AN ON-DEMAND SIMULTANEOUS ANNOYANCE AND INDOOR NOISE RECORDING TECHNIQUE

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A novel methodology is presented for the simultaneous measurement of noise and personal annoyance at the exact times that the affected person is annoyed. The system is described and applied to a test case, a farmhouse close to a wind farm where the resident claims to be annoyed by noise. The system was successfully able to characterise the level and spectral content of the noise in the house when the resident was annoyed, and there was some correlation with personally recorded annoyance level. As the system cannot identify noise sources, no conclusions can be made about noise source; however, the methodology is shown to be a useful aid for diagnosing the type and severity of an indoor noise problem. To help interpret the results from this type of testing, a discussion concerning the subjective nature of noise annoyance is presented before some suggestions are made for further improvements in the measurement system.

INTRODUCTION

Traditional means of measuring noise in residents' homes affected by environmental or other noise may not have the required fidelity to capture important features of noise character. Some aspects, such as low-frequency noise or short-duration events, are not able to be resolved from standard techniques that rely upon 10-minute averages and A-weighting. However, it is difficult to record noise in sufficient detail in the field to resolve these effects due to large data storage and post-processing requirements. Annoyance events may occur infrequently, at random, or when particular weather conditions are present. Sometimes the source of the annoying sound is unknown; hence characterisation in terms of spectral content, annoyance and time of day may lead to its identification or at least a quantification of its severity. Continuous recordings in these situations are sometimes impractical (due to data storage issues, unreliability of the recording method and long data processing times) so a different methodology is needed. To overcome these issues, a new resident-controlled noise and annoyance recording system has been devised and is presented in this paper.

The aim of this paper is to describe a new methodology to record noise and annoyance in situations where the observers perceive unwanted, external environmental noise that may not be easily characterised or analysed by traditional means. The technique records time-series recordings that allow analysis of the signal using a variety of post processing techniques. In order to demonstrate the implementation of the methodology, preliminary results from a trial of the system in a home near a wind farm are presented and show the type of data that is obtained and the different ways it can be analysed. Note that the noise and other data presented in this paper are for a variety of situations where the resident *perceives* that the wind farm is annoying them. For a review of wind turbine noise perception, annoyance and low frequency emission see [1]. As the authors did not have direct control of the noise source attributed by the resident to annoyance, the recorded noise data cannot be directly attributed to the wind farm. However, the data is important as it characterises (in terms of level and spectral content) noise at the exact time observers find it annoying, whether it is caused by turbines, wind noise or another source.

METHODOLOGY

The system was designed to be placed in a resident's home and operated by them when they noticed and were annoyed by environmental noise. Importantly, the resident rates the annoyance level of the noise using a ten-point scale, where 1 represents not-annoyed and 10 represents the highest level of annoyance. The resident is also able to provide comments describing the character of the noise source or any other information of interest (e.g. weather conditions).

The system uses a Brüel & Kjær 4958 20 kHz precision array microphone connected to a 4mA constant current microphone signal conditioner. This microphone has a flat frequency response over the 10 Hz–20 kHz frequency range and was held approximately 1.5 m from the floor (in a separate room to the other components of the system) in a microphone stand with a 105 mm diameter wind sock placed on it. The output of the microphone and signal conditioner was amplified using a Krohn-Hite Model 3362 Dual Channel Filter before recording the signal using a LabJack U3-HV data acquisition device. The system records 10 seconds of time-series signal at a rate of 12 kHz onto the hard drive of a laptop computer connected to the data acquisition device. A value of 10 seconds is recommended for infrasound measurements in ISO:7196 Annex A [2].

A software interface was programmed in the Visual Basic 6 language. An easy interface between the resident and the data logging system was required so that the system is as user friendly as possible for people who were unfamiliar with computers.

Prior to commencing the acoustic tests, the system was calibrated using a pistonphone in the anechoic chamber at the University of Adelaide. Additionally, the noise floor of the system was measured and is shown in Figure 2.

TEST CASE

The system was placed in a home that was situated approximately 2.5 km west of an operational wind farm in Australia. The home was of weatherboard construction, located on flat farm land and surrounded by a few large trees. The microphone and wind sock were placed in the centre of a room, approximately 1.5 m from the walls, pointing at a partially open window that faced the wind farm. This room also contained a single bed. All other system components were placed in a neighbouring room from which the resident would operate the system. As the noise levels were low, it was necessary to isolate all of the other system components from the microphone to prevent extraneous noise sources (e.g. the computer fan) from being recorded. The results shown in this paper were recorded by a single resident and taken over a 24 hour period from 22/4/2012 to 8/5/2012. A total of 53 recordings were derived from the test and will be used to demonstrate the system.

In this paper, spectral data are presented in one-third-octave band and narrowband format with a frequency resolution of 2 Hz. Narrowband spectra have been calculated using Welch's averaged modified periodogram method of spectral estimation with a Hamming window function and 75% overlap. According to Bendat and Piersol [3], the 95% confidence interval on the narrowband autospectral density is -1.2/+1.4 dB/Hz. One-third-octave band spectra have been calculated using a filter bank from time-series data.

RESULTS

Table 1 provides a summary of the results obtained during the test period. It has a column describing the average noise level (for various weightings) for each self reported annoyance level and the number of samples collected at each annoyance rating. The final column states all descriptive comments relating to the wind farm and the resident's perception of the noise, just before the noise was recorded.

Table 1. Summary of results

Annoyance/ Location	dB(Z)	dB(A)	dB(Z) 10-30 Hz	Number of samples	Selected Comments
1	51	31	50	2	Hardly turning
2	54	33	53	11	Turning slowly / quiet hum / murmur from turbine
3	53	31	52	7	Faint rumbling can be heard
4	55	32	54	11	Slowly moving / thumping / rumbling noise / humming noise / can hear a rumbling?
5	57	33	57	11	Turbines moving slowly / rumbling
6	54	31	53	7	Turbines turning quite fast, not as much wind by house / slowly spinning
7	54	31	54	2	Can feel pounding / turning strongly
8	67	34	66	1	Loud thumping / rumbling
9	56	31	56	1	Roaring, rumbling noise
Noise floor	39	30	36	1	

Table 1 also lists the overall sound level of the equipment noise floor measured in the anechoic chamber at the University of Adelaide (referred to as 'Noise floor'). The table shows that for all annoyance ratings, the overall sound levels measured in the resident's home are significantly above that of the noise floor. The A-weighted noise measurements sit only just above the noise floor indicating that the majority of the noise measured is at low frequencies.

The total number of samples measured in the home is small, therefore any conclusions are limited to this data set and cannot be made general to a resident's perception of wind farm noise. The data do give an insight into the character of noise that a rural resident perceives as annoying and the operation of the noise recording system itself.

While the levels of noise measured in the home are low, the unweighted data show an increase with annoyance rating, although care must be taken for data at the highest annoyance ratings due to low number of repeat data measurements. Figure 1 plots the mean overall sound levels using three different weightings (Z, C and A) against annoyance rating over the frequency range of 10-1000 Hz. Regression and correlation coefficients for this data are given in the figure caption. The Z (unweighted) and C weighted data show an overall increase with annoyance rating while the A weighted data do not. This is because the majority of the acoustic energy is contained in the lower frequencies. This can be illustrated by examining Figure 2, which shows the single sided power spectral density versus frequency of recordings at various annoyance ratings. The figure shows that as annoyance increases, energy levels increase in the 10-30 Hz band as well as increasing levels of broadband energy to 1000 Hz, the most of which occurs at an annoyance rating of 8. The levels of this spectrum are higher than others suggesting that additional noise sources may be contributing to this measurement. Figure 2 shows that the noise environment is low at high frequencies and that the levels are close to the noise floor of the measurement system at frequencies above 200 Hz.

Note that the peaks at 50 Hz and its harmonics are due to electrical interference. These components have not been removed from the noise measurements as this study is

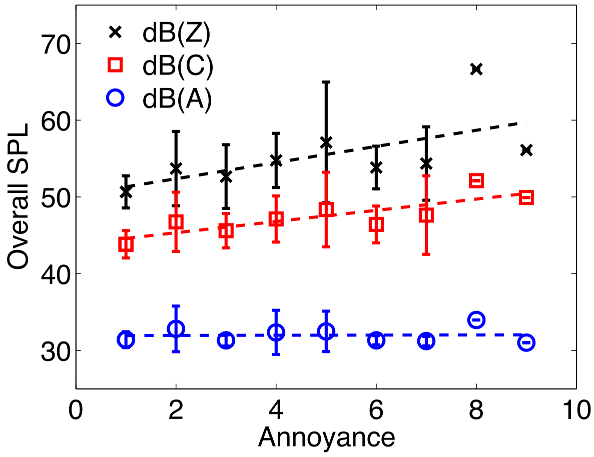

Figure 1. Overall sound pressure level versus annoyance rating by the resident. The levels were calculated over the 10-1000 Hz frequency range. Error bars indicate standard deviation. Regression and correlation coefficients for unweighted data: b = 1.1, p = 0.63; C-weighted data: b = 0.73, p = 0.83 and A-weighted data: b = 0.01, p = 0.03.

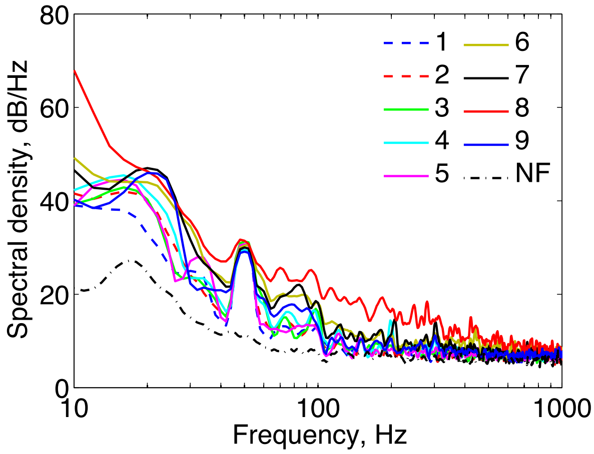

Figure 2. Power spectral density (unweighted) of the acoustic data for various resident-rated annoyance levels. NF indicates noise floor.

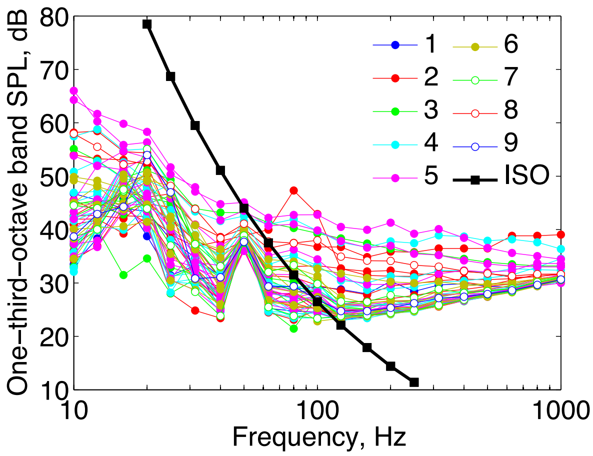

Figure 3. One-third-octave band spectra (unweighted) for all annoyance ratings. ISO refers to the median threshold curve in ISO:226 [5]

comparative and the acoustic energy at 50 Hz and harmonics does not change with each reading, so these noise components do not affect trends in the data. This is confirmed by an examination of the data in Table 1; the difference between the 10-1000 Hz and 10-30 Hz unweighted levels show 1 dB or less variation, showing that noise above 30 Hz is not affecting the trends in Figure 1.

The descriptive comments provided in Table 1 show that the resident is able to perceive unwanted and annoying noise, whatever the source is, and describe it. The comments suggest that the noise is perceived as thumping, rumbling, pounding and roaring. It is possible that acoustic energy below 10 Hz may be responsible for thumping noise; however, future measurements with new microphones capable of measuring below 1 Hz will be performed to help resolve this issue as well as determining what frequency content is responsible for the rumbling and roaring. For a discussion of wind turbine noise sources see [4].

The overall levels are low and are at the limits of detectability. Figure 3 shows all measured noise spectra presented in one-third-octave bands compared to the curve representing the median hearing threshold as listed in ISO:226 [5]. The recorded noise only just exceeds the mean hearing threshold at low frequencies between 50 and 100 Hz. At such low levels, individual differences in hearing sensitivity will make large differences in the rating of annoyance. Further, the levels in the 10-30 Hz band are about 20 dB or more below the ISO curve. A recent review by Leventhall [6] examines the link between low frequency noise and annoyance. The major conclusions from the review are that annoyance by low frequency noise is individual due to a combination of personal and social (non-acoustical) moderating influences. Personal sensitivity to low frequency noise can be influenced by age, gender and social context as well as the ability to cope with an external background stressor, such as noise. Further, Leventhall [6] suggests that there is a possibility of a “learned aversion” to low frequency noise so that a person may be able to develop an enhanced perceptibility to low frequency noise by focussing on it over long periods of time. Thus the sensitivity of a person to low frequency noise is highly individualistic and relates not only to the noise levels but the context of the person’s life that affects the personal and social moderators that influence their sensitivity and reaction.

The subjective nature of an individual’s annoyance rating is illustrated in Figure 4. Here, all single-sided power spectral density results collected for an annoyance rating of 5 are presented. Most spectra have the same shape, showing a broad peak over the 10-30 Hz range and some broadband energy below 1000 Hz. However, some results show higher levels again and are entirely broadband in nature. Thus, the rating of annoyance may be influenced by the particular time of day or personal situation the resident finds himself or herself in. For example, the annoyance to a low level noise may be higher at night than in the day, due to the masking effects of background noise or a personal judgement that it can be noisier in the daytime. Alternatively, if the resident is stressed by other personal or social factors, a lower level noise may be rated as more annoying than at a time when these factors are not

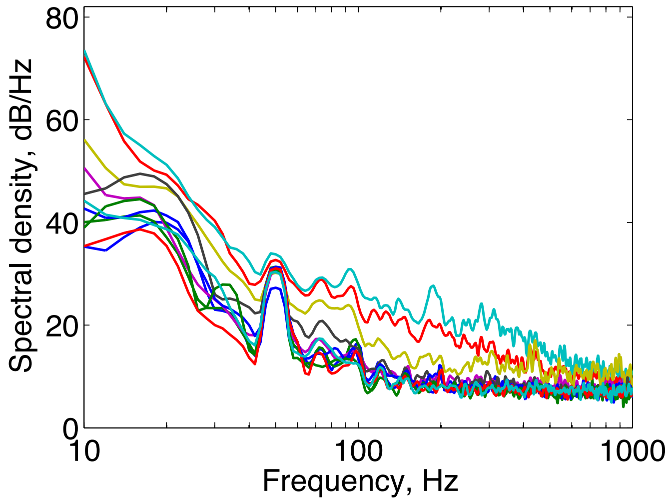

Figure 4. All power spectral density results (unweighted) for acoustic signals rated with annoyance = 5 by the resident

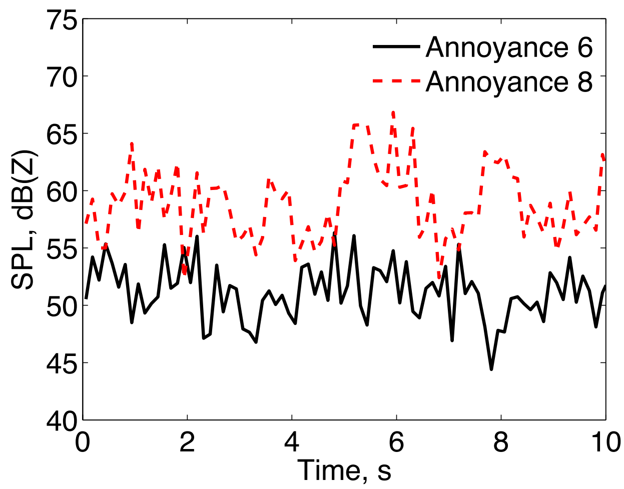

Figure 5. 125 ms time averaged (FAST) unweighted time series sound pressure data for two resident-rated Annoyance levels. The data were band-passed over 10-1000 Hz

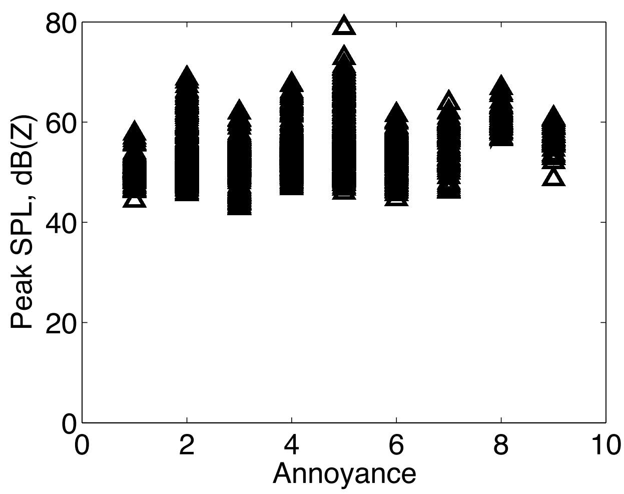

Figure 6. Peak SPL (dB(Z)) from each 125 ms time averaged time series

present. Confusing the issue further is the possible incorrect identification of the noise source by the resident. Annoyance and how noise is related to its causation is a complex psychological process, confounded by many subjective non-acoustical variables (e.g. [7]) which helps explain the variation in the results. It also makes the process of identifying the causes of noise annoyance difficult and the reduction of personal annoyance even more so, especially at low noise levels.

Another factor that may influence a person's sensitivity to low frequency noise is level variation [8]. Figure 5 shows the 125 ms time averaged unweighted sound pressure data for two resident-rated Annoyance levels. The mean level is different for each Annoyance, however, there is significant (up to 10 dB) level variation in each signal. The period of this level variation changes throughout the noise recording and is not associated with blade pass frequency.

To further investigate the link between level variation and annoyance, a peak detection algorithm was used to extract each peak from each 125 ms time averaged data record. These peaks are plotted against Annoyance rating in Figure 6. There is considerable scatter in the data and no trend can be discerned.

The depth of level variation, defined here as the difference in dB between the maximum and minimum levels in each 125 ms time-averaged data record (ΔL), is plotted against Annoyance rating in Figure 7. While there is much scatter, there is no trend with Annoyance. Further, the degree of modulation (m) can be used to characterise the depth of level variation [8]. The degree of modulation is defined by

$$\Delta L = 20\log_{10}\left[(1 + m) / (1 - m)\right] \qquad (1)$$

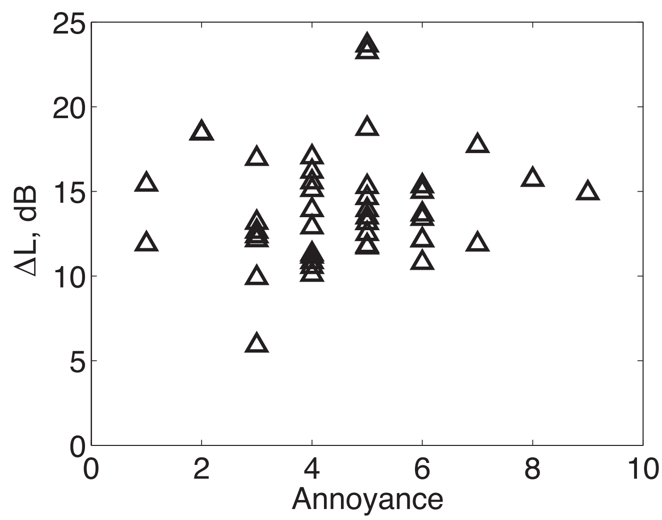

Figure 7. Depth of level variation versus resident rated Annoyance level

Figure 8 plots the mean value of m for each Annoyance rating. This result, and those in Figures 6 and 7, show that there is significant level variation in the recorded signals, but the degree of modulation is relatively uniform for each Annoyance rating and no trend with annoyance can be found. While an interesting result, further studies are required to determine whether the presence of level variation is needed to make this type of low frequency noise more perceptible or annoying, or if it is the solely a function of overall level.

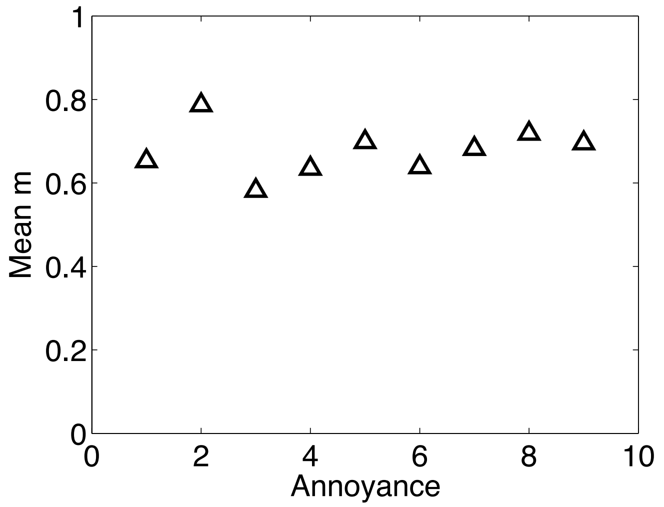

Figure 8. Mean values of the degree of modulation (m) versus resident rated Annoyance level

SUMMARY

This paper has described a new methodology for recording noise and annoyance within homes or workplaces affected by unwanted noise. The technique records time-series microphone data that allows analysis using a variety of post processing techniques.

A test case, a home near a wind farm, was presented to demonstrate the use of the technique. No link can be made between the noise data and the operation of the turbines; however, the data presented gives an insight into the type and level of noise experienced by residents and that they personally attribute to wind turbines. Measurements show an increase in the overall mean Z (unweighted) and C weighted sound level with annoyance rating. No increase was, however, observed in the mean A weighted sound level and this is due to the majority of the acoustic energy being contained in the lower frequencies and the noise levels being close to the noise floor of the measurement system at higher frequencies. In particular, the energy levels within the 10-30 Hz band were observed to increase with annoyance rating. Additionally, significant level variation was detected in the noise signals; however, no trend with annoyance was observed.

FUTURE WORK

This study has measured the noise that a resident *attributes* to a wind farm. The question remains whether the source of this noise is actually the wind farm. It is possible that this noise is just wind noise from foliage and building facades, or another source. Taking simultaneous measurements of wind speed and direction with noise and resident rated annoyance would determine if noise level was more strongly correlated with wind speed. Cooperation with the wind farm operators is also desirable to obtain on/off noise measurements; however this is not always possible, so additional work is needed to determine the source location and strength using instrumentation at the measurement location.

Future measurements with the system will incorporate use of a microphone capable of measuring below 1 Hz to capture noise over a larger frequency range than is reported in this study. Another improvement is the incorporation of a high-resolution data acquisition system that will eliminate the need for an amplifier. A weather station located near the home would also be beneficial to record local meteorological conditions that will help identify wind noise. Multiple microphones would also be desirable to measure the variation throughout the home. Longer measurement and averaging periods should also be investigated.

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