CHARACTERISING NOISE AND ANNOYANCE IN HOMES NEAR A WIND FARM

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This study examines the relationship between indoor sound pressure level, local weather conditions, wind farm output power and resident rated annoyance in homes near a wind farm. A new methodology is presented that simultaneously records resident rated annoyance and corresponding time-series noise data while continuously monitoring one-third octave band noise levels and local weather conditions. Results of indoor noise and annoyance monitoring are presented for two homes near a wind farm whose residents claim to be annoyed by wind farm noise. Annoyance was found to be related to the overall noise level; however, noise levels were more strongly controlled by local wind speed.

INTRODUCTION

Annoyance due to wind farm noise has been shown to occur at lower sound pressure levels than annoyance due to other environmental noise sources such as road, rail and aircraft and the reason for this is unclear [1]. It is worth mentioning here that noise exposure is often calculated as an outdoor exposure and the level difference between outdoor and indoor exposure is frequency dependent, which may in part explain differences in indoor annoyance from various noise sources. Only a few field studies have investigated the relationship between wind turbine noise and annoyance in the past [1 − 7] and almost all of these studies use A-weighted sound pressure level as the sound emission metric to correlate with annoyance. Standard techniques of measuring noise in residents' homes that rely upon 10-minute averages and A-weighting may not have the required fidelity to capture important features of the noise character such as amplitude modulation and low frequency noise [8, 9]. However, it is difficult to record noise in sufficient detail in the field to resolve these effects due to large data storage and postprocessing requirements. Additionally, annoyance events may be hard to predict and only occur once per day, or occur when certain conditions are present.

To overcome these issues, a system that records time series noise data in a home at the precise time that the resident claims to be annoyed was recently developed by Doolan and Moreau [7]. 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 needed to increase its usefulness. Specifically, it is 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 determine if certain weather or other conditions are related to noise level and annoyance.

In this paper, an improved resident controlled noise and annoyance recording system is presented. The system records resident rated annoyance and two minutes of corresponding time-series noise data while performing continuous one-third octave band noise monitoring. This detailed dataset has been taken at two homes near a wind farm in conjunction with continuous local weather measurements. The aim of this study is to determine whether annoyance is more closely linked to overall sound pressure level, low frequency noise, infrasound, local wind speed or wind farm output power. It is worth noting that in their previous study, the authors [7] examined whether amplitude modulation is related to personal annoyance. The results of [7] showed significant level variation was present in the home however; the degree of modulation was relatively uniform with annoyance. For the current study, analysis showed amplitude modulation was not present in the signals recorded in the homes so this can not be a factor controlling annoyance.

METHODOLOGY

The noise and annoyance recording system

The noise and annoyance recording system consisted of 4 low frequency ½" microphones (GRAS type 40AZ) connected to preamplifiers (GRAS type 26CG) and 4 mA constant current power modules (GRAS type 12AL) with a flat frequency response down to 0.5 Hz. Acoustic data were recorded using a 24 bit National Instruments data acquisition device (NI USB-9234) at a rate of 51.2 kHz onto the hard drive of a laptop computer (Dell Vostro 3550). The microphones were calibrated in the frequency range from 0.1 to 100 Hz prior to testing using a low frequency calibrator (GRAS 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.

Personal annoyance level was reported via a graphical user interface (GUI) that was programmed using Matlab and ran on the laptop computer. In all tests, the laptop was placed outside of the room containing the microphones. The system was designed so that the resident rates the annoyance of the noise they hear as either 'Not annoyed', 'Slightly annoyed', 'Moderately annoyed' or 'Very annoyed'. Additionally, they could leave a comment about the weather conditions, noise characteristics etc.

With the recording system, continuous unweighted one-third-octave band noise levels were recorded every two minutes and saved to the hard drive of the computer. The one-third-octave band measurements were calculated using the entire two minute time-series noise sample, ensuring low levels of uncertainty. When a resident reported their personal annoyance level using the computer program, the two minute time-series noise sample during which the button was pressed was saved directly to the hard drive of the computer for further analysis. Narrow-band spectra associated with an annoyance rating are presented and have been calculated from the entire two minute time-series noise sample. It should be noted that the time-series noise samples associated with an annoyance rating were carefully analysed and there was no indication that amplitude modulation was present or related to annoyance.

Test sites

Noise and annoyance measurements have been taken in two homes near a wind farm with capacity of 111 MW in South Australia. The first home, referred to as Residence A, is located approximately 2.5 km east of the wind farm. The second home, referred to as Residence B, is located approximately 8 km west of the wind farm. The wind farm is visible from Residence A but not from Residence B. In both homes, the residents claimed to be annoyed by noise that they attributed to the wind farm in all rooms of their homes.

Local wind speed and direction were also recorded in 5 min intervals at the homes using a weather station to determine if noise level and annoyance are related to wind induced noise at the home. At Residence A, weather conditions were monitored 5 m from the house façade at a height of 1.5 m above the ground. At Residence B, weather conditions were monitored 40 m from the house façade at two heights of 1.5 m and 10 m.

Noise and annoyance testing was conducted at Residence A over the period of 2/5/2013 – 7/5/2013 and during this time, 20 self reported annoyance measurements were taken. Testing was conducted at Residence B over the period of 22/4/2013 – 28/4/2013 and during this time, 8 self reported annoyance measurements were recorded. It should be noted that the total number of samples measured in the two homes is small and any conclusions are limited to this dataset and cannot be made general to a resident's perception of wind farm noise.

Microphone placement

To determine the effect of room geometry and standing waves on the results, measurements were first recorded with all four microphones placed in an unoccupied room of Residence A as shown in Figure 1. The room has dimensions of 3.9 m × 3.5 m × 3 m and is located on the side of the house that faces the wind farm. In particular, one microphone (M4) was positioned close to the window and another (M3) was located 10 cm from the ground in the corner of the room. Microphones M1, M2 and M4 were all located at a height of 1.5 m from the floor. During all tests in this study, the microphones were covered with 90 mm spherical foam wind caps.

Figure 2 shows narrowband acoustic spectra measured with the four microphones in Residence A calculated from one two minute time-series noise sample. Apart from microphone M3 which was located in the corner of the room and showed an increase in amplitude compared with the others, the signals of the remaining three microphones located in the centre of the room were essentially equivalent. As microphone placement was found to have little influence on the recorded noise signals, all remaining results presented in this paper have been taken with a single microphone located in the centre of an unoccupied room that faced the wind farm. Only indoor noise levels are presented in this paper as the focus of this study is noise and annoyance inside homes, however, a previous study by the authors has employed both indoor and outdoor microphones to examine the relationship between noise and personal annoyance [10].

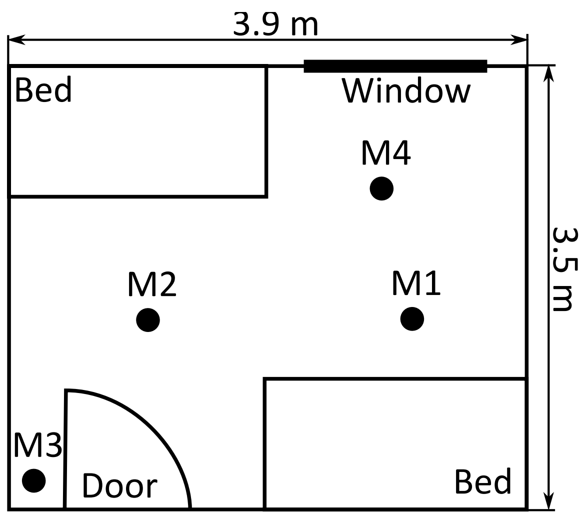


Figure 1: Microphone positions (M1 − M4) in an unoccupied room of Residence A.

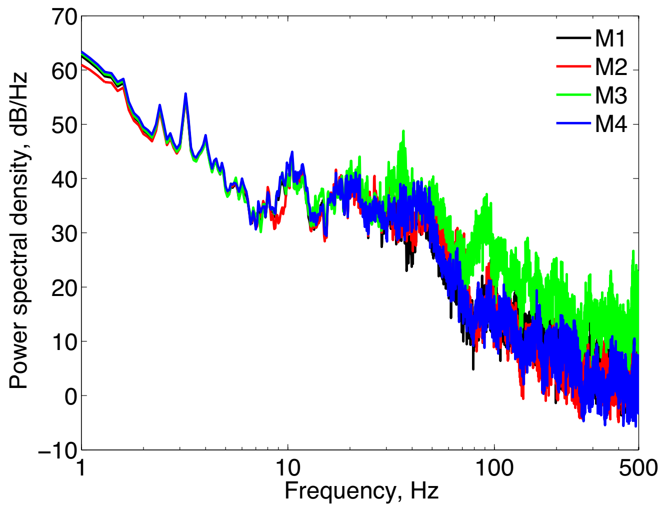


Figure 2: Acoustic spectra measured in Residence A at the 4 microphone positions.

RESULTS

Residence A

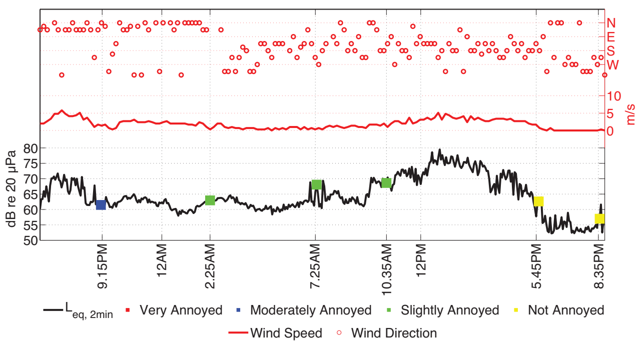
During the complete measurement period at Residence A, 20 self-reported annoyance measurements were taken with 3 rated as 'Very Annoyed', 6 as 'Moderately Annoyed', 7 as 'Slightly Annoyed' and 4 as 'Not Annoyed'. The comments accompanying each annoyance rating are presented in Table 1. These comments show that the resident perceives unwanted noise and can describe it. Additionally, the comments suggest that the noise is perceived as thumping, rumbling or roaring.

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

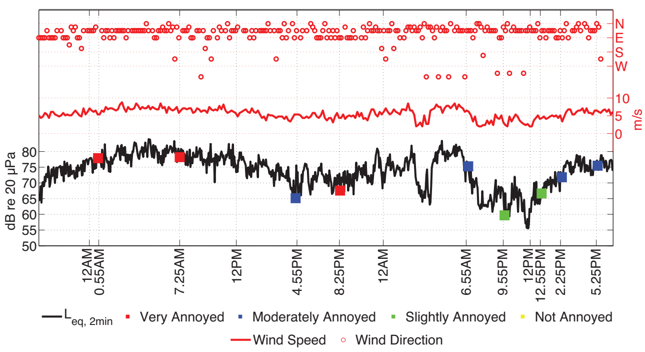
Annoyance rating	**Comments**
'Very Annoyed'	• Loud rumbling noise
'Moderately Annoyed'	• Thumping, roaring noise • Rumbling noise • Weird dreams and slight headache
'Slightly Annoyed'	• Bad nights sleep, not much noise • Weird dreams, hardly any noise • Rumbling • Felt pressure in ears • Mild whirring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

Figure 3 shows the un-weighted $L_{eq,2min}$ level, local wind direction and wind speed with annoyance ratings at Residence A. The data from 2/5/2013 to 7/5/2013 are divided into three figures for clarity.

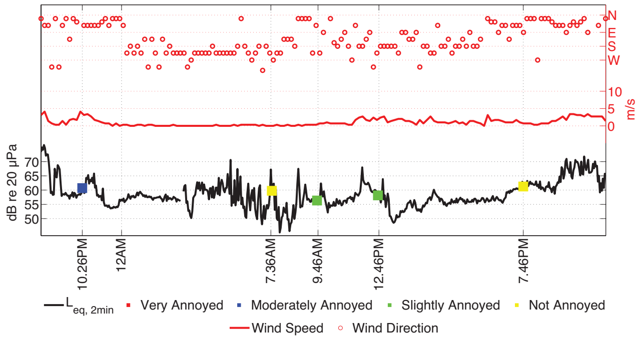
In general, the data in Fig. 3 reveal a strong relationship between local wind speed and noise level. In dataset 1 (Fig. 3 (a)), the wind speed ranges from 0 to 5 m/s. The dominant wind direction from the evening of 2/5 until the early morning of 3/5 is N/NE. For the rest of the measurement period of dataset 1, the wind direction is scattered. During this period, the resident rated themselves as 'Not Annoyed' to 'Moderately Annoyed'.



(Figure 3a) Dataset 1 from 6.25PM 2/5 to 8.25PM 3/5.



(Figure 3b) Dataset 2 from 7.55PM 5/5 to 7.06PM 6/5.



(Figure 3c) Dataset 3 from 8.26PM 6/5 to 10.46PM 7/5.

Figure 3: Wind direction, wind speed and $L_{eq,2min}$ with annoyance ratings at Residence A.

Dataset 2 in Figure 3(b) shows the largest portion of the measurement period during which the resident was most annoyed. During this time, the local wind speed was high at up to 8 m/s and the dominant wind direction was NE. Of the three times that the resident was 'Very Annoyed', two occurrences correspond to relatively high noise levels between 75 and 80 dB (0.55AM 5/5 and 7.25AM 5/5). However, the third 'Very Annoyed' measurement does not follow this trend and occurs when the noise level is between 65 and 70 dB (8.25PM 5/5).

In dataset 3 (Fig. 3(c)), the local wind direction was mostly scattered and the wind speed was low, measuring 0 m/s half of the time. During this measurement period, the resident rated themselves as 'Not Annoyed' to 'Moderately Annoyed'.

Figure 4 shows all measured noise spectra associated with the annoyance ratings in one-third octave bands compared to the curve representing the median hearing threshold as listed in ISO:226 [11]. This figure shows that as annoyance increases from 'Not Annoyed' to 'Very Annoyed', there is a general increase in the noise levels at low frequencies below 100 Hz as well as a slight increase in the levels of broadband energy to 1 kHz. At the highest annoyance rating, the highest noise levels are recorded across the entire frequency range of interest. The levels of noise in Fig. 4 are low and are at the limits of detectability. The recorded noise is observed to only just exceed the median hearing threshold at low frequencies between 50 and 100 Hz at the highest annoyance rating.

In Figure 5 the acoustic narrow-band power spectral density of two annoyance cases are compared. The noise floor of the recording system measured in the anechoic chamber at the University of Adelaide is also included for comparison. The spectra in Fig. 5 have been calculated using Welch's averaged modified periodogram method of spectral estimation with a Hanning window of length 512000 points, 50% overlap and 512000 FFT points. The power spectral density has also been corrected by dividing by the bandwidth in order to compensate for the use of a Hanning window [12]. In both annoyance cases, the wind farm was operational and the power output was high at 60% and 90% for the 'Not Annoyed' and 'Very Annoyed' cases, respectively. When the resident rated themselves as 'Very Annoyed', higher noise levels were recorded and the local wind speed was high at 8 m/s. Conversely, when the resident was not annoyed, the noise levels were lower and the local wind speed was 0 m/s. High amplitude peaks are visible in the 'Not Annoyed' noise spectrum at frequencies of 1.6 Hz, 2.4 Hz and 3.2 Hz which corresponds to harmonics of the blade pass frequency at 0.8 Hz. These peaks are likely visible in the noise spectrum due a reduction in the background noise at very low wind speed.

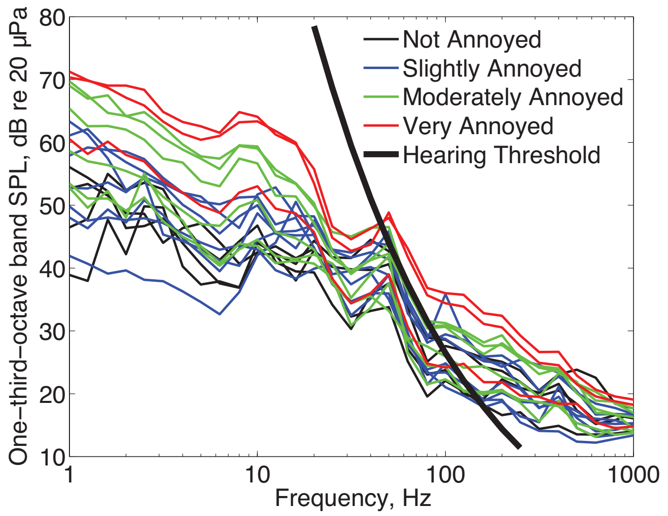


Figure 4: One-third-octave band spectra (un-weighted) for all annoyance ratings at Residence A compared to the median hearing threshold.

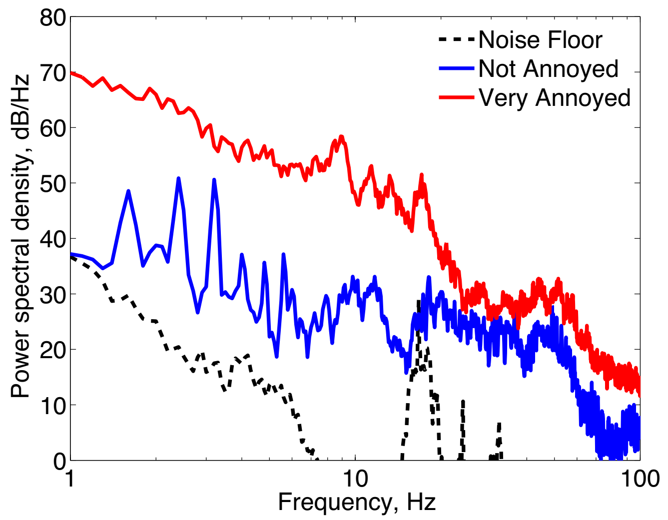
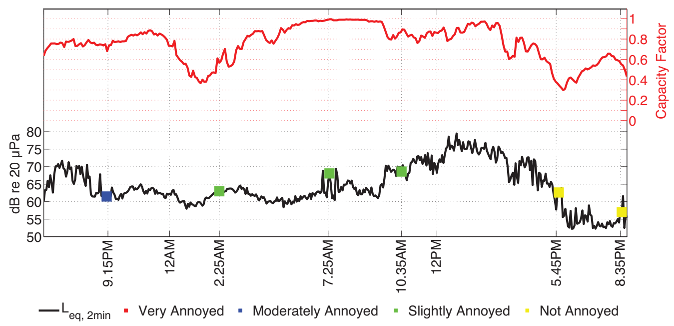
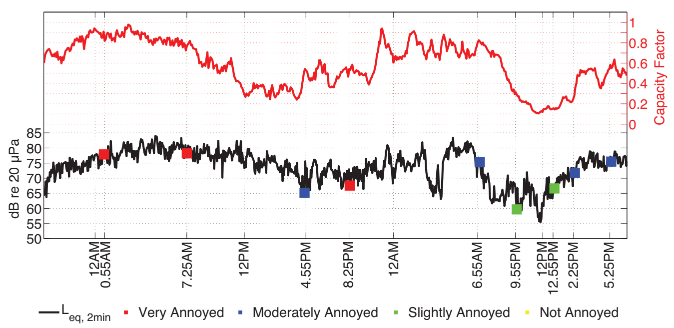


Figure 5: Power spectral density (un-weighted) of acoustic data for two annoyance ratings.

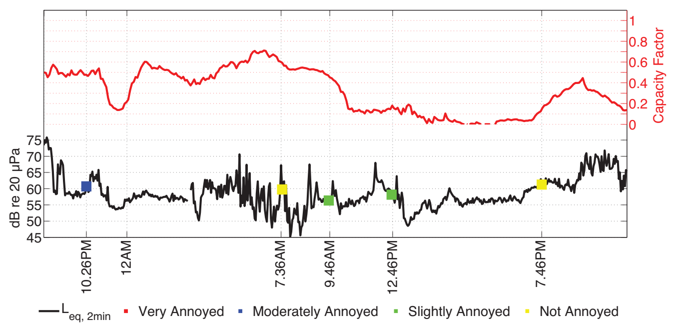
Figure 6 shows the wind farm capacity factor over the measurement period compared with the un-weighted $L_{eq,2min}$ level and annoyance ratings. Again the data from 2/5/2013 to 7/5/2013 are divided into three figures for clarity. Figure 6 shows that when the wind farm output power was close to maximum, the resident was either 'Slightly Annoyed' (Fig. 6(a)) or 'Very Annoyed' (Fig. 6(b)). The wind speed at the residence at these times was 0 − 2 m/s and 5 − 8 m/s, respectively and the corresponding noise level was measured to be 65 − 70 dB and 75 − 80 dB, respectively. If the wind farm was the source of annoying noise, it would be expected that the highest annoyance level would be to be reported when the local wind speed was low (minimising masking noise) and when the wind farm output was high. However, from the results, it appears that annoyance is most likely related to sound level and local wind speed at Residence A.



(Figure 6a) Dataset 1 from 6.25PM 2/5 to 8.25PM 3/5.



(Figure 6b) Dataset 2 from 7.55PM 5/5 to 7.06PM 6/5.



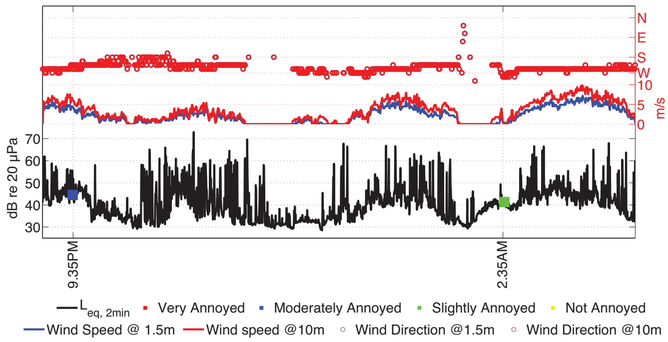
(Figure 6c) Dataset 3 from 8.26PM 6/5 to 10.46PM 7/5.

Figure 6: Wind farm capacity factor and $L_{eq,2min}$ level with annoyance ratings at Residence A.

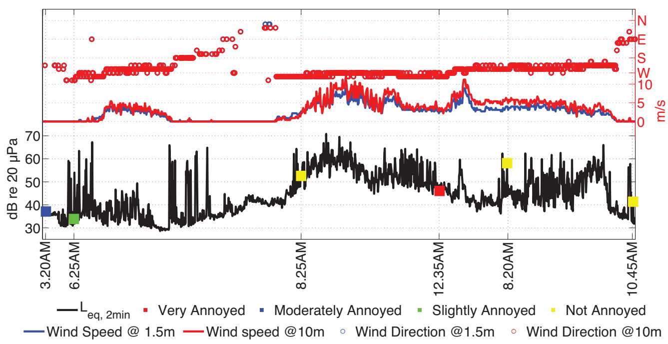
Residence B

During the complete measurement period at Residence B, 8 self-reported annoyance measurements were taken with 1 rated as 'Very Annoyed', 2 as 'Moderately Annoyed', 2 as 'Slightly Annoyed' and 3 as 'Not Annoyed'. No comments were left by the resident. Figure 7 shows the un-weighted $L_{eq,2min}$ level, local wind direction and wind speed with annoyance ratings at Residence B. The data from 22/4/2013 to 28/4/2013 are divided into two figures for clarity.

As seen for Residence A, the data taken at Residence B in Fig. 7 reveal a strong relationship between local wind speed and noise level. During times of high local wind speed and noise level, the dominant wind direction was SW. Interestingly, the times that the resident was either 'Very Annoyed' (12.35AM 28/4) or 'Moderately Annoyed' (9.35PM 25/4, 3.20AM 26/4) do not necessarily coincide with the highest noise levels or times of highest local wind speed.



(Figure 7a) Dataset 1 from 5.00PM 22/4 to 4.00PM 25/4.



(Figure 7b) Dataset 2 from 3.00AM 26/4 to 11.05PM 28/4.

Figure 7: Wind direction, wind speed and $L_{eq,2min}$ with annoyance ratings at Residence B.

Figure 8 shows all measured noise spectra associated with the annoyance ratings at Residence B in one-third octave bands compared to the curve representing the median hearing threshold. The highest noise levels are evident in the low frequency and infrasonic region. Again the levels of noise are low and only exceed the median hearing threshold at frequencies above 100 Hz.

One of the 'Slightly Annoyed' measurements (2.35AM 25/4) contains tonal components that may correspond to harmonics of the blade pass frequency at 1.6, 2.4, 3.2 and 4 Hz and these tones are also visible in the 'Slightly Annoyed' one-third-octave band spectrum in Fig. 8. This measurement was taken when the local wind speed was 0 m/s and therefore when very low background noise levels were present. Conversely, when the resident rated themselves as 'Very Annoyed' (12.35AM 28/4), broadband noise levels were recorded and the local wind speed was higher at 3 m/s.

The sound levels at Residence B (in Fig. 7) contain a lot of peaks during the day time and additionally peaks are visible in the spectra of Fig. 8. It is worth noting that the authors did listen to the audio obtained at Residence B but the source of these peaks could not be determined as they did not occur during times of reported annoyance.

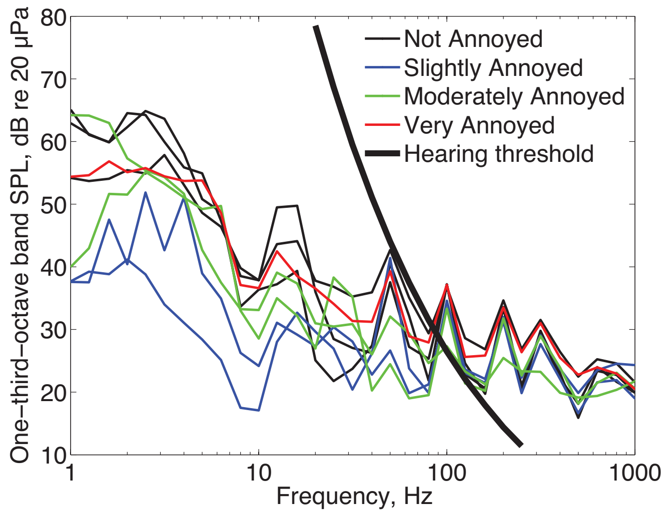


Figure 8: One-third-octave band spectra (un-weighted) for all annoyance ratings at Residence B compared to the median hearing threshold.

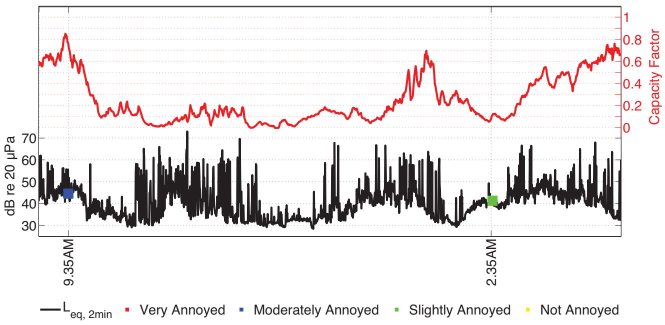
Figure 9 shows the wind farm capacity factor over the measurement period compared with the un-weighted $L_{eq,2min}$ level and annoyance ratings at Residence B. Again the data from 22/4/2013 to 28/4/2013 are divided into two figures for clarity. Figure 9(b) shows that when the wind farm output power was close to maximum, the resident was either 'Not Annoyed' (8.25AM 27/4) or 'Very Annoyed' (12.35AM 28/4). The local wind speed at both of these times was 2 − 3 m/s and the noise measured in the home was broadband at a level of 50 – 55 dB and 45 − 50 dB, respectively.

CONCLUSION

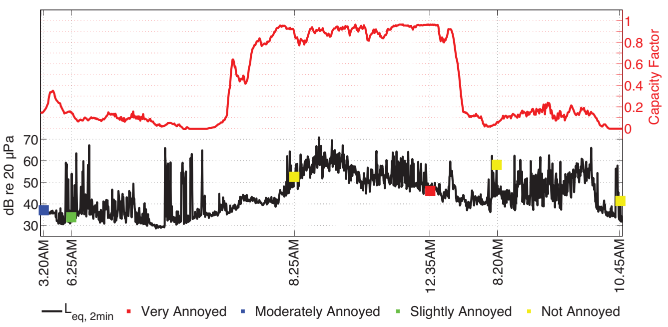
This paper has presented measurements of noise level, local wind speed and direction and personal annoyance in two homes near a wind farm. The noise level measured in both homes was found to be controlled by local wind speed more than any other factor. The highest noise levels were measured in the low frequency and infrasonic range however the levels at these frequencies were below the median hearing threshold making them unlikely to be audible by a person with normal hearing.

Annoyance was found to be related to noise level and local wind speed in the home located 2.5 km from the wind farm. However, at the home located 8 km from the wind farm, annoyance was not controlled by noise level. In this case, time of day seemed to be a more important factor.

When the local wind speed was at a very low level, with correspondingly low background noise levels, tones at harmonics of the blade pass frequency were measured inside both homes. These tones were however below the threshold of hearing.



(Figure 9a) Dataset 1 from 5.00PM 22/4 to 4.00PM 25/4.



(Figure 9b) Dataset 2 from 3.00AM 26/4 to 11.05PM 28/4.

Figure 9: Wind farm capacity factor and $L_{eq,2min}$ level with annoyance ratings at Residence B.

ACKNOWLEDGEMENTS

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