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## Signal Processing in Acoustics: Paper 4pSP7

# Wind farm infrasound – Are we measuring what is actually there or something else?

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In the olden days of acoustics (pre digital), low frequency analysis used analogue narrow band filters and cathode ray oscilloscopes for special problems leading to the general use of peak values. Analogue filters have time constants that can affect the derived rms values requiring caution where high crest factors are involved. Modern narrowband digital analysis is based on a FFT of the time signal to extract the periodic function that occurs in the time domain that are then displayed as discrete peaks in the frequency domain. FFT analysis of turbines show discrete infrasound peaks at peaks at multiples of the blade pass frequency in addition to sidebands in the low frequency range spaced at multiples of the blade pass frequency. Are these signals actually there or are they a product of modern day analysis. Is the infrasound signature a clue to a different area of investigation? The paper will show the results of testing to compare old fashioned and modern day analysis.

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# 1.0 INTRODUCTION

General acoustics deals with audible sounds, dB(A) levels, octave bands and sometimes 1/3 octave bands. Environmental acoustics incorporates these measurement parameters and looks at noise levels emerging above background levels.

Normally the acoustic assessment of a wind farm is based on the energy average of the A-weighted level over a sample period (e.g. 10 minutes). The A-weighting filter dramatically reduces the contribution of low frequency components when compared with the mid band and high frequency components.

Wind turbines generate noise detected in the normal range of hearing and also generate energy in the infrasound range of hearing (generally expressed as below 20 Hz). Wind turbines follow the laws of physics in relation to fans and create a specific signal at the blade pass frequency and harmonics of that frequency. However, due to the size of the turbines and different wind speeds that may occur over the vertical profile of the turbine the noise across the radiation plane in front (or behind) the swept path is not uniform.

Measured levels of infrasound in proximity to wind turbines are generally below what is assumed to be a threshold of hearing for such frequencies. Similarly, our testing of infrasound levels in houses impacted by turbines consistently find levels below the threshold of hearing.

Guidelines, Standards and permits used in Australia [1], [2], [3] & [4] provide an allowance for “special audible characteristics” identified as low frequency noise, tonal noise and amplitude modulation. The nature of variation in noise levels as a result of the operation of turbines, that may also include the concept of tonality and amplitude modulation, are not addressed in the A-weighted Leq level.

Audible noise in the low frequency region (below 200Hz) is often reported by residents for both internal and external locations. In some cases, the low frequency sound is supplemented by a mid-band varying sound resulting in descriptions of both a swish and a thump.

In guidelines used for wind farm assessments in Australia [2] & [3] “amplitude modulation” is identified as the variation of the A-weighted level occurring at the blade pass frequency. However, extraneous ambient noise can often influence the A-weighted levels and mask the amplitude modulation.

A more detailed concept to distinguish between amplitude modulation and excessive amplitude modulation has been used in the UK [5] as a tool for identifying the audible characteristics of turbines that do not appear in the variation of the A-weighted level.

The author has previously raised the question as to whether the variation of the measured signal is “amplitude modulation” or “modulation of the amplitude that is occurring at an infrasound rate”.

The abstract for this paper covers a wide area of investigations which are not complete. As a result, this paper looks to the results of infrasound measurement with respect to amplitude modulation and uses a method recently suggested in the UK [6]. Further work in relation to discrete frequency analysis (using pre digital analysis techniques) has not yet been completed.

# 2.0 METHODS OF ASSESSMENT - DIGITAL ANALYSIS

Those acousticians old enough to remember the introduction of digital instrumentation for acoustic assessments may recall debates concerning the picket fence approach and that generation of additional components required anti-aliasing filters.

For general acoustic purposes as the speed of the analysis processing increased then the issue of obtaining reliable data expressed as being in real time became less of a problem.

The concept of Bandwidth x Filter Response Time ($BT_R$) = 1 for the analysis of acoustic parameters [ref 7 pp86] and the provision of appropriate confidence limits for laboratory testing requires a long sampling period. Use of narrow band analysis (as an Leq) requires high rates of sampling as the discrete bandwidth of the individual lines is reduced, and an increase in the integration time by averaging over a longer period.

The time signal of the pressure wave from turbines do not show constant sine waves but pulses (at the rate of the blade pass frequency) than can be described as transient pulses. However, for the analysis of transient signals one ends up in a whole world of intrigue in terms of analysis periods, sampling rates and different window shapings that may be applied.

When moving from the world of constant percentage bandwidth (say 1/3 octave = 23%) to looking at narrowband frequencies (by the Fast Fourier Transform method) additional issues arise that have both plus and minus benefits in such analysis.

Those familiar with undertaking assessments of vibration on gearboxes would be aware of modulation of various gear frequencies leading to the concept as expressed by Bruel & Kjaer of ghost frequencies [ref 7 Chapter 8], which by further analysis involving the Cepstrum and Envelope Detection, can reveal meaningful data.

When one reduces the frequency, as in the case of consideration of very low-frequency and infrasound noise associated with turbines, there can be limitations in standard off-the-shelf instrumentation/analysis packages and meters that for the same noise samples do not give consistent results.

The general expression of criteria for wind farms utilises an energy average (Leq) over 10 minute samples that are then compared with the results of a regression analysis method that is different to the standard concept used in acoustic assessments for the ambient background level.

## 2.1 FFT Analysis

The presence of a discrete signature associated with the blade pass frequency, and harmonics of that signature that occur in the infrasound region (that are not present when the turbines are off) is a tool that can assist investigations into wind turbine impacts, whereas for the exact same sample the A-weighted value is of no assistance.

The conduct of simultaneous measurements undertaken by different organisations (Adelaide University [8], South Australia EPA [9], Huson & Associates [10] and The Acoustic Group [11]) with different types of equipment and analysis packages (Labview based vs Matlab based), has found both consistent and inconsistent results leading to questions as to the relationship of what we are displaying in the measurement results versus what as is actually occurring.

For example, if one was to have a signal generator that provided a pure sine wave tone of 100 Hz every time a button was pushed then we could experience that sound and (assuming there are no issues with the amplification equipment that is used) there would be a fundamental frequency at 100 hertz, and potentially higher harmonics but at a significantly lower level that can be ignored in this example.

If we now make the pressing of the button to automatically control the generation of the 100 Hz sound for a period of say 50 ms and then automate the pressing of the button to occur every second, then on a subjective basis we would hear a short sample of the 100 Hz tone every second. That would be the only sound that would be generated.

However, when a sample of the above signal is recorded and the Fast Fourier Transform is applied to that recorded signal the resultant frequency domain spectrum shows a signal at 100 Hz and a signal at 1 Hz. This is because the time signal for the above sample has periodic functions related to both of these frequencies. However, we know that there is no such actual sound level generated at 1 Hz, it is the result of the analysis method that is employed. Placing a filter to eliminate all frequencies below 50 Hz on the input to the analyser will not alter the FFT result.

Despite hundreds of hours of measurements of the Cape Bridgewater wind farm [12] and the Waterloo wind farm [11] using Bruel & Kjaer Pulse/Data Recorder systems and wave files, and analysis from SVAN 979 meters (with appropriate microphones etc. to go to 0.5Hz), we have been unable to obtain clear and distinct frequency patterns identical to those reported by Adelaide University [8] using Matlab for an analysis of similar time periods. At present the differences have not been resolved.

Changing the averaging time constants and sampling frequency for measurements and/or utilising exponential averaging rather than linear averaging leads to differences in the spectral results, as can also be found by restricting and/or expanding the overall bandwidths of such measurements.

Use of micro barometer transducers for measurements in the infrasound region and limiting the bandwidth of the monitoring to below 40 Hz permits the use of different sampling techniques (and moving window concepts) to that normally associated with acoustic assessments.

However, does the provision of such analysis in the frequency domain lose or eliminate valuable material that exists in the time domain associated with transient or time varying noise?

As a basic concept, taking a time varying signal over the sample period and reducing that material to narrowband FFT results (on an Leq basis) does not mean that if one takes those Leq FFT results and reproduce those specific tones will result in the generation of the original signal.

If the primary narrow band infrasound result is derived from the modulation of low frequency sounds, then producing a combination of pure tones at the blade pass frequency and harmonics of that frequency cannot create the original modulated low frequency signal.

Viewing the original unfiltered time signal in the pressure domain will show there are significant variations in the pressure level during a small duty sample of an operating turbine. Utilising acoustic cameras for identification of average sound pressure levels [13] reveals for typical turbine operation a hotspot about 2 o'clock when looking at an operational turbine from the upwind direction.

Could the narrow band infrasound level obtained by FFT be a combination of?

- Infrasound discrete frequencies generated by turbines,
- The modulation of low frequency sounds, and
- The FFT analysis of pulses (e.g. a square wave)

# 3.0 Measurement Results & Discussion

In 2014 an investigation was carried out at the Cape Bridgewater wind farm, located in south west Victoria, Australia, to investigate complaints from specific local residents, with the brief to determine certain sound levels at certain wind speeds that related to the complaints.

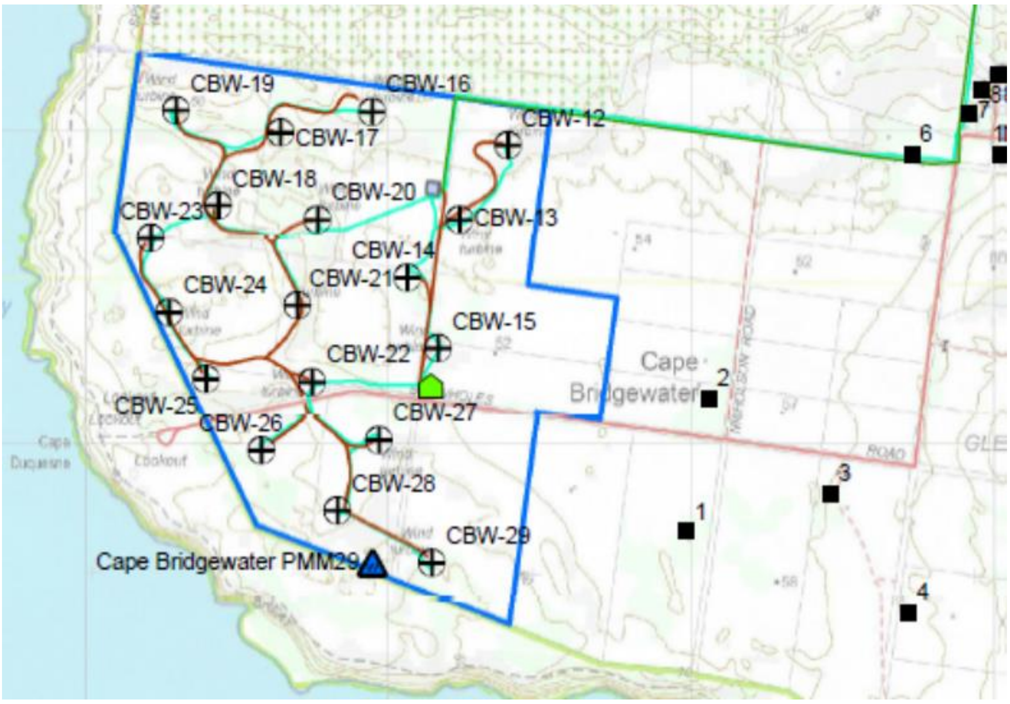



***Figure 1 – Southern Portion of Wind Farm***

Figure 1 presents a view of the southern portion of the wind farm with the black squares indicating residential dwellings for which house 2 and house 4 were included in the study

The third house in the study is adjacent to the northern portion of the wind farm (not shown in Figure 1).

Monitoring was conducted over a period of eight weeks at the three houses, with continuous monitoring recorded by unattended loggers having the capability of recording noise data down to 0.5 Hz that was supplemented by a multichannel Bruel & Kjaer Pulse system with the majority of measurements being conducted at house 4, being a house abandoned by the residents a number of years ago citing ill health as a result of the operation of the wind farm.

As defined in the study report [12] the use of a social survey that separated the resident's responses in terms of "noise", "vibration", and "sensation" found that the majority of disturbances reported by the residents related to sensation being something that they experienced rather than heard, or felt as a physical vibration through the building.

The study report [12] identified that a trend was found in the reporting by the residents for different operating scenarios of the wind farm giving rise to higher levels of sensation than for steady operation. The highest severity level was representative of a level at which the residents wished to leave (or actually left) their dwellings to escape the impacts of the windfarm noting that the specific residents in the study had a pre-exposure to the operation of the windfarm for some six years and therefore may be considered as having a heightened sensitivity to the subject windfarm [14].

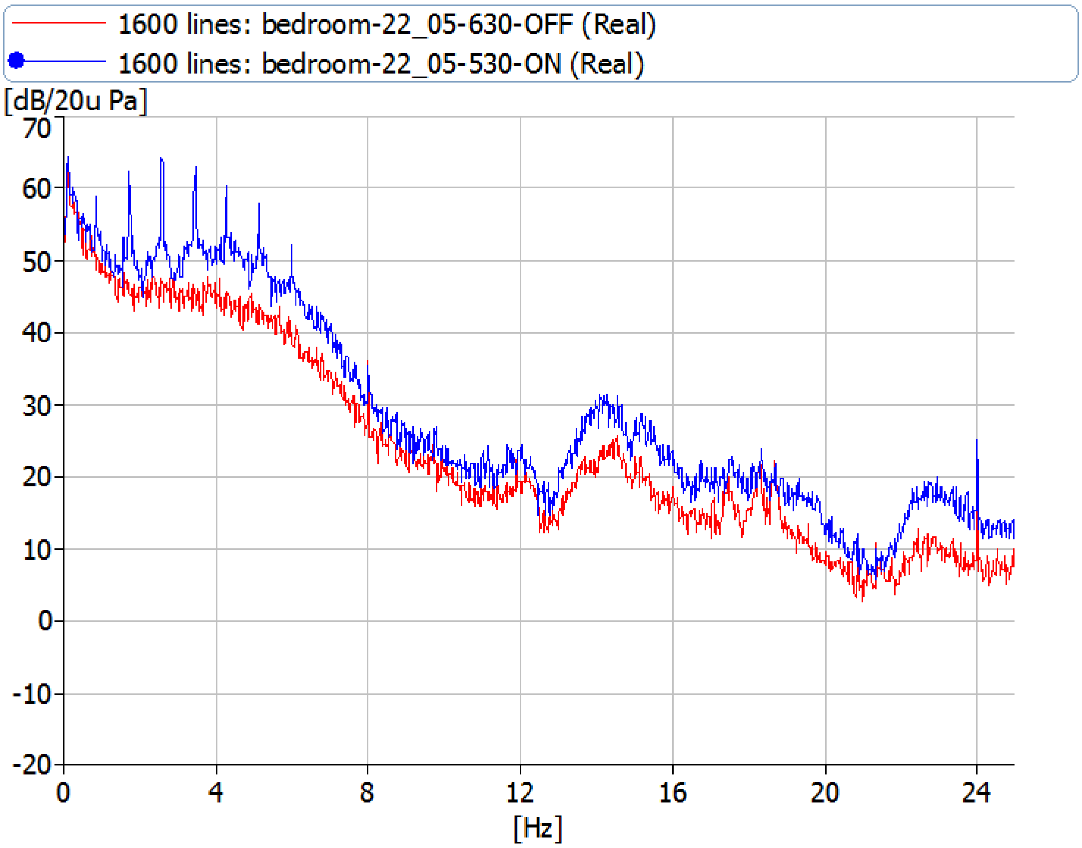
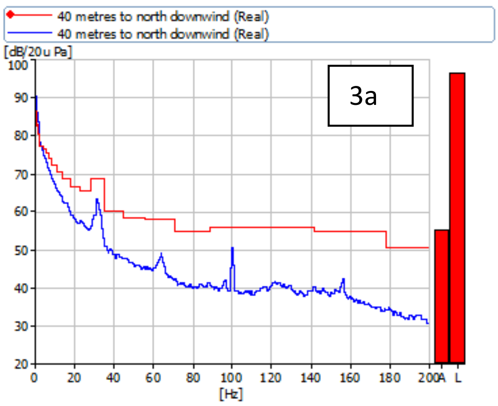
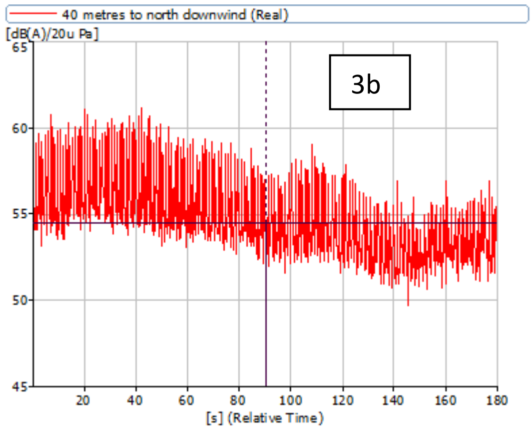



***Figure 2 – Inside Bedroom***

Figure 2 presents the results of narrowband analysis for a frequency span of 0 – 25 Hz recorded in the main bedroom for measurements related to the operation of the windfarm, and then the results one hour later with the windfarm turned off completely, that for the purpose of the exercise provided consistent weather conditions. The upper trace in blue indicates the typical signature associated with turbines when utilising narrowband measurements.

Figure 3 (being conducted 40 m downwind of an operational turbine) identifies the 31.5 Hz frequency that was found at all residential locations (see Figure 3a). Figure 3b shows that in proximity to the turbine there is variation in the A-weighted level throughout a three-minute sample period. The expanded view of the A-weighted time signal (in Figure 3c) reveals a variation occurring at a rate equivalent to three times the rotor speed being slightly below 17 RPM (also defined as the blade pass frequency). This near field measurement of the turbine provides a basis for identification of the presence of the blade pass frequency (or resultant modulation at that frequency) which clearly is not a natural event in an acoustic environment where there are no turbines.



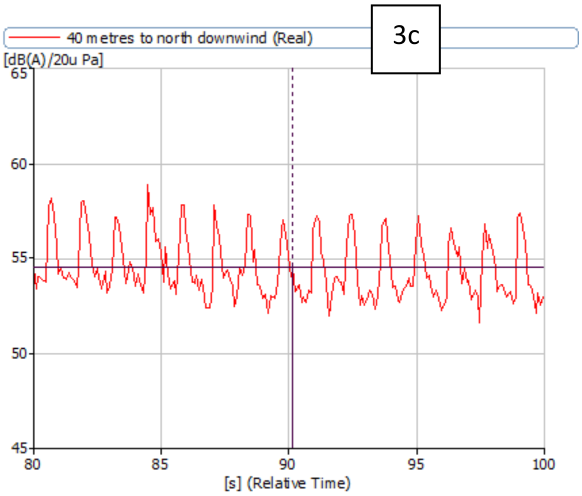




*Figure 3 - Nearfield turbine measurements*

Figure 4 presents the A-weighted 10-minute statistical results recorded inside a bedroom 1600m from the nearest turbine (house 4 in Figure 1) and the power output of the southern portion of the windfarm. The upper graph provides verification that the A-weighted level occurring inside the house is consistently at the noise floor of the SVAN 979 meter but does not vary with the output of the wind farm.

The graph includes the observations of the residents (of the abandoned home, who were in attendance at the time of the measurements) with respect to their perception of Noise (green arrow), Vibration (blue arrow) and Sensation (red arrow) despite inside the house there was no change in the A-weighed level. The colour coded arrows include the ranking to reveal the two residents could hear noise they attributed to the turbines, could detect a slight degree of vibration and perceived a high level of sensation.

No noise, vibration or sensation could be detected by the author who was present at the time (inside the house). The residents detected a change in their perception that when subsequently plotted versus the power output of the wind farm revealed the observations corresponded with a drop in the power output.

The peak levels between 1pm and 3.30pm relate to activities of the residents inside the dwelling whilst in attendance, in that for the majority of the 7 weeks of testing that house was unattended.

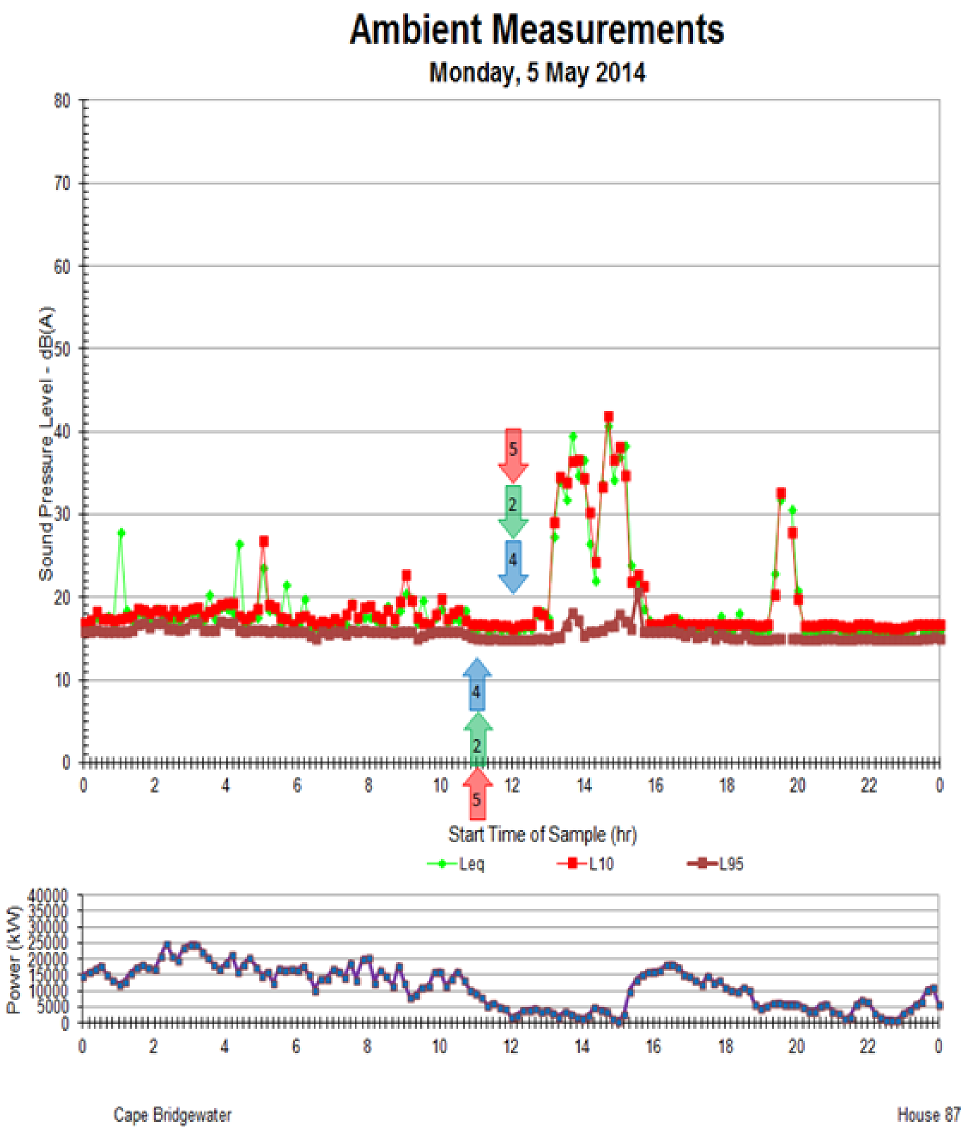



*Figure 4: A-weighted level inside bedroom*

The power output of the windfarm is shown in the lower trace for Figure 4 and indicates that the windfarm was undergoing a drop in wind speed that resulted in a reduction in the power output of more than 20% during the observations, and then involved a wind speed that fell below the cut-in speed for the turbine (the wind speed at which the turbine commences to generate power).

The resident's observations did not relate to the A-weighted Leq level.

By utilising the specific observations of both residents (during that sample period) the raw data has been reanalysed for the purpose of the investigation and revealed the typical turbine narrow band spectrum inside the house.

Figure 5 presents two graphs of a 10 minute Leq level for both an external location and inside the master bedroom where the input to the recording system was attenuated above 1 kHz so as to permit concentration on the low-frequency and infrasound components.

The left-hand graph in Figure 5 provides the results in a linear format, whilst the right-hand graph provides the same results as A-weighted values that reveal relatively low levels as a result of the ambient background noise level being less than 15 dB(A) inside the bedroom. The linear results indicate that on a 1/3 octave band basis there are no discrete tones external to the building but inside the building there is a peak in the 5 Hz and 16 Hz 1/3 octave bands. The A-weighted curve reveals a slight peak in the 125 Hz 1/3 octave band. This indicates the need for measurements inside dwellings to investigate impacts on people and not rely upon only external measurements – which is the basis of permits and guidelines [2], [3] & [5] used in Australia.

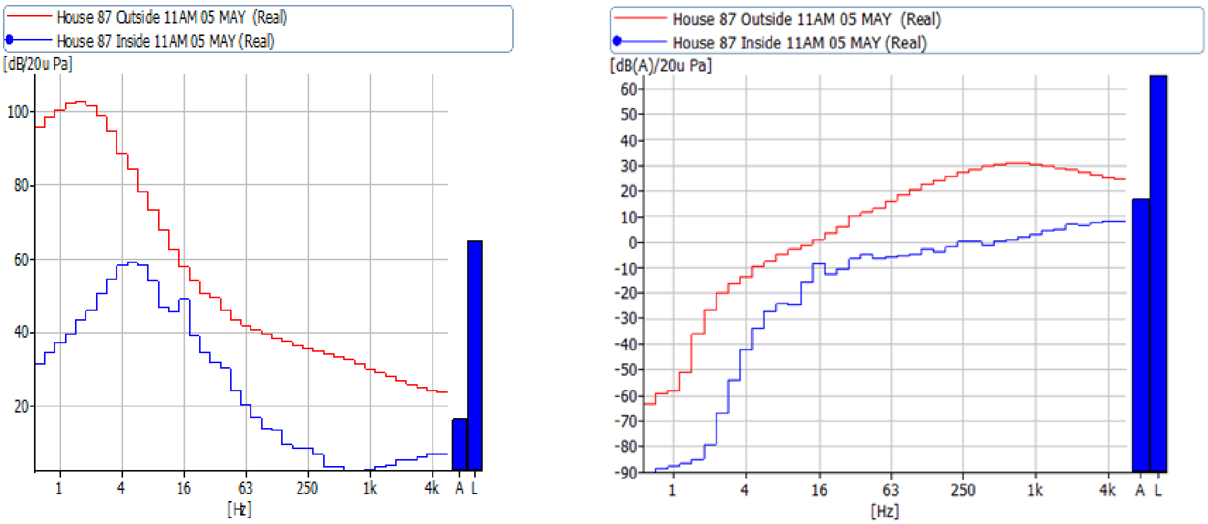



*Figure 5: 1/3 octave band results*

Figure 6 presents a narrow band analysis of the same time period with the left-hand graph considering the frequencies below 200 Hz and the right-hand graph for frequencies below 50 Hz. The outside location indicates the only discrete tonal components evident in the signature that rise above the ambient Leq level are associated with frequencies around 31-32 Hz region. Inside the dwelling there are minor peaks around 4 Hz, 31-32 Hz, 63Hz, and a broadband peak around 15 Hz.

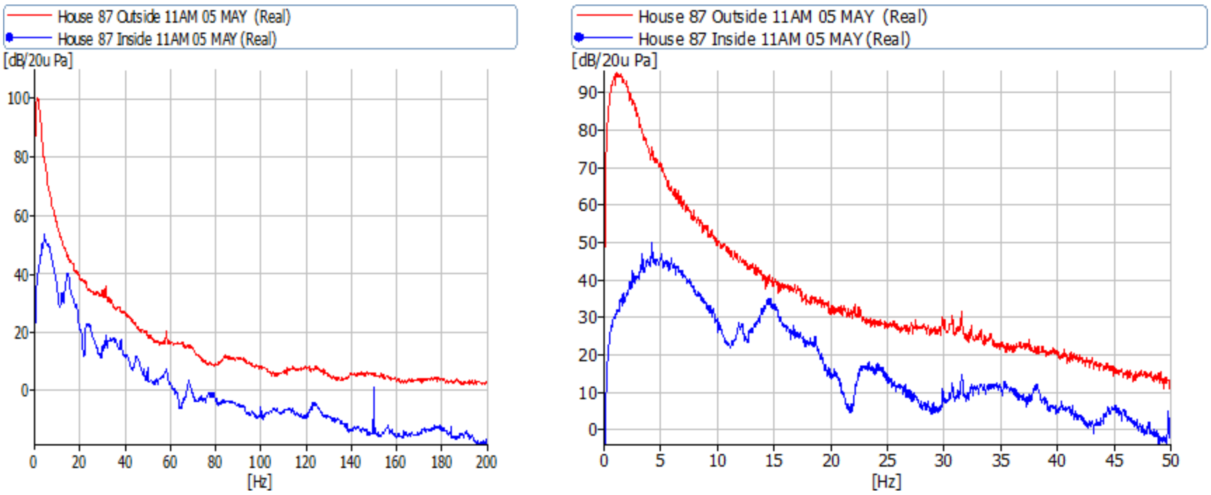



*Figure 6: FFT*

Figure 7 looks at the un-weighted/unfiltered time signal for the outside location (on the left) and internal location (on the right) where the results are examined as a pressure wave noting that the amplitudes for the inside and outside location are different.

The upper figures on Figure 7 represents the entire 10-minute sample, whilst the lower figures identify a zoomed section of the sample where the pressure pattern for the inside location clearly identifies the presence of a modulation of the signal.

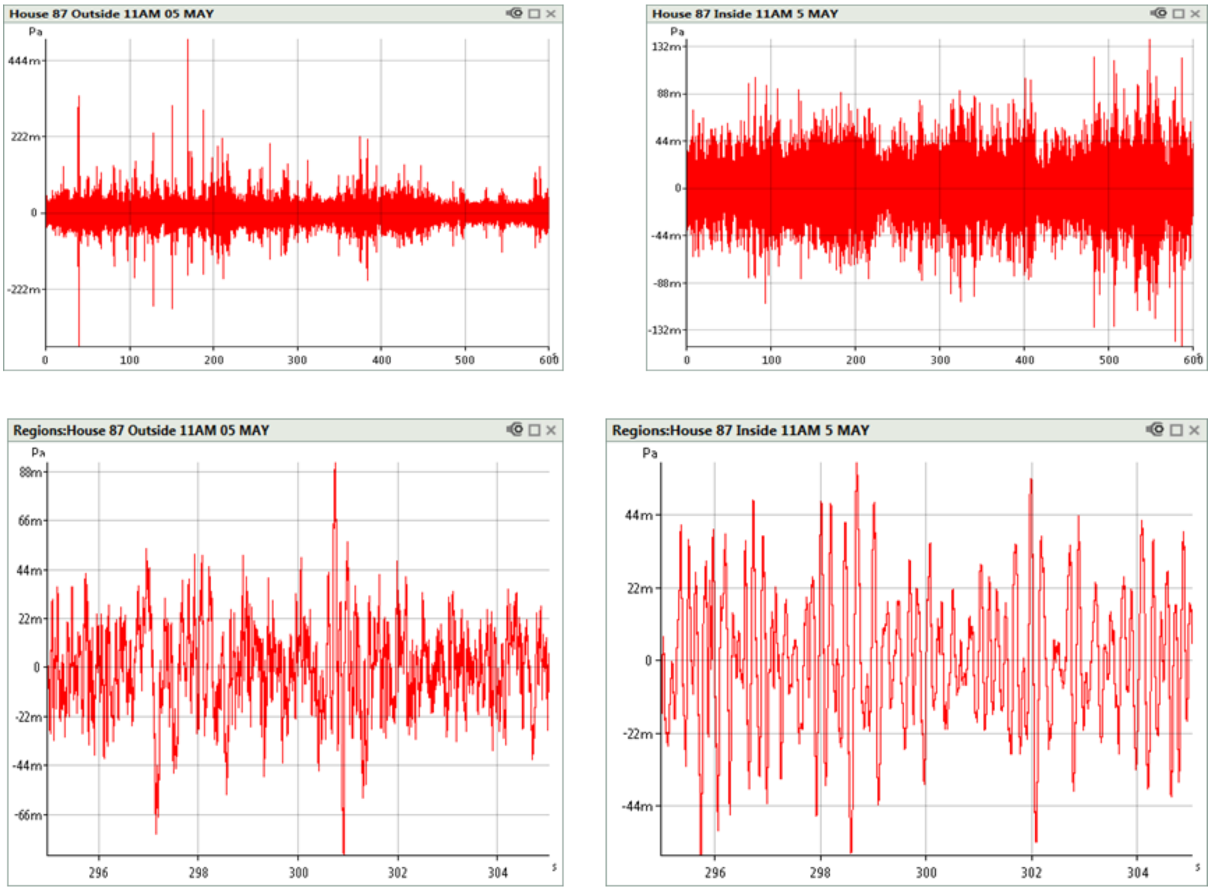



*Figure 7 – Pressure waveforms (Pa)*

Figure 8 is the same sample (as Figure 7) but presented as a single sided unweighted sound pressure level. The zoomed component, whilst indicating fluctuations in the overall level does not show the modulation concept as clearly as the double sided pressure signal in Figure 7. However, there is no doubt that inside the dwelling (without any people present) there is a significant range in the variation of sound pressure levels during the measurement.

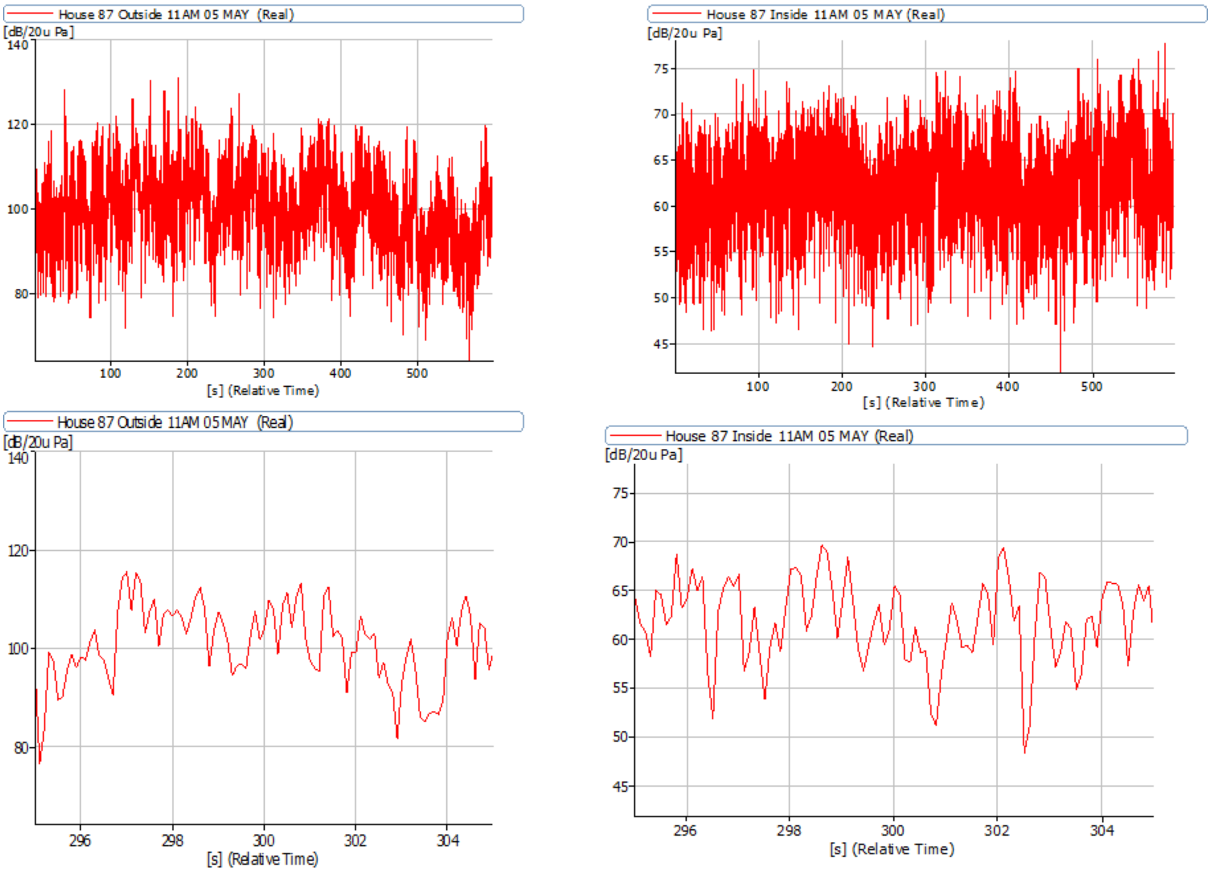



*Figure 8 – Sound Pressure level (dB)*

Figure 9 presents the A-weighted (dB) time signal and whilst there is some variation, the modulation has significantly reduced. As a general concept it could be suggested the inaudible A-weighted noise obtained inside the house is not subject to any modulations.

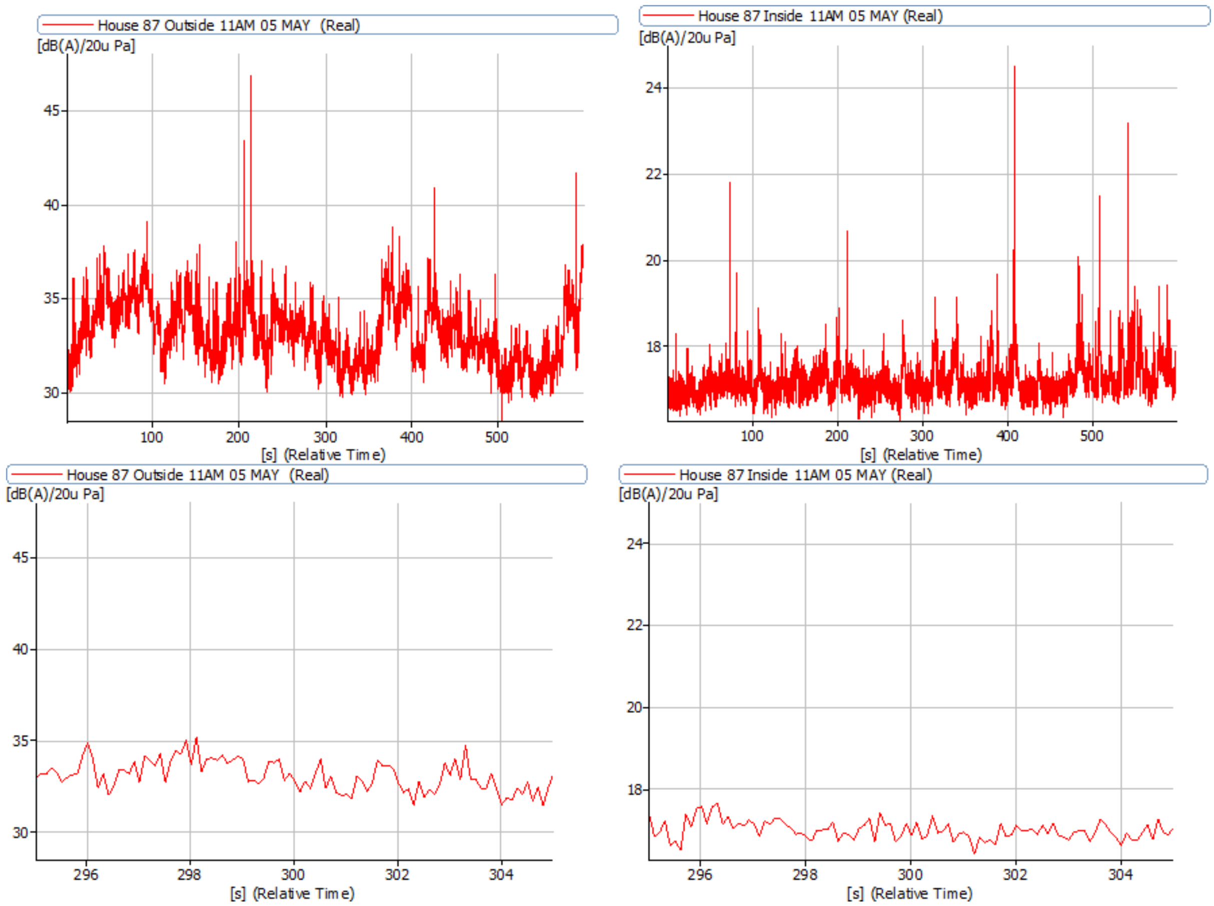



*Figure 9 – A-weighted sound pressure (dB)*

An assessment procedure for amplitude modulation utilised in the UK to describe the audible characteristic is to undertake analysis using 100ms or 125ms Leq averaging rates for plotting a time history. The overall A-weighted 1/3 octave band spectrum of the total sample period is plotted. Peaks that are identified in the time signal (of that 1/3 octave band) are then viewed for determination of any modulation that is present.

Figure 10 provides the results of such an exercise for the 31 Hz and 125 Hz 1/3 octave bands for the previous sample (inside the dwelling) and indicates modulation occurred where the depth of the modulation is significantly greater than for the A-weighted result shown in Figure 9. The spacing of the modulation reveals the modulation to occur at an infrasound rate.

It is noted that the sound pressure levels in the 31 Hz and 125 Hz 1/3 octave bands are well below what is accepted as a threshold of hearing in the normal audible frequency range.

Utilising the digital recordings for inside house 88 and looking at periods when sensation 5 has been reported by the residents (whilst in attendance for testing), together with attended observations in the various rooms, found that the noise of the turbines was inaudible to the author, yet the residents without being able to see the turbines could determine the turbines to be in operation.

Listening to WAV file with the benefit of an additional 50 dB gain or thereabouts found the typical audible noise of turbines of a periodic thump could be heard where the period of the thumps occurred at the blade pass frequency.

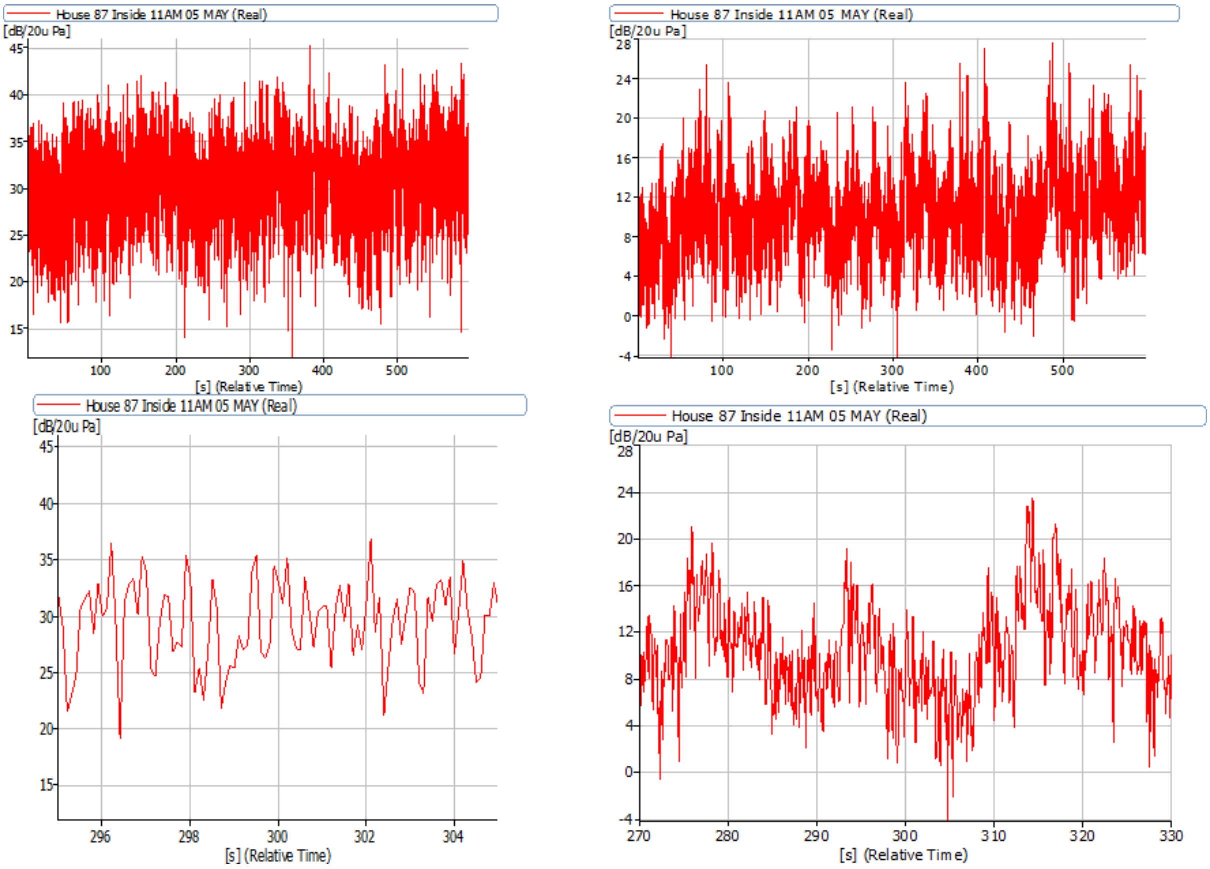



*Figure 10 - 31.5Hz and 125 Hz 1/3 octave band sound pressure (dB)*

# 4.0 CONCLUSION

There are challenges in obtaining accurate full spectrum recordings of the source signals or obtaining a linear analogue output (valid from DC) for existing full spectrum WAV files.

The use of unfiltered time signals in terms of pressure variations (double sided) shows a clear modulation in terms of the pressure level that is not so apparent when expressed in terms of the dB SPL (one-sided), and becomes non-existent when considering the A-weighted SPL.

In a “traditional” narrowband analysis of 10-minute sample the results indicate the presence of discrete tones associated with the blade pass frequency and harmonics of that frequency.

Adopting the UK approach [6] to examine individual 1/3 octave bands that stand out above the ambient Leq level (when A-weighted) show that there is a modulation of those frequencies occurring at the blade pass frequency with the time signal having a mixture of pulses related to the blade pass frequency and harmonics of that frequency.

The internal sound pressure levels are below the nominal threshold of hearing (obtained using 1/3 octave bands) for both the general audible frequency range and the infrasound range.

With additional amplification, the playback of the signals led to the identification of typical turbine audible components that produced maximum levels as a time varying signal which varies at the rate of the blade pass frequency.

The preliminary results of the investigation suggest that the amplitude modulation method adopted in the UK may very well have a corresponding relationship to the presence of discrete infrasound frequencies described by the author in the Cape Bridgewater study [12] as the Wind Turbine Signature (the "WTS"), and that an increase in the amplitude modulation by the UK method relates to an increase in the WTS.

The work to date has not identified the discrete infrasound signature is generated by the turbines in the normal sense of a sine wave. A question yet to be addressed is "Is the WTS the result of a FFT analysis of the modulation of the low frequency noise generated by the blades?"

The preliminary results indicate another current line of our investigations into the thresholds of infrasound (hearing and perception – for both sine wave and pulsed waves) should be extended to include inaudible modulated low frequency noise.

Further work in examining other infrasound measurement results (different turbine types and large ventilation fans) will be carried out in light of the preliminary analysis described herein.

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