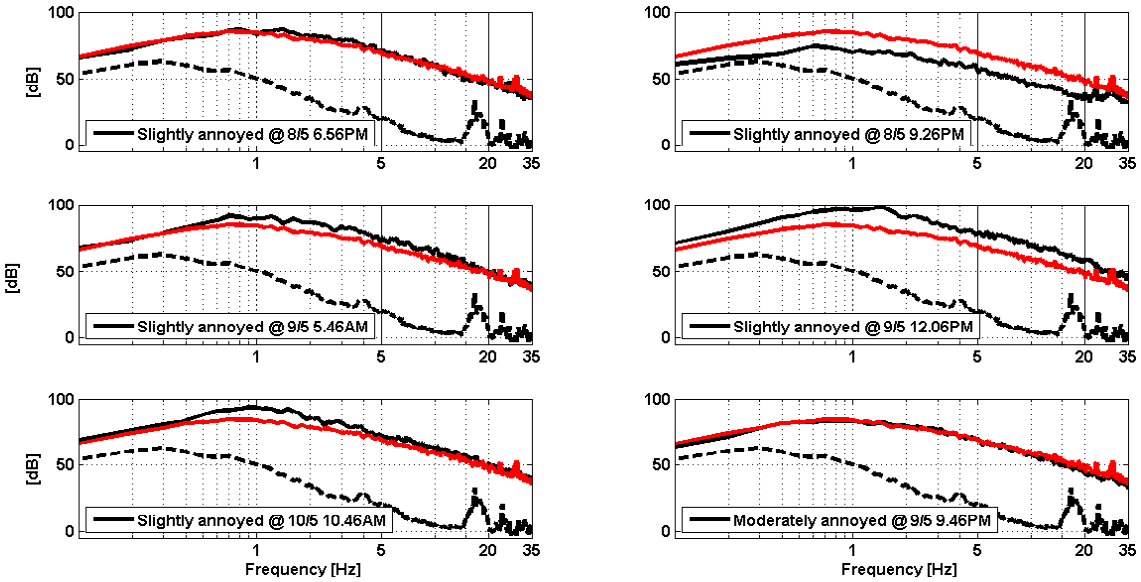

Figure 6: Narrow band power spectra density comparison between 'Very Annoyed, 'Moderately Annoyed' and 'Slightly Annoyed'. The red curve represents ‘Very Annoyed @ 8/5 11.06PM’ and the dashed black line shows the measurement system noise floor. Frequency resolution is 0.1 Hz.

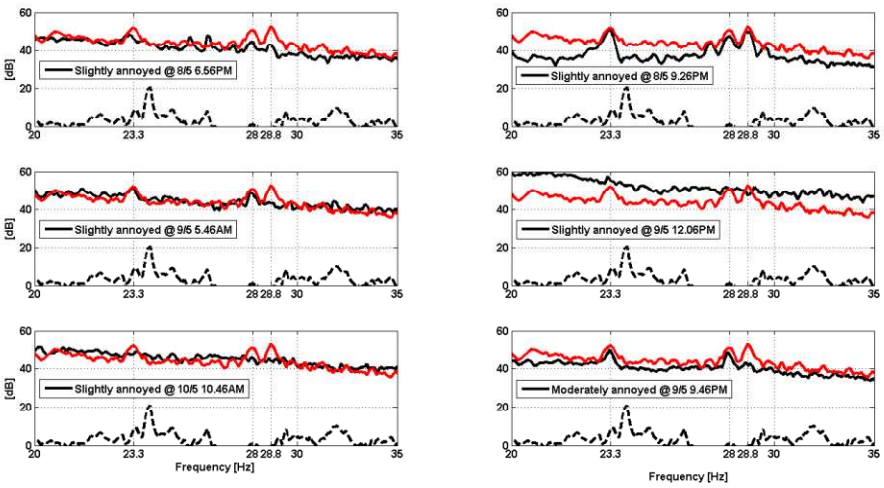

Figure 7: Narrow band power spectral density comparison between 'Very Annoyed, 'Moderately Annoyed' and 'Slightly Annoyed'. The red curve represents ‘Very Annoyed @ 8/5 11.06PM’ and the dashed black line shows the measurement system noise floor. Frequency resolution is 0.1 Hz.

The comparison in Figure 8 shows that according to the ISO:226-2003 median hearing threshold curve, the 23.3 , 28 and 28.8 Hz frequencies are well below the perception threshold.

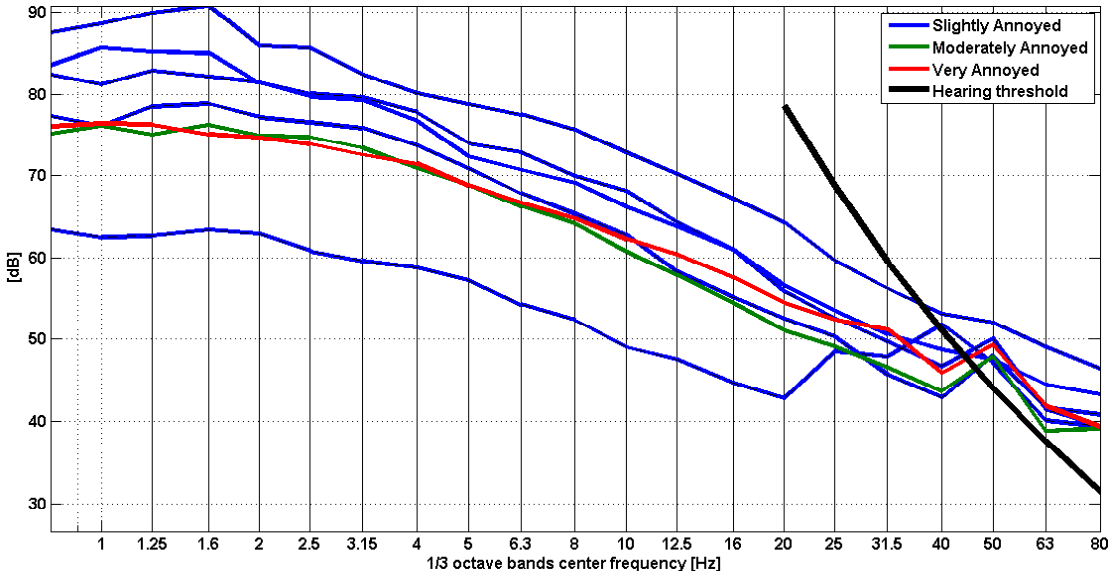

Figure 8: 1/3 octave bands annoyance in comparison to the median hearing threshold as listed in ISO:226-2003.

3.2 Household B

At Household B the measurements were taken during the period from 22/4/2013 to 28/4/2013 (results split into 2 figures; Figure 9 and Figure 10). During that time, 8 recordings were obtained among which one was rated 'Very Annoyed', two 'Moderately Annoyed', two 'Slightly Annoyed' and three 'Not Annoyed'.

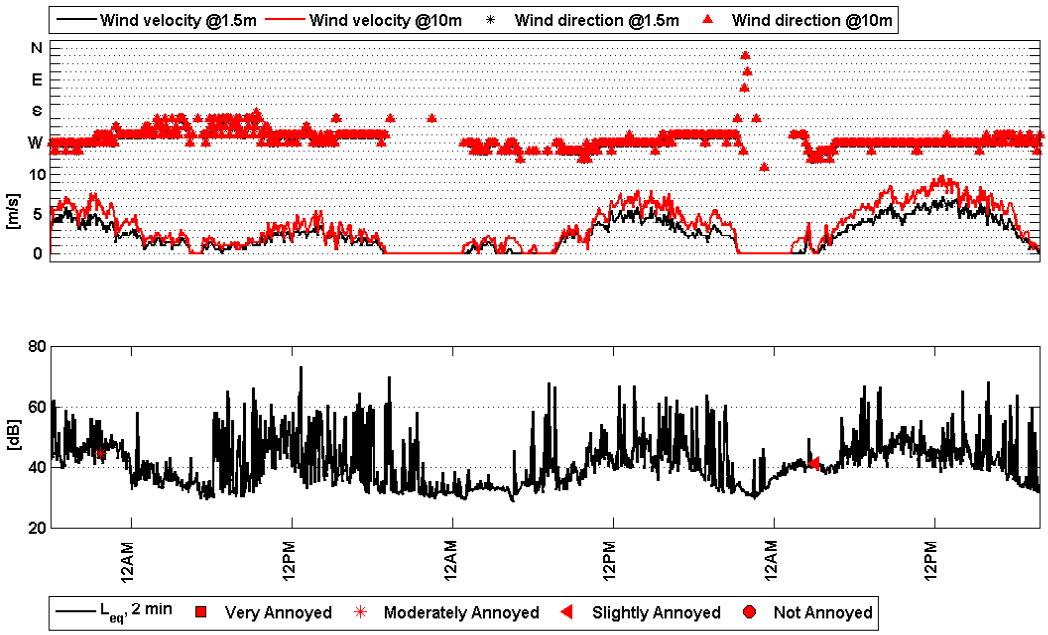

Figure 9: Top: wind direction and wind speed. Bottom: overall sound pressure level with annoyance rating. From left to right the annoyance ticks are spaced as follows: 22/4 9.35AM, 25/4 2.35AM.

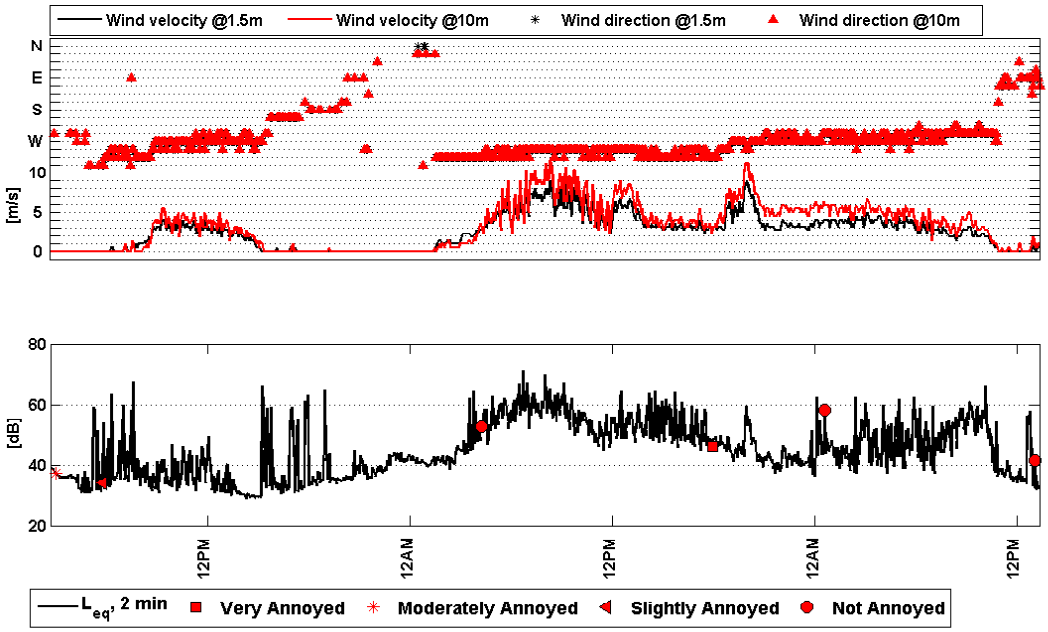

Figure 10: Top: wind direction and wind speed. Bottom: overall sound pressure level with annoyance rating. From left to right the annoyance ticks are spaced as follows: 26/4 3.20AM, 26/4 6.25AM, 27/4 8.25AM, 28/4 12.35, 28/4 8.20AM, 28/4 10.45AM.

From the comparison between the upper and bottom left graph in Figure 11 one can see that a typical 'Not Annoyed' curve is in fair agreement in terms of SPL, in the 1.6 to 4 Hz frequency region, with both the 'Very Annoyed' curve and the typical 'Moderately Annoyed' curve. The main difference is the existence of tonal components (0.8 Hz, 1.6 Hz, 2.4 Hz and 3.2 Hz) which can clearly be seen in Slightly Annoyed @ 25/4 2.35 AM' but are absent in the 'Not Annoyed' curves.

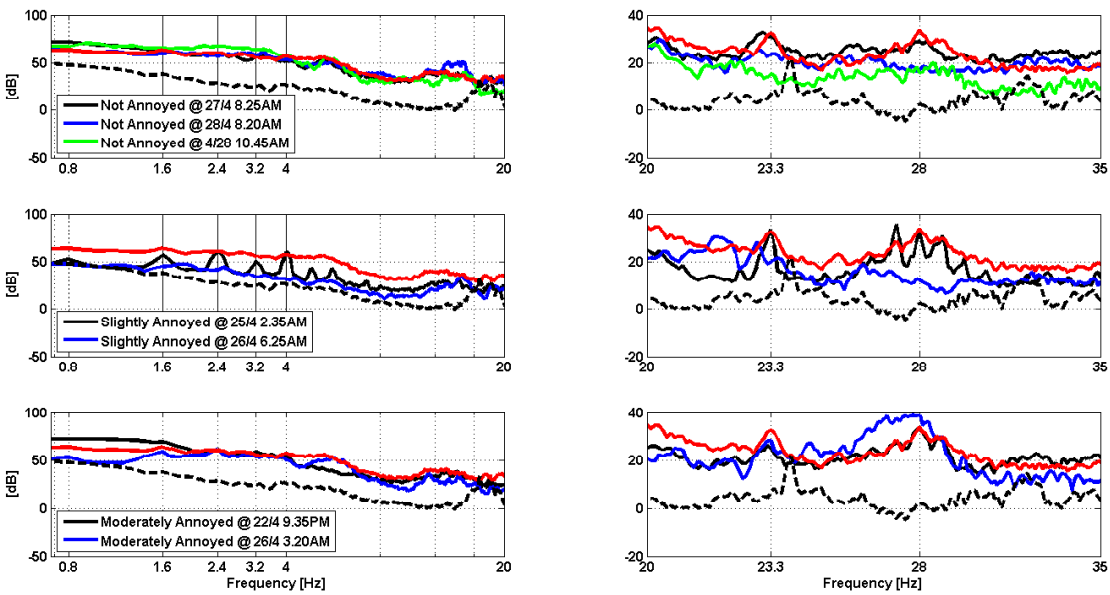

Figure 11: Narrow band comparison between 'Very Annoyed, 'Moderately Annoyed', 'Slightly Annoyed' and 'Not Annoyed'. Left and right columns show the same signals in different frequency regions for better clarity; 0 – 20 Hz and 20 -35 Hz respectively. The read curve represents 'Very Annoyed @ 28/4 12.35' and dashed black line measurement system noise floor. The tonal components in noise floor measurement are believed to be due to the characteristics of the anechoic room and not the measurement system. Frequency resolution is 0.1 Hz.

The 'Slightly Annoyed @ 25/4 2.35' curve contains very distinct tonal components, in both frequency regions, where some peaks have a SNR of around 20 dB (3.2 Hz and 4 Hz). It is interesting that this is measurement was taken when there was low background noise level due to a drop in wind speed. It is possible that this reduction in wind speed and background noise reveals other noise sources that may be wind turbine noise; however, without conformation of the operation state of the wind farm, we can only speculate that the source of these peaks in the narrow band spectra are due to the wind farm.

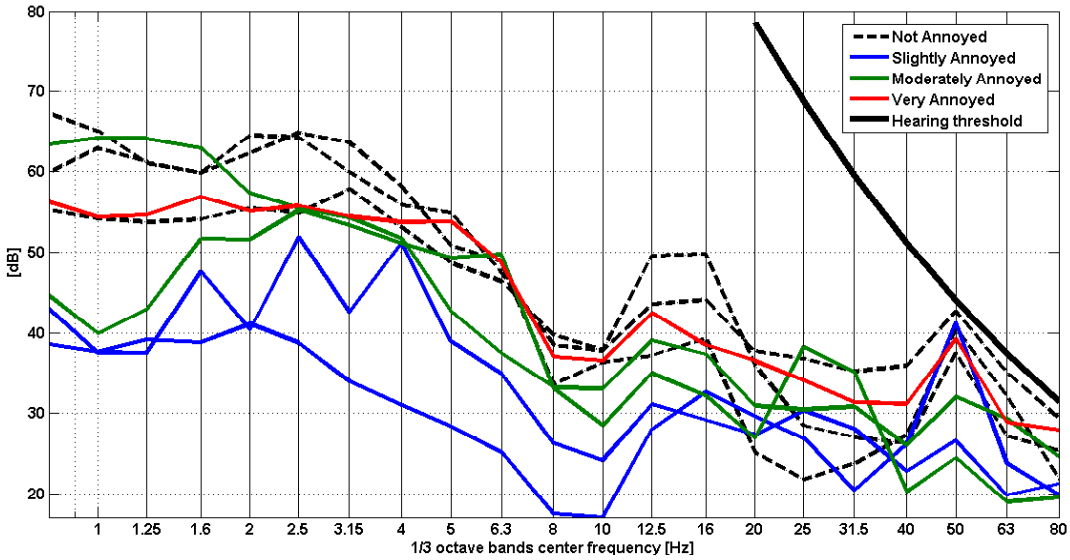

Figure 12: 1/3 octave bands annoyance in comparison to the median hearing threshold as listed in ISO:226-2003.

In any case, all levels in the infrasonic and low-frequency region are well below the median hearing threshold as it can be seen in Figure 12, thus making it unlikely that they are audible.

The DOA measurements were taken for each household; however, the differences between measurements taken at varying Annoyance levels were at frequencies below the resolution limit of the arrays. Therefore no direction data is available.

4.0 Conclusions

Noise levels and personal annoyance ratings were measured for two residents who lived at households next to a wind farm in South Australia. The major conclusions are:

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

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

3. Annoyance measurements do not directly correlate with the highest noise levels.

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

5. Without information concerning the operational state of the wind farm, the wind farm cannot be confirmed as the source of noise at low-frequency.

6. Since tonal components appear at very low and infra-sound frequencies their direction of arrival could not be resolved by arrays whose low frequency limits were 50 Hz and 85 Hz respectively.

According to the small data set collected in this preliminary study, no further conclusions can be drawn. In the future, measurements should be carried out with a bigger population and the methodology should preferably take into account the hearing conditions of the participants, their view on wind turbines and health aspects. It is likely that non-acoustical moderating factors are playing a role in the perceived annoyance of residents to wind farm noise (Doolan, 2013).

References

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