

## A simplified method for determination of “amplitude modulation” of audible and inaudible wind turbine noise

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### ABSTRACT

The operation of a wind turbine results in a series of pulses where there is a significant instantaneous increase in the amplitude of the pressure signal dependent upon the loading (power output and wind strength) of the wind turbine. Such amplitude variations can be significant. The modulation of the amplitude of the acoustic signature for wind turbines is often referred to as “amplitude modulation”. One method of assessment of the degree of amplitude modulation for a wind turbine used in the UK is complex, time-consuming and expensive to undertake. A simplified method has been developed that is not just restricted to the dBA level and can be used to cover both inaudible and audible dynamically pulsed amplitude modulation. This simplified analysis method is not just restricted to wind turbine noise but has uses for other pulsating noise sources. Investigation of recreational music and industrial noise sources that give rise to the generation of pulsations occurring at an infrasound rate using the simple methodology is discussed.

Keywords: Wind Turbine, Amplitude Modulation

### 1. INTRODUCTION

The operation of a wind turbine generates non-steady broadband sound that exhibits fluctuations at the blade pass frequency rate that for modern turbines occurs around 1 Hz, being in the infrasound region, i.e. less than 20 Hz.

In an ideal situation the angle of the blades (pitch) is adjusted to be at the most efficient angle for extracting power from the wind. In reality, due to variation in wind strengths and/or direction(s) there is usually a timing factor to determine the average wind strength before the electronic systems adjust the pitch of the blades.

During changing wind conditions, start-up of power generation, or at high wind speeds (where the blades are intentionally feathered to reduce the speed of the turbines) the blades are not positioned at an ideal/efficient angle and under those scenarios the wind turbines have been found to generate higher levels of pulsations.

The typical variation in the noise generated from a turbine is often described as a “swish” if one is in reasonable proximity to the turbine. At locations further removed from the turbine the additional distance attenuates the high frequency components resulting in the noise being described as a “whoosh” or even a “thump”. Both the “swish” and the “thump” occur at a timing period being the reciprocal of the blade pass frequency (e.g. for a 3 bladed turbine operating at 17rpm the blade pass frequency is 0.85 Hz which gives a pulse every 1.18 seconds).

On an A-weighted approach the amplitude of the signal can vary at the rate of the blade pass frequency. This variation is commonly identified as “amplitude modulation”. At times the audible amplitude modulation is negligible, but at other times the amplitude modulation can be significant.

Plotting the A-weighted values over time reveals the depth of the modulation of the signal. One system used in the United Kingdom [1], provides a methodology to determine “excessive amplitude modulation”, where large modulation depths occur.

Figure 1 demonstrates the difference in noise downwind from a 2.05 MW Senvion MM82 turbine (at the same position) for different power settings. At the 50% power setting the modulation depth (as a peak to peak difference) is an average of 3dB, whilst at 14% the modulation depth varies from 4.5 dB – 7 dB.

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**TURBINE 13 LOCATION 7  
A-WEIGHTED OVERALL VS. TIME**

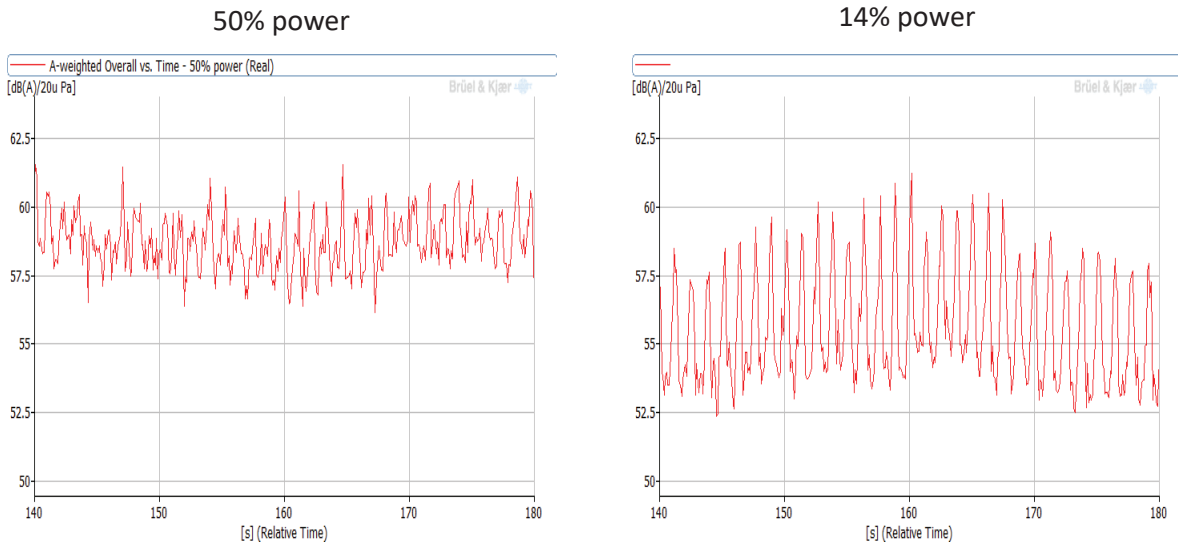


Figure 1 – Amplitude Modulation for different power settings – CBW Study – ref [2]

In relation to external noise levels versus internal noise levels for wind turbine noise there is a difference in the spectrum shape as a result of the attenuation of the building elements. This can lead to significantly different levels of modulation as shown in Figure 2, where the modulation series for this dwelling indoors is greater than outdoors [3].

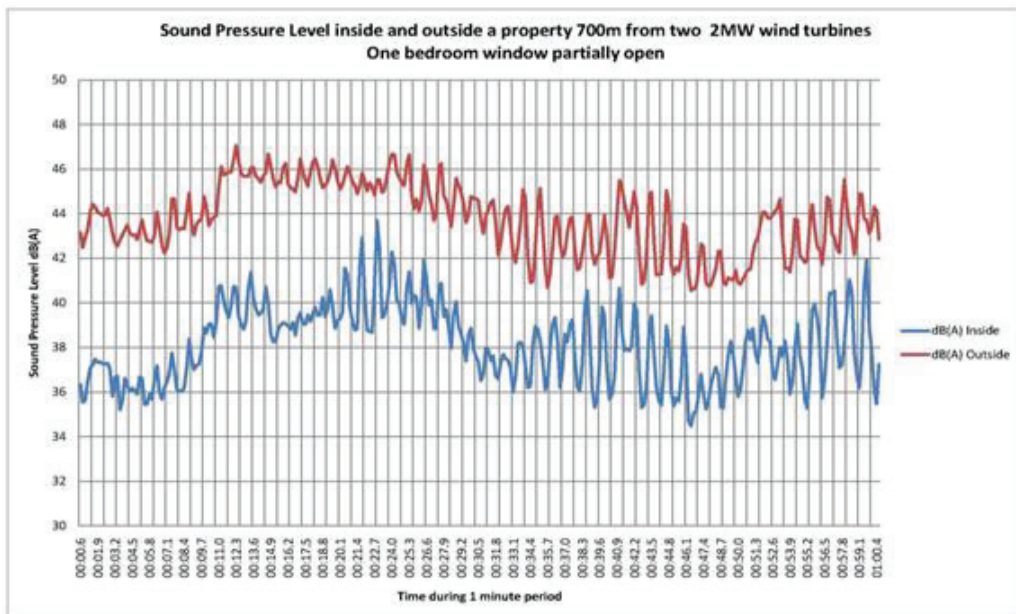


Figure 2 -Simultaneous Measurements of Amplitude Modulation – Leonards Hill Wind Farm Victoria, Australia

## 2. AMPLITUDE MODULATION

Amplitude modulation is in electrical engineering terms typically expressed with respect to radio waves (the AM band on a radio) where the intensity (level) of the high frequency carrier signal is modulated at a much lower frequency being the audio component of the information (audio signal).

Noise from wind turbines is an audio signal which in itself varies across the audio spectrum and is not a steady carrier frequency. A more appropriate definition for amplitude modulation of wind turbines is the change in level of the dB(A) value where the modulation occurs at an infrasound rate (i.e. the blade pass frequency).

One exception to the generalized modulation for a turbine is in the discrete frequencies associated with the output shaft speed of the gearbox where that frequency is modulated by the blade pass frequency and give rise to sidebands to the output shaft frequency. However, that component does not influence the A-weighted level.

The importance of the presence of audible “amplitude modulation” for wind turbines relates to the subjective annoyance of the audible signal that may warrant an adjustment for that subjective/annoying characteristic.

The dB(A) level is a combination of changing frequency components as the blades rotate and are subject to different loadings (dependent upon the wind). Technically, “amplitude modulation” may not be the correct description as an engineering definition.

In the frequency domain the fluctuation for a turbine occurs across the entire spectrum. At distances removed from the turbine the high frequency components are reduced and can alter the audible fluctuations to more of low frequency noise.

Use of narrowband analysis of turbine signals reveals a discrete signature based upon the blade pass frequency and harmonics of that frequency- with some researchers considering there to be turbine noise in the infrasound region.

One of the issues in terms of assessing noise impact from wind turbines arising from the fluctuations/pulsations that occur is considered by some people of there being a sound (in the concept of an audible tone) that is occurring, but in the infrasound region. The “infrasound levels” that are generated under that concept are inaudible as they are well below the threshold of hearing. It is the author's view that it is not really an infrasound signal (like a tone) but the result of a digital frequency analysis of the pulses that are generated. The same signature can be observed, even if a high pass filter is utilised in the sound system to eliminate any frequencies below 20 Hz (i.e. no actual infrasound).

Viewing the acoustic signal in the time domain reveals a series of pulses occurring at the blade pass frequency. An FFT analysis of a repetitive DC pulse at the same timing as the blade pass frequency produces a similar infrasound signature to a wind turbine.

Leventhall has identified that in his opinion infrasound is not an acoustic issue of annoyance associated with turbines, but the emphasis should be on low frequency noise. In Leventhall's DEFRA report [4] in 2004 he referenced work undertaken by Bradley in 1994 [5] that changed the modulation rate of low frequency noise and obtained a subjective assessment of the annoyance factor for different rates of modulation. Bradley indicated that for the critical region of between 2 and 4 Hz (being the rate of modulation of the low-frequency noise) could require an adjustment for annoyance of up to 17 dB, due to the subjective assessment of the severity of the annoyance when compared to no modulation.

In terms of psycho-acoustics, Zwicker and Fastl [6] described modulation at an infrasound rate (i.e. less than 20Hz) to be “fluctuation” and can be readily sensed by the human ear when the modulation exceeds 3 dB. The depth of the modulation affects degree of sense of fluctuation.

The mechanism by how the ear/brain responds to the fluctuations in low frequency noise at an infrasound rate is not identified in any of the above studies and warrants further investigation.

This becomes relevant in that one can also have infrasound fluctuations of the wind turbine noise where they are inaudible - yet still perceived by residents.

Zwicker and Fastl identified the critical sensitive frequency of 4 Hz is also related to the modulation of speech. Rand [7] considers the human brain is attuned to frequencies around 4 Hz and could be registering the presence of modulation and seeking to decode information that is not there.

Wind turbines generate different levels of fluctuation leading to different perceptions of annoyance.

The UK concept [1] has been criticized at it considers three groups of 1/3 octave band data (50-200Hz, 100 – 400Hz and 200 – 800 Hz). The Independent Noise Working Group [8] have examined a number of AM assessment methodologies. Under the Den Brook Method, one looks to a difference in peak to trough levels of more than 3 dB(A). Other AM concepts described in ref 8 look to derive a

value for AM relating to the power in the band containing the blade pass frequency.

Another UK concept for further analysing and defining amplitude modulation has been developed [8] to address the subjective annoyance by extending the analysis to focus on 1/3 octave band peaks in the A-weighted spectrum.

The UK method of assessing amplitude modulation looks at the audible characteristic of a fluctuating sound. Having identified peaks in individual A-weighted 1/3 octave bands the method obtains LAeq levels at 100ms millisecond intervals for a 10 second sample, plots the variation in the amplitude and determines the depth of the modulation in those critical bands. The exercise is then repeated for multiple 10 second samples.

The procedure by the above method is labour-intensive and therefore time-consuming.

### 3. ALTERNATIVE ANALYSIS

Narrow band analysis (such as Fast Fourier Transform (FFT)) is not suitable for viewing amplitude modulation. It is necessary to see the time information as the normal FFT analysis as an Leq level. However, as a starting point an FFT analysis of the infrasound section of the spectrum is of assistance in identifying the blade pass frequency, or for non-wind turbine noise sources under consideration the rate of modulation.

A graphical method was developed of showing the change in the turbine signature that highlighted pulsations, amplitude modulation and frequency modulation to assist in understanding the dynamics of the acoustic signature and showed the failings of just using Leq levels [9].

The method (both in FFT and 1/3 octave bands) analyses an un-weighted time sample derived by using a waterfall approach. By orienting the waterfall view to look at the spectrum at each point in time one could progressively scroll through the sample (in time) to view the variations. This viewing method can be made into a video that in turn highlights any relevant investigations into different components of turbine noise.

For example, the FFT movie view is suitable for infrasound and low frequency (available at <http://acoustics.com.au/media/ICA2019AM01.mp4>) However, for mid and high bands the 1/3 octave band movie view is better (available at <http://acoustics.com.au/media/ICA2019AM02.mp4>). By use of the waterfall data, one can view any individual 1/3 octave bands to show the modulation in the time domain to appreciate the UK method in determining amplitude modulation.

For recording the time capture, one obtains a better signal to noise ratio using a Linear (unweighted) parameter when compared with an A-weighted recording. Recording A-weighted signals requires a much larger dynamic range due to the A-weighting filter and also introduces additional filter response time constants that can lead to different analysis results.

To identify the alternative method, measurements were conducted at a location on a public road (Taylors Creek Road) approximately 750 metres east of turbine 9 for the Capital Wind Farm (in NSW Australia). The A-weighted 1/3 octave band Leq spectrum reveals peaks at 25Hz, 125Hz and 800 Hz as shown in Figure 3.

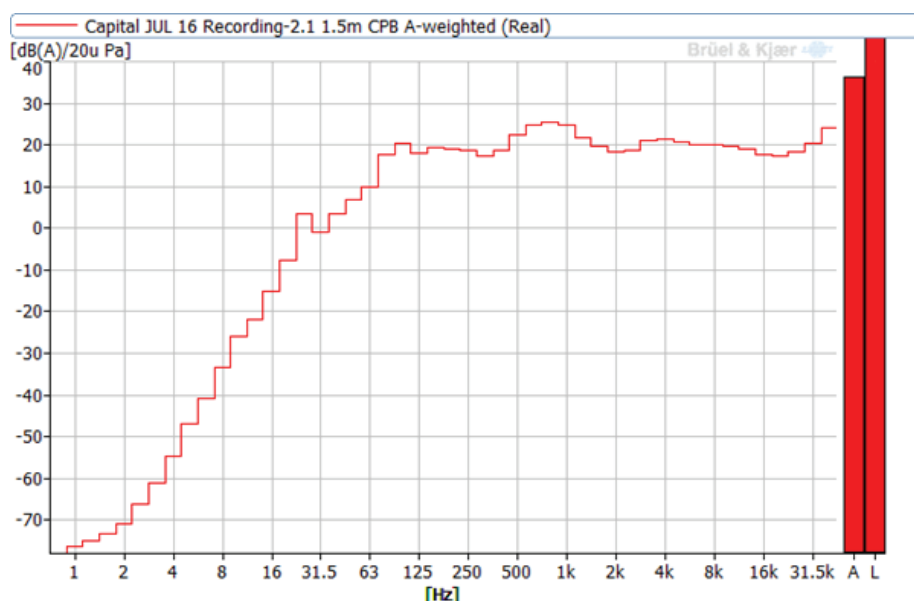


Figure 3: Capital Wind Farm – A-weighted 1/3 octave band Leq Spectrum

To assess a number of the alternative methods described by the INWG, utilising an exponential FAST response and analyzing the signal in 100ms increments to produce a waterfall analysis gives rise to the following time trace of the 25Hz 1/3 octave band where the modulation can be clearly seen. In this case the monitoring location is influenced by a number of turbines (not just a single turbine) and therefore can have phasing issues with the interaction of the pulses of multiple turbines.

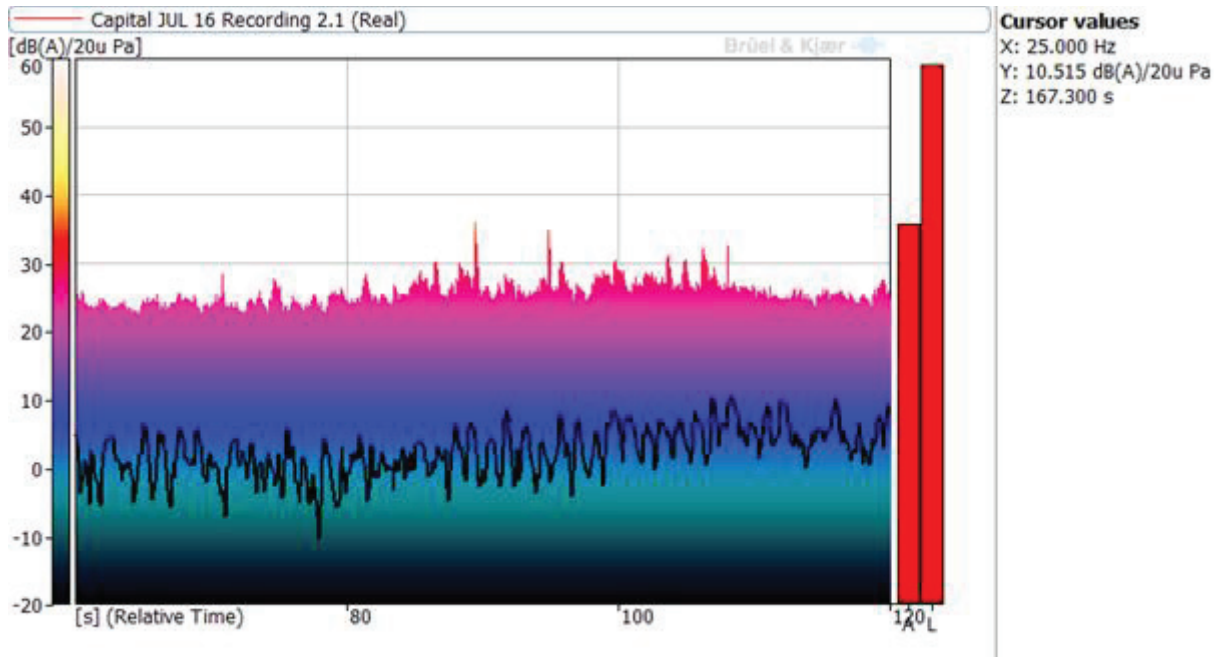


Figure 4: Time Trace for 25 Hz 1/3 octave band for Figure 3

Similar time traces can be obtained for the other peaks in the A-weighted 1/3 octave band spectrum (see <http://acoustics.com.au/media/ICA2019AM03.pdf> for additional traces).

Having identified that the time signal in the relevant 1/3 octave bands are modulated, the alternative analysis method is to take a 10-minute or a 15-minute recording of the sound associated with a wind turbine and undertake a statistical analysis.

On a statistical basis one can show a significant difference between the L1 and L10 versus the L90 level. If the “amplitude modulation” is based upon the maximum level of the pulse versus the background level (between the pulses) then a simplified method to assess the amplitude modulation for individual 1/3 octave bands is to conduct a statistical analysis and compare the L1 versus the L90, and the L10 versus the L90 level. It is noted that under the UK method the analysis is set for an exponential FAST response and as such the time constant of the averaging method does not give true maximum or minimum absolute values that are obtained from using shorter averaging sampling times.

The amplitude modulation index using simplified alternative method of the statistical L1 minus L90 of each of the samples have been superimposed on the frequency spectrum to indicate the difference in the degree of modulation (see Figure 5) across the various bands.

From Figure 5 the modulation index in the dB(A) level is 9 dB whilst at the blade pass frequency the modulation index is 20 dB.

We undertook the evaluation of the alternative method utilising a number of different wind turbine measurements from the Cape Bridgewater study (we have over 9 TB of recorded data) to determine the statistical results for the alternative analysis and also at the same time undertook the analysis by the improved Den Brook methodology.

Using the L1 level minus the L90 level for Cape Bridgewater results we found the quick analysis method to agree with the UK method when applied to individual 1/3 octave bands.



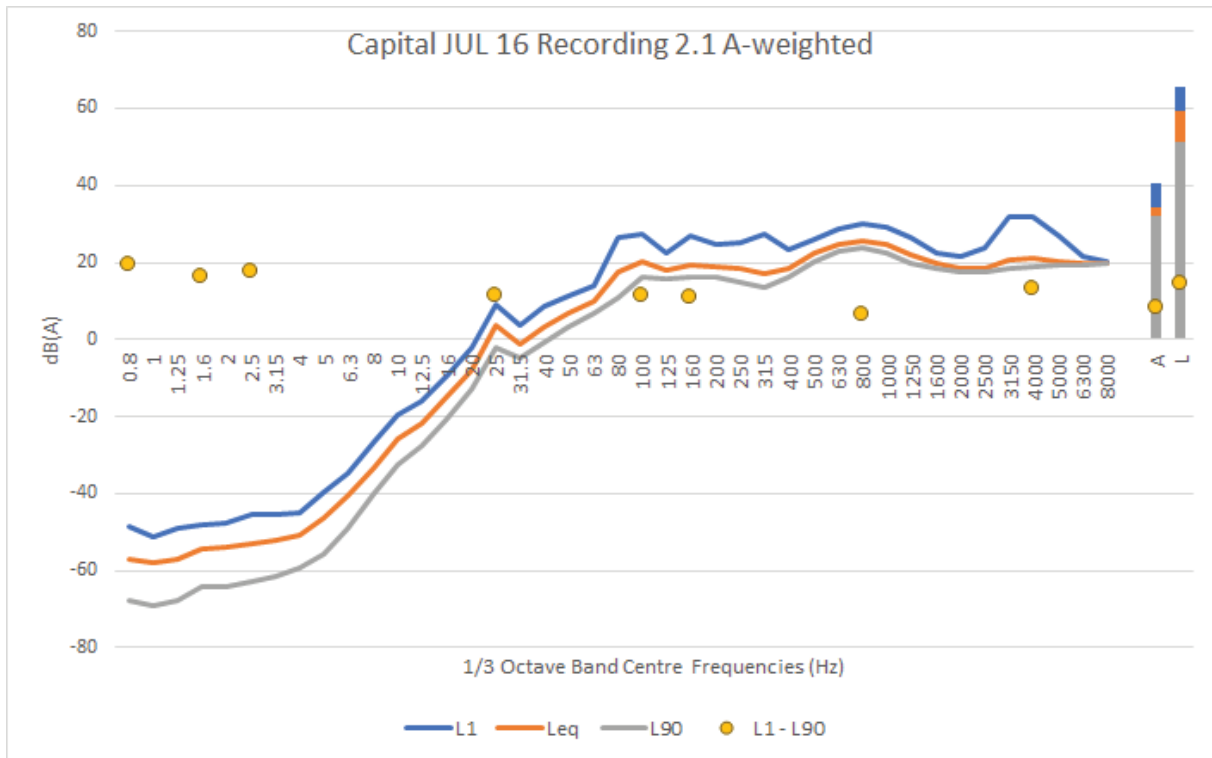


Figure 5: Amplitude Modulation derived from alternative method

#### 4. DISCUSSION

The A-weighted Leq level is typically used for environmental assessments in relation to wind turbine noise. The operation of a wind turbine involves a modulation of the amplitude with authorities claiming that “amplitude modulation” is inherently included in the Leq level.

However, the degree of modulation of turbine can vary significantly with residents identifying the presence of audible modulation can at times be expressed as “excessive modulation”

On the basis of audible noise, the modulation index used in the UK is evaluated on a dB(A) basis and can be extended to address noticeable 1/3 octave band peaks in the A-weighted spectrum. This method is used for assessment of the external noise level.

What constitutes excessive modulation and for how long in time is excessive modulation unacceptable govern the degree of analysis to be undertaken.

Consider the determination of the modulation index under the UK method for a wind turbine operating at 17 rpm on a dB(A) basis there would be 8 or 9 pulses per 10 seconds for which an average is determined. Extending the analysis to a 10 minute sample would need to determine the modulation depth at least 480 times. Utilising the alternative method gives the modulation index in a significantly shorter amount of time that becomes even more efficient if one considers determining the modulation index over an entire night.

Many of the noise complaints from residents relate to the wind turbine noise interfering with sleep (occurring inside the dwelling). As the attenuation of the building is not linear across the frequency spectrum the dB(A) value is not appropriate for evaluating internal environments. Applying the alternative method to a Linear (Un-weighted) spectrum of the above signal leads to the following result.

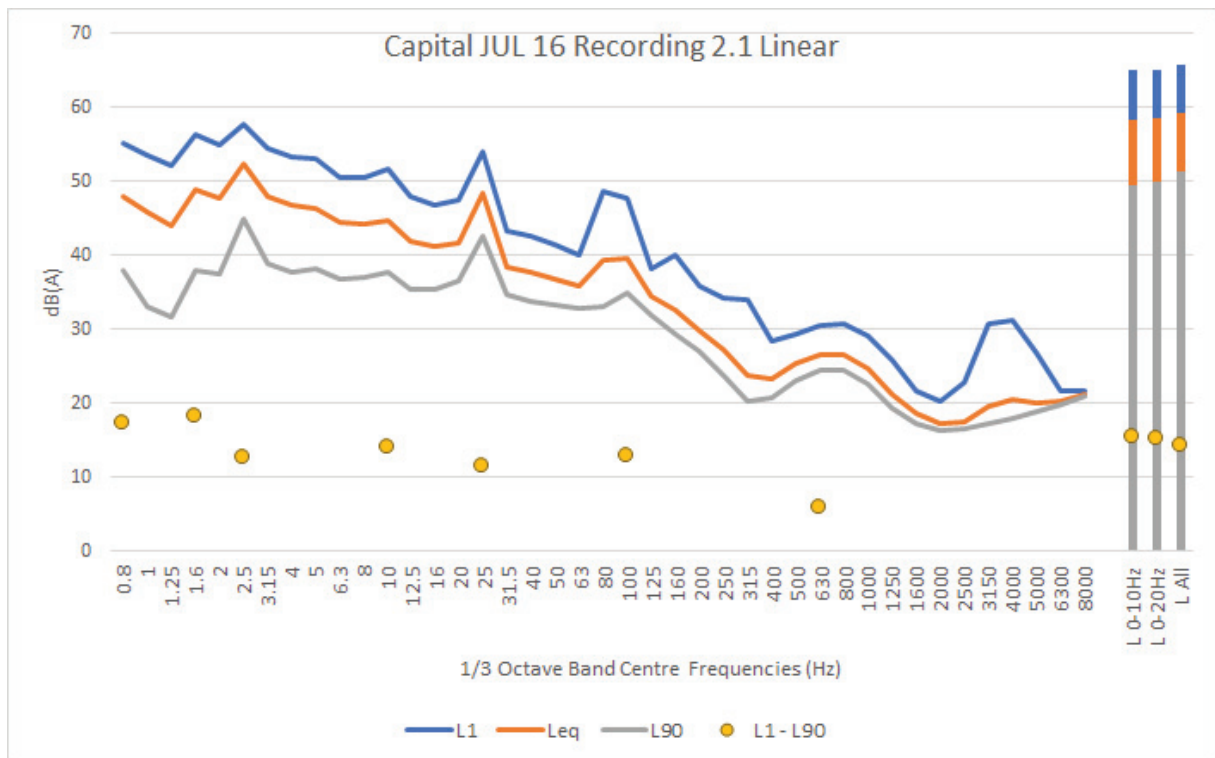


Figure 6: Linear (Unweighted) statistical results and Modulation Index

Figure 6 reveals a significantly greater depth of modulation occurred in the infrasound region and controls the modulation of the Linear level. The 2.5 Hz 1/3 octave band represents the 3<sup>rd</sup> harmonic of the blade pass frequency.

The blade pass frequency and in the above example the 3<sup>rd</sup> harmonic lie in the critical region for fluctuation identified by Zwicker and Fastl that in turn leads to a heightened annoyance. Is the fluctuation the dominant component responsible for the excessive modulation?

We have since applied the alternative analysis method to other forms of industrial noise where it has been established there is infrasonic energy giving rise to disturbance.

Measurements using high-performance recording of dance music and a dance party were undertaken where the predominant peak in terms of spectrum characteristic appears at 50 Hz, but the 50 Hz, such as being modulated at a rate of approximately 3.3 Hz. Due to the nature of the variation in the music level at such dance parties, there can be a significant difference in the modulation of the 50 Hz 1/3 octave band between different music tracks. Utilising a small sample where the levels were reasonably consistent throughout the track is more representative of that signal. Whilst not giving rise to a significant level of amplitude modulation there is a fluctuation in the 50Hz 1/3 octave band that is worth considering in terms of annoyance.

On this basis, recorded dance music that can give rise to disturbance to residents may not be the music at 50 Hz but the modulation of that 50 Hz component being the beat of the music, typically between 120 bpm and 230 bpm. If the bass pitch was a constant noise it would not be as disturbing to residents to that of a fluctuating bass beat, with the typical complaint being the “thump, thump, thump”.

A monitoring program by the coal mine operator found a 120 Hz tone from a large ventilation fan that modulates at an infrasound rate had a dramatic impact on two families involved in the acoustic investigation study into the disturbance complaints.

The relevant noise data and analysis for the above two noise sources are presented in the following link <http://acoustics.com.au/media/ICA2019AM04.pdf>.

## 5. CONCLUSIONS

“Amplitude Modulation” typically associated with wind turbines varies over time as a result of different wind speeds and changing power output. The degree of modulation on the dB(A) level can

vary significantly with higher modulation depths identified as excessive amplitude modulation.

What constitutes excessive modulation, and how long the occurrence of excessive modulation requires a correction to the A-weighted Leq level, has not been established. If a modulation index greater than 3 for say 10% of the night represents the necessity to add a penalty of +x dB to account for the subjective impact then a more efficient analysis method is required than either of the current UK methods.

The alternative method using statistical analysis presented in this paper has been found to be a relatively straightforward and simple method to evaluate “amplitude modulation” or “fluctuation”, not only for wind turbines, but has been used for other noise sources exhibiting pulsations occurring at an infrasound rate.

## ACKNOWLEDGEMENT

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