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Subjective perception of wind turbine noise

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The evaluation of wind turbine noise impacting upon communities is generally related to external noise environments and has a problem with separating wind turbine noise from ambient noise (which includes the presence of wind) which is not normally the case for general environmental noise. Subjective testing of wind turbine noise to examine amplitude modulation and subjective loudness has tended to use large baffle speaker systems to produce the infrasound/low-frequency noise and one high-frequency speaker - all as a mono source. Comparison of mono and stereo recordings of audible wind turbine noise played back in a test chamber and a smaller hemi-anechoic space provides a distinct different perception of amplitude modulation of turbines. A similar exercise compares use of high-quality full-spectrum headphones with the two different sound files applied to just the ears is discussed.

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1. INTRODUCTION

Measurements conducted in proximity to wind turbines, generally at ground level, permit identification of noise characteristics that reveal a variation in the noise levels over time and under different wind conditions.

Figure 1 presents the statistical results in one third octave bands for a 10-minute sample at a position 150 m from the base of a 3 MW turbine tower, where the orientation of the microphone is to the side of the turbines and on a line at 90° to the wind direction [1].

In the low-frequency and infrasound region of the spectra there is a significant difference between the ambient L90 background noise level and the Leq noise level of the turbines, whilst a small increment for the mid band and high frequency components.

Of significance with respect to low frequency and infrasound components is the greater difference between the L1 levels attributed to the operation of the turbine versus the background level. One would expect maximum peak levels to be higher than shown in Figure 1.

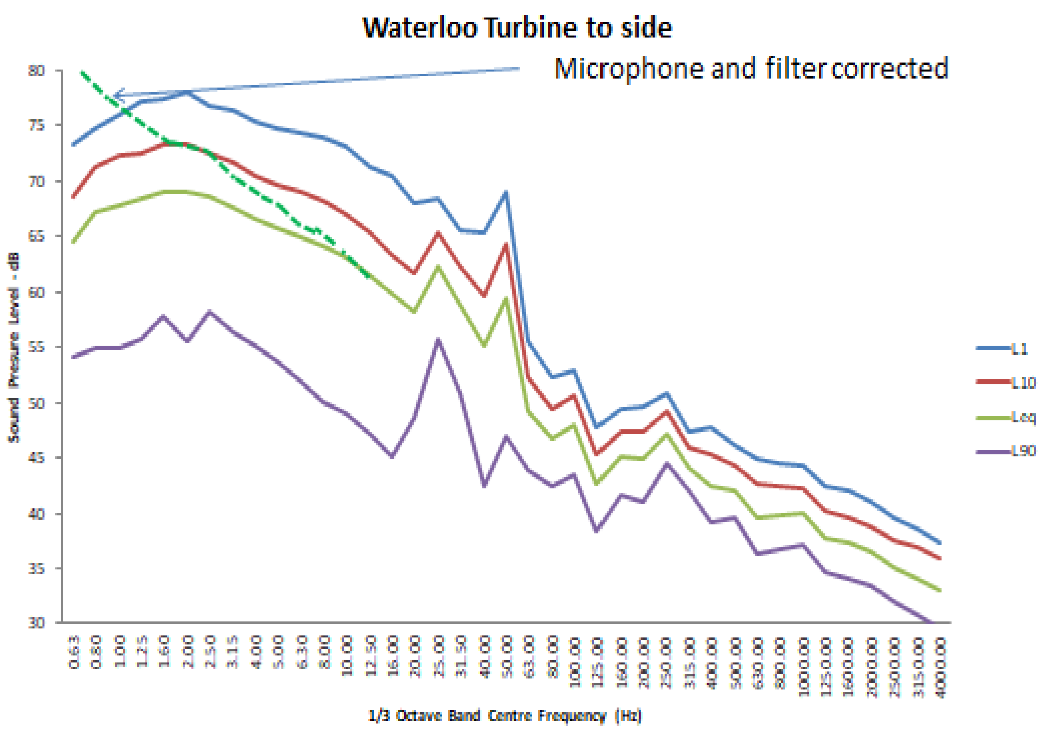


Figure 1: Statistical Results near turbine – 10-minute sample.

The operation of turbines at residential receivers often contains a modulation of the A-weighted value that occurs at the rate of the blade pass frequency of the turbine. Interference/phasing effects between multiple turbines can lead to significant changes in measured levels over time.

Access to individual turbines in the nearfield identifies by use of acoustic cameras and objective assessments, a maximum noise level to occur at about a 2 o'clock position when looking from the upwind side of the turbine.

Depending upon the power output of the turbine, related to the available wind speed at the time [2], the depth of the modulation can vary significantly (Figure 2).

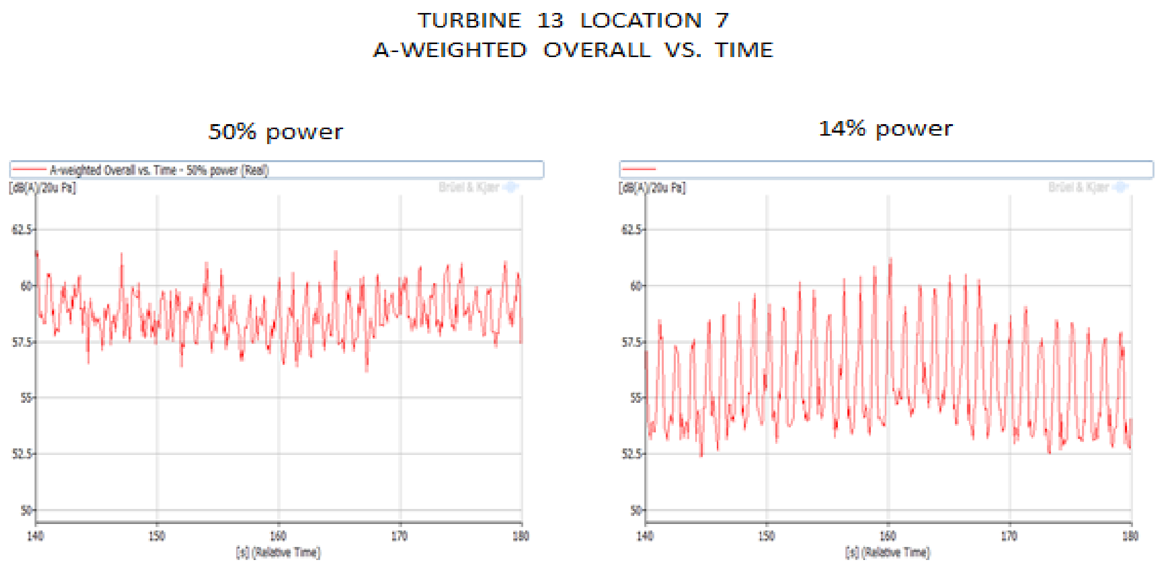


Figure 2 – Different power settings – CBW Study – ref [2]

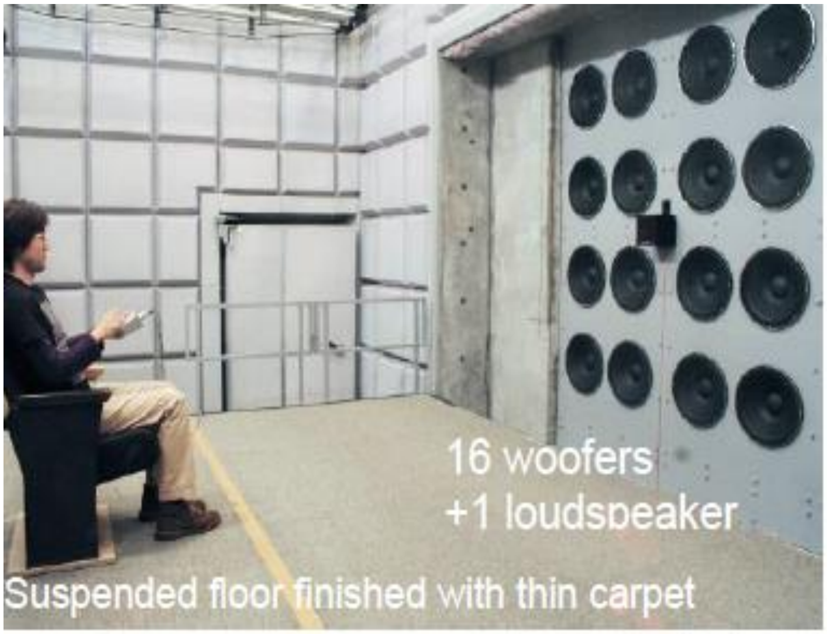
2. AUDIBLE CHARACTERISTICS OF WIND TURBINES

Narrowband (FFT) Leq analysis of turbine noise indicates in the infrasound region, a signature showing the presence of the blade pass frequency, with multiple harmonics of that frequency, with narrowband tones (with side bands) in the region of 23 to 33 Hz (depending upon the make and model of the turbines) and broadband noise at higher frequencies.

The presence of periodic pulses of noise emitted from the turbine (at an infrasound rate) that can be seen in the time domain, have consistently identified the level of FFT derived “infrasound” at residential receivers (determined by FFT analysis) to be significantly below the threshold of hearing. The presence of infrasound (or not) in the real wave file signals does not appear to address the perception of the operation of turbines when such signals are played back on systems designed to replicate (or “synthesise”) such pulsations.

Common complaints in relation to the subjective nature of wind turbine noise identify a general low-frequency tone or broadband drone commonly expressed as “like the sound of the plane that never lands”, whilst other observers refer to periodic pulsation of the noise which typically may be identified as a “swish” noise which tends to be broadband mid frequency noise that varies in its amplitude at an infrasound rate being the blade pass frequency. The amplitude modulation of the total noise as a variation in pressure to the body (and not just the ears) has been suggested as triggering the startle reflex [3] [4].

Dependent upon different wind speed conditions, the depth of the modulation of the swish noise can vary significantly on a subjective basis. Subjective testing in relation to this component has focused on what has been described as the amplitude modulation for turbines as a “special audible characteristic”.



Simulated tests of amplitude modulation have tended to use test subjects in a controlled environment. In an endeavour to obtain sufficient energy in terms of a balanced spectrum have utilised large speaker installations such as shown in Figure 3, with the assessment in that study reporting the A-weighted value correlation with the noticeable impacts of the turbine noise and that frequencies below 100 Hz do not create impacts in terms of subjective loudness [5].

Figure 3: Subjective Testing – Tachibana ref [5]

With respect to the debate of infrasound generating sensation/perception of noise for residents, the baffle situation by Tabinachi [5] was implemented in a 126-cubic metre reverberation room that also evaluated audibility of infrasound and low-frequency noise with pulsations.

Figure 4: TAG Test Room 1

The difficulty in undertaking that work was obtaining a relatively flat response of the speaker system, clean reproduction of the sound signal, and appropriate signal-to-noise ratios, where the digital to analogue converter and amplifier combination generated its own self noise that interfered with the results.

General analysis of frequency spectrum associated with wind turbine noise utilise free running averaging triggers. Walker [6] [7] has utilised a triggered result based upon the blade pass frequency pulses to identify patterns of periodic noise in the spectra and the groupings of those patterns identified as "haystacks".

Focusing on the issue of infrasound and low-frequency noise for the detection of wind farms, Walker has normally utilised a speaker with a synthesised infrasound signal for evaluation with test subjects. However, in one instance Walker [7] presented the use of external wave files with an adjustment for outside to inside attenuation, then being synthesised and an evaluation of different combinations of frequency cut-offs with test subjects.

Walker identified that the presence of infrasound made no difference to the test subjects. However, about two thirds into the paper there is a remarkable acknowledgement of the sensation of the turbines was more apparent when frequencies above 80 Hz were evident.

Walker [6] refers to use of the FFT spectrum from the Cape Bridgewater study [2] with a derived synthesis of the pressure wave. However, the derived synthesis does not agree with the original time signal noting that the original time signal includes discrete peaks in the low frequency component of the audio spectrum that also influence the time signal. Audible comparison, spectral analysis and time analysis of the original time signal and the Walker synthesised presented in Figure 12 of reference 7 found they were different.

The original CBW signal presented in Figure 12 of reference [7] represented an internal level of 18 dB(A). The provision of an additional 50 dB gain to present a clearly audible signal found on a subjective basis the synthesised signal was vastly different to the original signal.

The Cape Bridgewater study conducted in 2014 [2] was not a matter of a compliance test but was a specific study with a brief to investigate and determine certain wind speeds and sound levels that related to complaints from specific local residents.

Simultaneous indoor/outdoor monitoring at a number of houses occurred over a nine-week period, resulting in over 9 TB of data which in some instances are still being processed three years later. Figure 5 presents simultaneous outdoor/indoor measurements in Pascals for a standard 10-minute sample for a vacant room in a house 1.6 km from the nearest turbine.

Figure 5 includes an expanded timescale view for both locations that indicate the presence of modulation in the pressure waveform that is not so obvious when converted into a trace of Linear (unweighted) decibels over time.

Figure 6 presents the one third octave 10-minute Leq inside the bedroom for the outside versus inside. The outside results do not reveal any distinct peaks. The left-hand graph presents the two 1/3 octave band results in a linear weighting whilst the right-hand graph presenting the results as A-weighted one third octave values.

There are limitations in terms of the dynamic range of the measurements that were recorded, based upon Pulse IDE module which has a maximum of 80 dB dynamic range and the instrumentation set to ensure maximum levels with wind gusts did not overload the system.

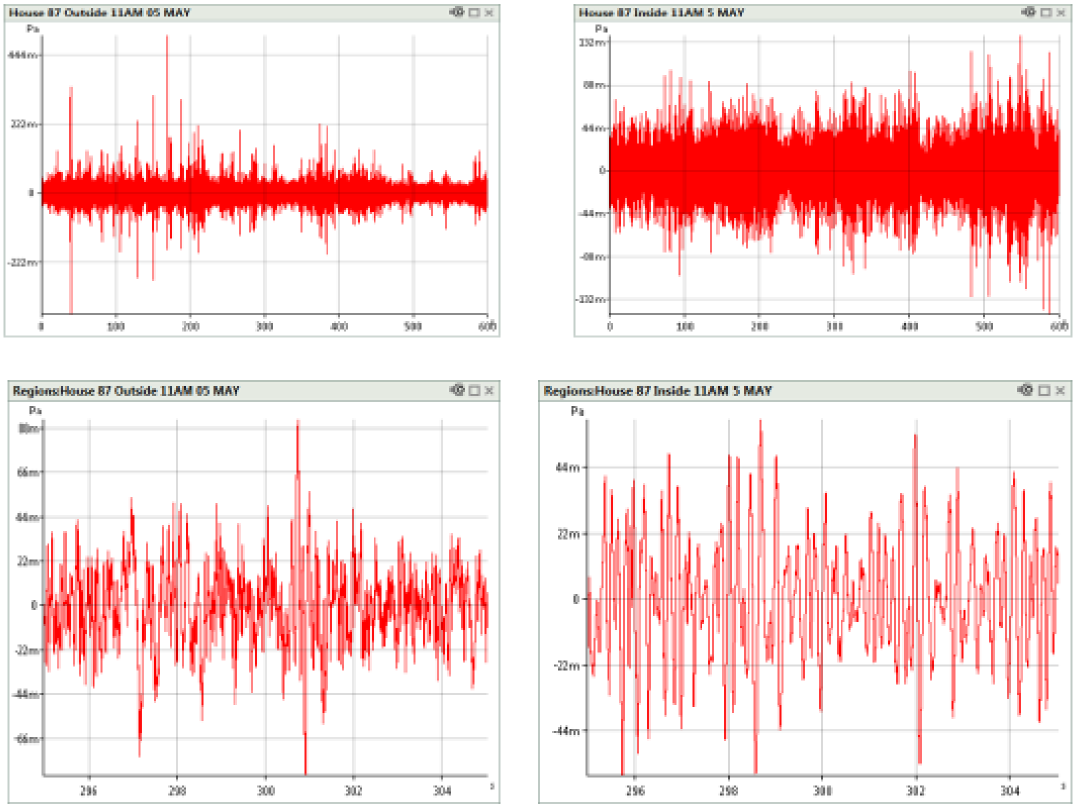


FIGURE 5: Simultaneous Inside and Outside pressure traces. Upper traces 10 minute sample, lower traces 10 second extract, ref [2]

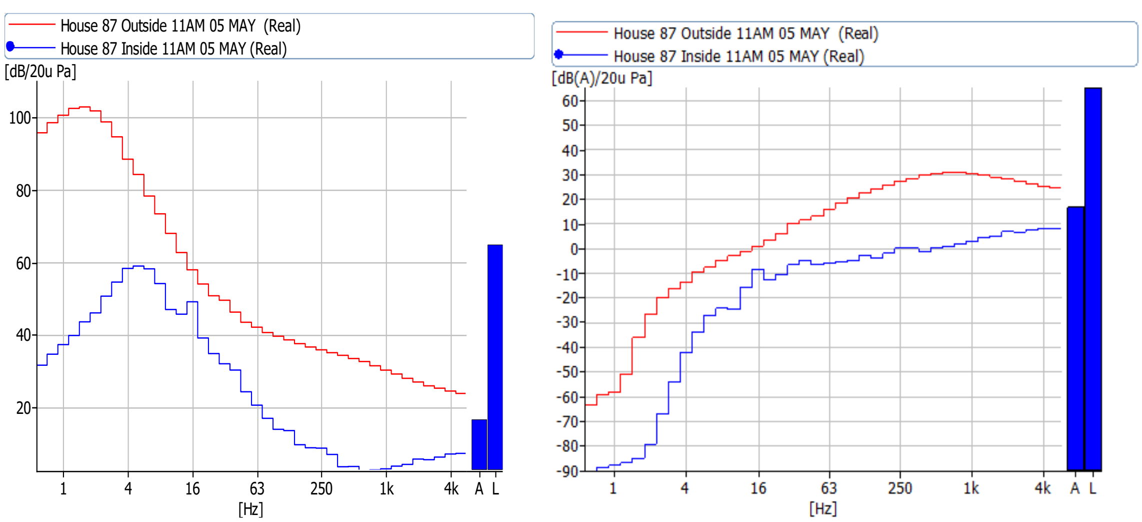


Figure 6: 1/3 Octave Band Results for Figure 5 (10 minute sample)

Utilising a UK method of assessing amplitude modulation by identifying peak 1/3 octave bands and then viewing those bands in the time domain would indicate focus on the peaks at 80 Hz, 125 Hz and 250 Hz, and basically ignore the other components in their modulation technique is looking for distinct peaks (see Figure 7).

However, the expanding the spectra in Figure 6 indicates that there are other peaks in the region of 800Hz to 4000 Hz that in themselves have higher A-weighted values but do not stand out as distinct peaks because there is a broadband increase rather than the concept of peaks on a double sided 1/3 octave band analysis.

The interesting matter about this dwelling and the results, is that the residents could detect the operation of the turbines during the test program, but the author was unable to identify any such noise.

Listening to the broadband wave file signals with some 50 dB gain did not detect any appreciable noise or characteristics inside the bedroom.

Utilising the actual wave files and adjusting the spectrum with a graphic equaliser enabled by eliminating the frequencies below 500 Hz and above 2 kHz (and with the benefit of some 50 or 60 dB gain) one could easily hear the swish of the turbines occurring in the audio signal.

Similarly, enhancing the frequencies between 25 Hz and 60 Hz found that on comparing the wind farm on and off tests (within half an hour under the same wind conditions) there was a rumble when the turbines were operating that was not present when they were off.

Based upon the audibility testing, the individual 1/3 octave band results were extracted for comparison with the A-weighted value. Figures 7 & 8 compare the A-weighted value with the 80 Hz and 1 kHz one third octave band time splices to show that the fluctuations in the A-weighted level tend to have agreement with the individual 1/3 octave bands and that the fluctuations in the 1 kHz band are at or above the threshold of hearing.

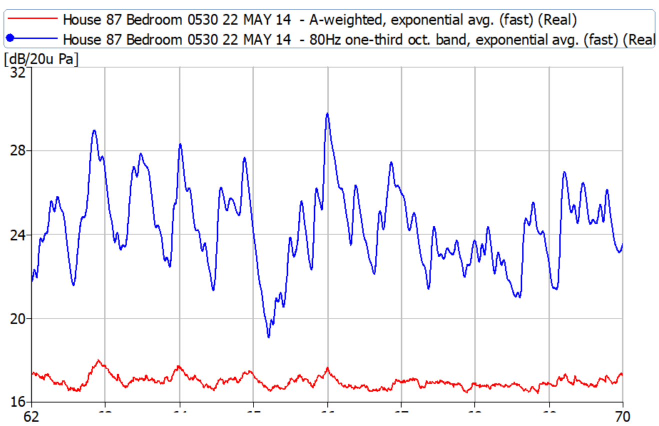


Figure 7: 80Hz 1/3 Octave vs dBA inside bedroom (from Figure 5)

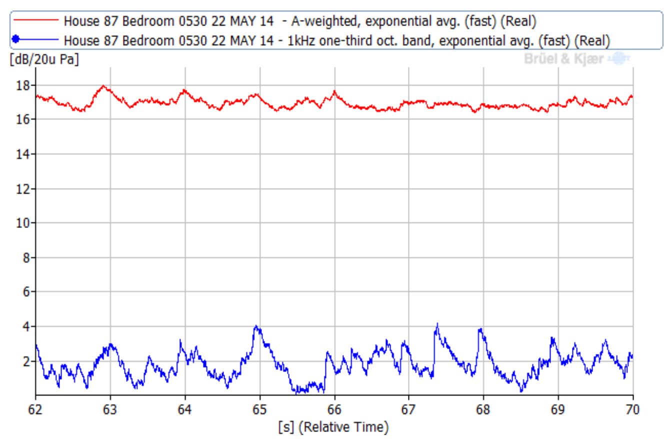


Figure 8: 1kHz 1/3 Octave vs dBA inside bedroom (from Figure 5)

For evaluating the perception of wind turbine noise additional measurements were conducted in proximity to the Capital Wind Farm, about a three and half hour drive SW of Sydney, where measurements conducted at 800 m from the nearest turbine included in one sample for a relatively short period of time the presence of audible amplitude modulation, barely audible amplitude modulation, and no audible amplitude modulation. The dominant peak in the low frequency regions was 25 Hz (see Figure 9).

Extraction of the 25 Hz 1/3 octave band found different levels of with modulation of the 25 Hz one third octave band that was masked by the broadband noise (see Figures 10 & 11).

The exercise in looking at the 1/3 octave bands during the audible swish (the amplitude modulation) revealed relationship between the A-weighted value and the frequencies between 600 Hz and 1.6 kHz.

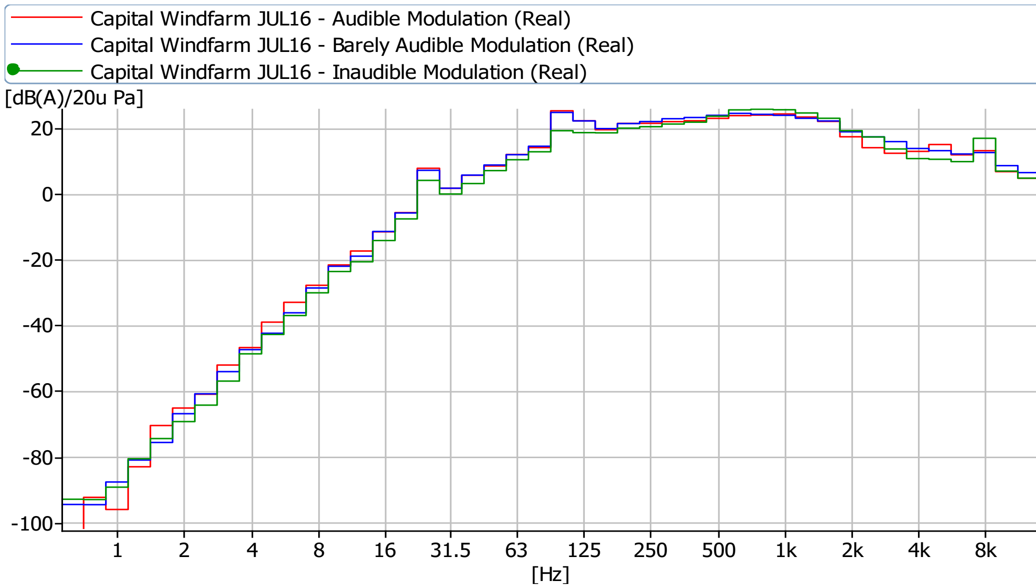


Figure 9: 1/3 Octave Band Spectra for Audible Modulation, Barely Audible Modulation and No Audible Modulation.

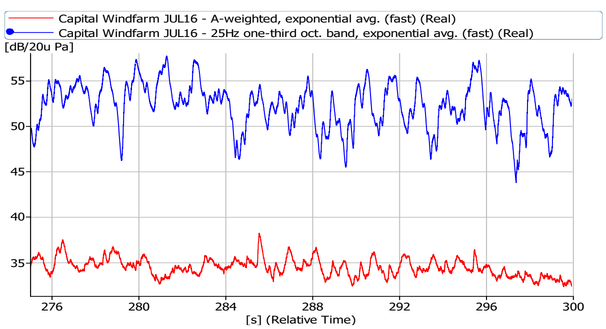


Figure 10: 25 Hz 1/3 octave band – audible swish

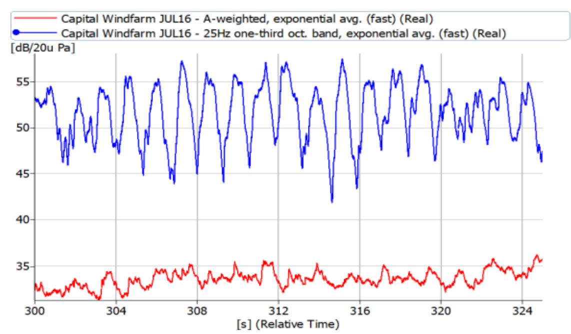


Figure 11: 25 Hz 1/3 octave band – barely audible swish

On a subjective basis, listening to music with the big baffle speaker system found that the clarity of low-frequency noise was subject to phasing issues and simply was not of an appropriate quality when compared to the placement of a single full-spectrum system in the same room. This observation questioned the Tachibana method for a subjective assessment.

Preliminary experiments by use of a small anechoic room indicated that a better appreciation of the differences in audibility of wind farm noise occurs in such a listening environment.

Persons familiar with audio recording techniques would know of the different methodologies for obtaining a stereo signal with a preference for an AB testing of individual instruments having a relatively short space between the microphones so as to not create a wide and unrealistic stereo image.

Different combinations of recording techniques were tried on several occasions at the Capital Wind Farm using a standard reference location, leading to different sampling speeds and different analysis resolutions being obtained.

Figure 12: Multiple microphone setup

There are standards in relation to the measurement of wind turbines that look to the preference of grazing incidence for the sound source (similar is that to aircraft noise) so that the diaphragm does not alter the signal.

The results which have the best promise for subjective testing involved a set up that incorporated four simultaneous measurements at a time where two microphones were placed 180° apart, but parallel to the wave front of the wind turbines, to have the sound passing the microphone at grazing incidence (see figure 12). A microphone was placed in a vertical orientation to obtain grazing incidence, and a fourth microphone pointed directly towards the windfarm and thereby not having grazing incidence.

Whereas the recording industry may use microphones with cardioid patterns, to have a focus on the noise source, in the acoustic industry one uses omnidirectional microphones with a precises linear frequency response. The use of the combination of precision microphones described above permits one to undertake normal acoustic testing and provide accurate signals recorded by the microphones. The directional response for the two microphones used for the stereo locations show that there was general consistency in the frequencies although there is slight variation in the high-frequency region which is not dissimilar to the human ear.

Utilising the wind farm microphone setup for the same sample, revealed an audible difference between the vertical microphone versus horizontal microphone. However, with the nearest turbine being to the left of the microphone position the use of the stereo sample was most significant in its perception of turbines and audible amplitude modulation that varies during the sample in response to variations in the wind.

The sound field that is recorded for subjective listening on headphones is different to that for listening on speakers and must take account of the difference in directivity that the ear experiences, particularly with the ear having an emphasis in the high-frequency region.

When running the same exercise by use of headphones where the single microphone result of a sound level recording becomes mono in both ears is an entirely different perception of the stereo signal.

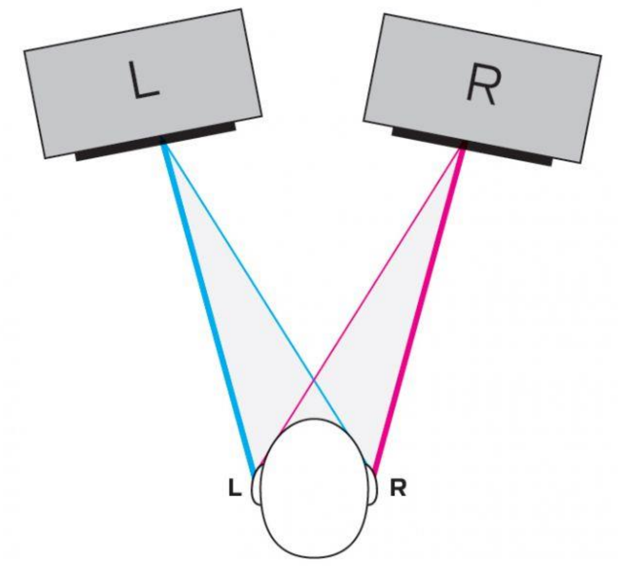


Figure 12 Spatial Orientation from Stereo Signals

3. CONCLUSIONS

Experiments with the method of large speaker baffles for the subjective perception of infrasound and low-frequency sound associated with wind turbine noise found difficulties in relation to accurately reproducing a signal which is discussed in another paper.

In looking at the subjective perception of wind turbine noise, it would appear that in the case of rural residents in Australia there is a perception of a pulsating noise source. The pulsations in some instances is described as a "swish", when in proximity to the turbine, but when removed from the turbine and subject to substantial amplitude modulation has a reduction in the high-frequency noise and is described as a "thump". In the UK, there is "amplitude modulation" and "excessive amplitude modulation".

Multiple experiments at a set position for the Capital Wind Farm under different wind conditions (over 12 months) found the presence of amplitude modulation under certain wind conditions and at other times there being no audible amplitude modulation yet in discreet frequencies amplitude modulation was always present.

In relation to the A-weighted value the major contributor to the audible modulation was found to be associated with the mid-band frequencies between 500 Hz and 1.6 kHz.

In seeking to reproduce a sound in a laboratory situation that may be used for audible tests, the use of a hemi-anechoic room with line array speakers in stereo mode provided a more realistic situation and permits the detection of amplitude modulation more easily than in the use of a mono (single) speaker system. Use of stereo speakers with a mono signal is not recommended.

Figure 12: TAG hemi-anechoic room with line array speakers

Compliance testing of wind farms has required post-processing to assess “special audible characteristics”.

Listening on headphones to a mono signal from a sound level meter automatically reduces the ability to assess the noise to that that would have been obtained in-situ.

Most of us listen with two ears and most people in gaining a high-quality perception of, or listening to high-quality music listen using speakers. The use of stereo recordings played in a hemi-anechoic space was vastly superior to the large baffle system in the lined reverberation room.

The use of headphones for monitoring purposes or evaluating the perception of wind turbine noise requires a different measurement procedure to that for using speakers.

The next stage in the investigations is to evaluate recordings using manikins versus parallel microphone 180° apart, and a set of microphones 1.9 m apart (to agree with the line array speaker systems) being directly pointed towards windfarm.

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