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Article

Wind Farm Noise—Modulation of the Amplitude

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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 wind speed at the turbine blades. The variations in the amplitude of the sound being emitted can be significant at receiver locations both as an audible and inaudible sound. The modulation of the A-weighted amplitude of the acoustic signature for wind turbines is often referred to as "amplitude modulation". Criteria have been proposed in the UK to define "excessive amplitude modulation". In a technical sense, the general descriptor for wind turbine amplitude modulation is incorrect. The correct term for the variation of the A-weighted level is modulation of the amplitude. The rate of the modulation of the dB(A) level occurs at the blade pass frequency, which is in the infrasound region. Turbines can exhibit amplitude modulation in the low frequency region. The differences between amplitude modulation and modulation of the amplitude occurring at an infrasound rate are discussed in the context for an environmental assessment of a wind farm with respect to permit conditions and a simplified method of assessment with respect to the Modulation Index.

Keywords: wind turbine noise; amplitude modulation; modulation index; fluctuation

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Citation: Cooper, S. Wind Farm Noise—Modulation of the Amplitude. *Acoustics* **2021**, *3*, 364–390. https://doi.org/10.3390/acoustics3020025

Academic Editor: Jian Kang

Received: 30 April 2021
Accepted: 28 May 2021
Published: 1 June 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

1. Introduction

The operation of a wind turbine generates non-steady broadband sound that exhibits fluctuations at the blade pass frequency rate. For modern turbines, the blade pass frequency occurs between 0.65 and 0.8 Hz. The blade pass frequency occurs in the infrasound region, i.e., less than 20 Hz.

In an ideal situation, the angle of the turbine blades (the blade 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 wind direction(s), there is usually a substantial delay 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 depower the turbines), the blades are not positioned at an ideal/efficient angle, and under those scenarios have been found to generate higher levels of pulsations [1] that correspond to a higher level of annoyance [2,3].

There are different types of wind turbine installations around the world that can vary from single individual turbines scattered across a large area in which there may be dwellings in relative close proximity to an individual turbine, groups of turbines that may be located on an elevated position that, under certain prevailing conditions, may generate an enhanced noise signature to downwind locations, and large-scale wind farms (40–120 turbines) having turbines covering a large area that can result in enhanced propagation in downwind situations and also create phasing issues with respect to noise from multiple turbines that do not operate at a synchronized speed.

The typical variation in the noise generated from an operational turbine is often described as a "swish" if one is in proximity to the turbine. At locations further removed from the turbine, the additional distance attenuates the high frequency components, resulting in a change of the spectral content of the noise, with the turbine noise often being described as a "whoosh" or even a "thump". The "swish", "whoosh", and "thump" occur at a timing period being the reciprocal of the blade pass frequency (e.g., for a three-bladed turbine operating at 17 rpm, the blade pass frequency is 0.85 Hz, which gives a pulse every 1.18 s).

2. Modulation of Wind Turbine Noise

There are different terms used for describing the modulation of the amplitude of the dB(A) level emitted by wind turbines. The change in descriptions/definitions of to the audible characteristics of modulated wind turbine noise creates confusion when reviewing different standards or guidelines for assessing wind turbine noise.

ETSU-R-97 (The Assessment and Rating of Noise from Windfarms) [4] is a base document referenced in the UK and Australian Standards/Guidelines for wind farms. ETSU-R-97 defined "blade swish" as the amplitude modulation at the blade passing frequency of the aerodynamic noise caused by the passage of blades through the air. ETSU-R-97 noted that there was insufficient data available at the time to formulate an accurate measurement methodology for blade swish, and that further research was required to enable proper measurements and assessment (of blade swish) to be devised.

"Amplitude modulation" (in relation to noise) from wind turbine installations is often expressed as relating to the change in amplitude (sound pressure level) occurring at the blade pass frequency, and may also be called swish, whoomph, thump, or whoosh [5].

Pedersen [6] identified listening tests for wind turbines to distinguish a beating noise, and described the beating noise as amplitude modulation: "the sound pressure level rises and falls with time". The most annoying noises from experimental studies were described as "swishing", "lapping", and "whistling", attributed to the aerodynamic noise, and "descriptions of a time varying (modulated) noise with high frequency content".

The attenuation of high frequencies over distance is significantly greater than that of low frequencies, leading to a different spectrum shape for receiver locations removed from wind turbines.

In looking at the modulation of the low frequency sound of wind turbines, van den Berg [7] noted that the audibility of the 'beating' character was stronger at night because of a stable atmosphere at night. Whilst van den Berg's work has been primarily associated the enhancement of the beating effect as a result of changes in the atmosphere, what has often been overlooked is van den Berg's suggestion that the level of the modulation of the amplitude can be quantified by the modulation depth ("MD") or measured 'peak to trough' sound pressure level, with higher MDs equating to greater levels of modulation. Van den Berg considered the modulation of low frequency of wind turbine noise to annoyance by reference to 'fluctuation', as defined by Zwicker and Fastl [8], and also used by Pedersen [6].

The Summary of the Department of Trade & Industry (DTI) report on the measurement of low frequency noise at three UK wind farms [9] found that the common cause of complaint was not associated with low frequency noise, but "with the occasional audible modulation of aerodynamic noise especially at night", leading to a recommendation to develop a means to assess and apply a correction for aerodynamic modulation of the wind turbine noise.

Fukushima [10] expanded the van den Berg modulation depth concepts to reveal that the modulation depth can be quantified by subtracting the L95 (noise level exceeded for 95% of the time) from the L5 (noise level exceeded for 5% of the time) over a specified time period.

Standards/Guidelines used in Australia and New Zealand for wind turbines utilize the dB(A) parameter for assessment/compliance purposes, and may require adjustments for the presence of Special Audible Characteristics. In Australasia, the modulation of the sound pressure level (amplitude) described above has become "amplitude modulation". Some state regulatory authorities in Australasia, re quire a correction to the overall noise level assigned to a windfarm where there is a presence of "Amplitude Modulation" may require a correction to the A-weighted level, although in some states "amplitude modualtion" is completely ignored.

In Clause 5.3.1 of New Zealand Standard 6808:1998 [11], special audible characteristics are described as clearly audible tones, impulses, or modulation of sound pressure levels. In the 2010 version of the New Zealand Standard [12], special audible characteristics are identified in Clause 5.4 as including tonality, impulsiveness, and amplitude modulation.

Appendix B of NZS 6808:2010 [12] expands special audible characteristics to include asynchronous or synchronous beating. Appendix B3.1 of NZS 6808:2010 permits an adjustment of + 5 dB to the measured sound pressure level by an enforcement officer if the wind farm creates sound with a clearly audible amplitude modulation. Appendix B3.2 of NZS 6808:2010 identifies that modulation special audible characteristics are deemed to exist if the measured A-weighted peak to trough level exceed 5 dB on a regularly varying basis, or if the measured third-octave band peak to trough level exceeds 6 dB on a regular basis in respect of the blade pass frequency. Within NZS 6808:2010, there are two different descriptors of modulation of the amplitude.

In the 2003 version of the South Australian EPA's Wind Farm Guideline [13], there is no assessment of amplitude modulation. Under annoying characteristics, there is a claim that the guidelines have been developed with the fundamental characteristics of noise from a wind farm taken into account, including the aerodynamic noise from the passing blades (commonly termed 'swish').

The 2009 version of the SA EPA's guideline [14] maintained the same position of no correction for modulation, despite the fact that there can be significant levels of modulation from wind farms in South Australia that give rise to a variation in the subjective annoyance of the turbine noise. The SA Guideline contradicts the provision of a correction to account for amplitude modulation, as utilized in the UK [15–18].

In 2019, the SA EPA issued a draft wind farm noise guideline for public comment [19] and maintained the position of no correction for modulation, despite the significant debate in the UK of corrections to account for amplitude modulation and excessive amplitude modulation, and the publication by Lenchine (an employee of the SA EPA), which stated that audibility of amplitude modulation frequently evokes the need for an additional penalty to be added to the measured level [20].

The Delta report "Low Frequency Noise from Large Wind Turbines" [21] on page 30 refers to a report in Danish [22] suggesting swish noise is best approximated by sine wave modulation, with a suggestion of just noticeable modulation that contradicts the concept of fluctuation (modulation at infrasound rates) presented by Zwicker and Fastl utilizing sine wave modulation for the modulating signal that was not attributed to wind turbine noise.

The concept of audibility of swishing noise presented in Figure 15 of the Delta report (Ref. [21]) refers to the NASA Wind Turbine Program [23,24], but fails to state that the results relate to external measurements and for a two-bladed downwind turbine.

The NASA wind turbine noise investigations did not use the terminology of amplitude modulation, but identified the infrasound regions to exhibit impulsive noise [23], which, in terms of the time signal, cannot be a sine wave modulation.

The above concepts raise the issue of different "modulation" impacts perceived by people external to their homes versus inside homes, as the spectral content will change due to the transmission loss of the building, as will the ambient noise levels. This highlights the fundamental question of utilizing external noise measurements for assessing the impact of wind turbine noise for residents.

Typical Turbine "Amplitude Modulation"

On an A-weighted approach, the amplitude (sound pressure level) 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, it can be significant.

Plotting the A-weighted values over time reveals the depth of the modulation of the signal. Large modulation depths determined using the assessment methods applied in the United Kingdom [15,16], may be described as "excessive amplitude modulation" or "enhanced amplitude modulation".

In 2014, a study undertaken at the Cape Bridgewater Wind Farm in SW Victoria (in Australia) [1] (now identified as Portland Wind Farm) was not a compliance test of a wind farm, but a study to investigate complaints from specific local residents. The study brief was restricted by the wind farm operator to determine specific wind and operation conditions that related to the complaints.

The Cape Bridgewater study had nine weeks of testing and included on/off testing where the entire wind farm was shut down in the day to permit high voltage cabling to be installed over a ten day period. The study had multiple locations being monitored at residential receivers (both inside and outside of dwellings) with additional monitoring on and around the wind farm.

Of significant benefit was the fact that the study team was given unlimited access to the wind farm, and given all of the wind farm's SCADA (Supervisory Control and Data Acquisition) information, allowing the author to consider variations in wind speed, wind direction, and operational turbine settings across the entire wind farm. Furthermore, the operator of the wind farm permitted the publication of a report (that was placed in the public domain) containing some of the SCADA information for specific tests.

There were no medical studies undertaken in conjunction with the Cape Bridgewater study.

In hindsight, the Cape Bridgewater study was possibly the first Soundscape Assessment of a wind farm, and is a valuable data source that has been used (and is still being used) by the author in determining the signature of wind turbine noise, for assessments of modulation, and for on-going subjective psycho-acoustic testing.

One outcome of the Cape Bridgewater study was the identification of modulation depth of the dB(A) value for different power setting scenarios in close proximity to individual turbines. Another outcome was that the main source of disturbance was not related to noise or vibration, but to "sensation", i.e., something the residents felt or sensed in their body.

The residents' diaries used throughout the study were cross-checked with the wind farm operational data (after the event) and shown to be in agreement with the Kelley report (in identifying the acoustic source of the annoyance) in relation to the NASA Mod-1 turbine [24].

Kelley et al. [24] identified the acoustic pulsations being emitted from the Mod-1 turbine (at the blade pass frequency), the level of sound above human perception thresholds, and the excitation of building/room modes in dwellings.

The Executive Summary of the Kelley report [24] stated that the perception of the complaints for the single Mod-1 turbine were similar to those obtained for current wind farm (multiple wind turbine) installations. The key findings in the Kelley report were that the annoyance was real and not imagined, and that the source of the annoyance was aerodynamic, involving the passage of the turbine blades through the lee wakes of the large, 0.5 m cylindrical tower legs. In some instances, the acoustic impulses transmitted through the air were being focused on the complainants' homes as a consequence of ground reflection and refraction by the atmosphere.

It is the combination of the modulation of the acoustic signal and the detection by sensitized residents of the signal (even when inaudible), together with the identification of the pulsing at an infrasound rate in the absence of any infrasound in laboratory studies, that has led to the rediscovery of Zwicker and Fastl's "fluctuation" [8] as an explanation for effects noted by residents in proximity to wind farms.

Figure 1 demonstrates the difference in noise downwind from a 2.2 MW REPower turbine (at Cape Bridgewater) for different power settings. In the normal course of monitoring wind turbines in rural areas, persons undertaking independent acoustic compliance testing have no material to identify the operating parameters of the turbines being measured, whereas in the Cape Bridgewater study, operating data for all turbines were provided.

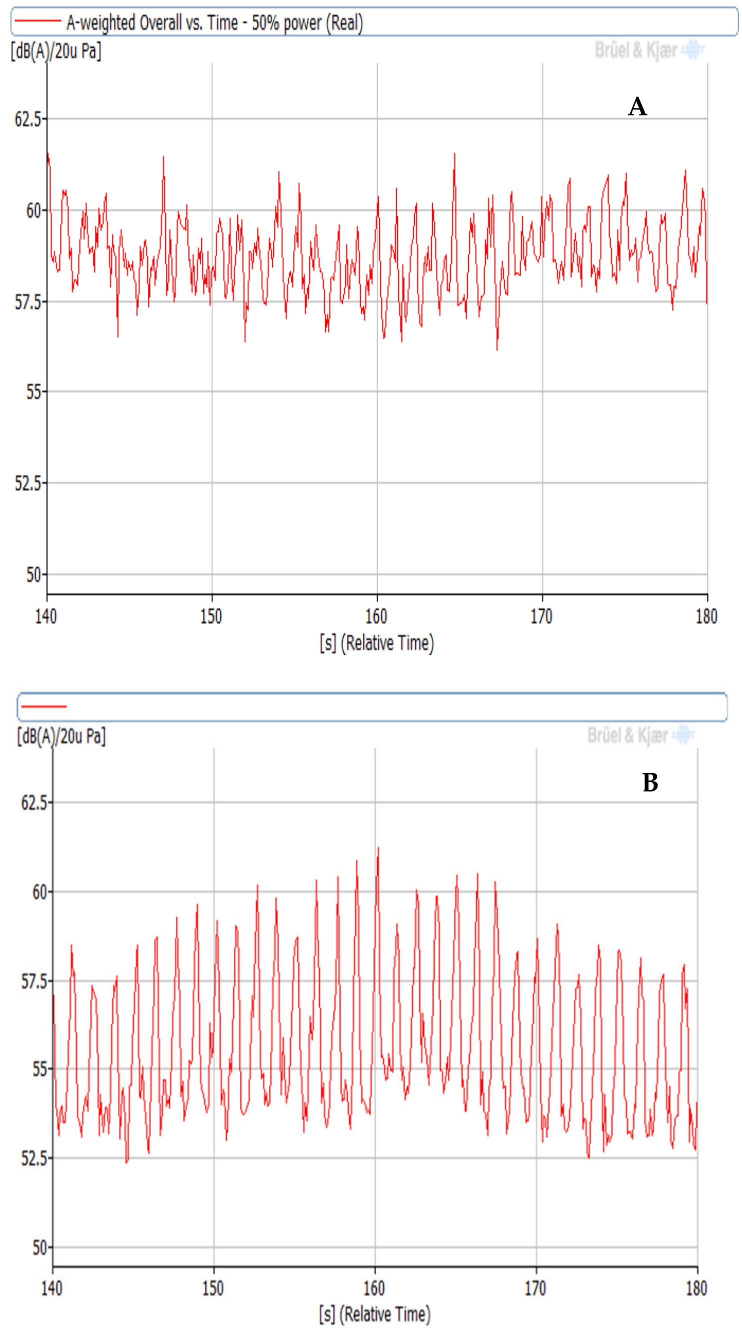


Figure 1. "Amplitude Modulation" for different power settings—(**A**) 50% power, (**B**) 14% power—Turbine 13, Location 7, CBW Study—ref [1].

The measurement results undertaken by the author (excludes the material in Figure 2) presented in this article utilized GRAS 40AZ microphones with B & K 2639 preamplifiers into a B & K LAN-XI modular Type 3050 data acquisition systems and Pulse Data Recorder at 135 ksamples/s and analysis on B & K Reflex or B & K Connect.

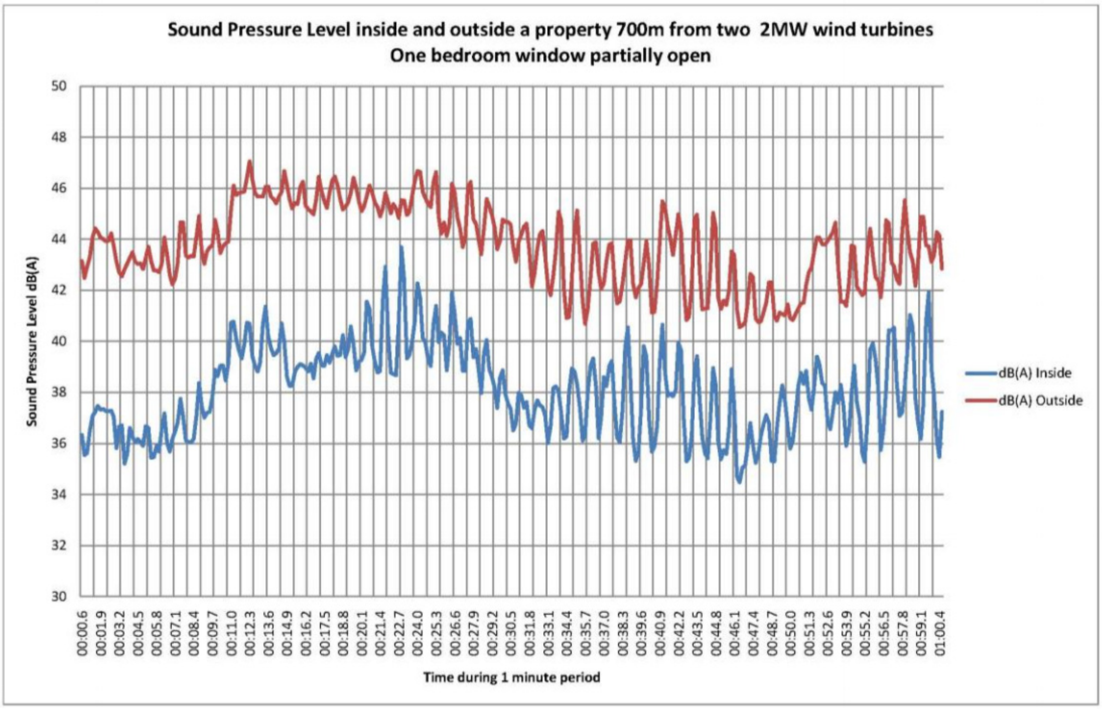


Figure 2. Simultaneous Measurements of "Amplitude Modulation" at Leonards Hill Wind Farm, Victoria, Australia [25], with permission of L Huson.

Both results in Figure 1 identify a modulation of the A-weighted level and the power output of the subject turbine (from the SCADA information)

At the 50% power setting, the modulation depth (as a peak to trough difference) is an average of 3 dB, whilst at the 14% power setting, the modulation depth varies from 4.5–7 dB.

Examining the time signals in Figure 1 does not identify a sine wave modulation.

Under the NZS 6808:1998 [11] (as specified in the planning permit for the Cape Bridgewater wind farm), the operation of the turbine at 14% power in Figure 1 would be classified as a special audible characteristic of modulation, and would require a penalty to the measured Leq or L90 level for that period of time.

Under the 2010 version of NZS 6808 [12], the continuation of the 14% power time signature in Figure 1 would be deemed to be "amplitude modulation" by an audible assessment, and modulation as a special audible characteristic by the variation in the A-weighted peak to trough level.

Whilst noise criteria specified for wind turbines are normally for outdoor locations, the impact of wind turbines is not related just to external environments. People live inside homes for parts of the day and tend to sleep indoors at night.

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. On an A-weighted basis, this can lead to significantly different levels of modulation, as shown in Figure 2, where the modulation of the time signature for this dwelling indoors is often greater than that observed outdoors [25].

3. Amplitude Modulation

The operation of a wind turbine gives rise to a variation in the noise as the blades rotate such that the noise is not a constant noise, but is subject to changes in the amplitude of the noise signal.

As mentioned above, the general assumption of modulation of the amplitude for wind turbines is that the modulation approximates a sine wave, with typical analyses of amplitude modulation also adopting that approach.

In the area of psychoacoustics and examination of the hearing mechanism, the term amplitude modulation has been used to describe broadband noise being modulation at a much lower frequency (with respect to the broadband noise). In terms of the technical definition of amplitude modulation, when qualified by the above description of the noise could be an acceptable approach for using the term amplitude modulation.

The problem that occurs with the general concept of amplitude modulation for wind turbines is the application in some regulatory documents for corrections to be applied to the A weighted value of the wind turbine noise. Due to the A-weighted value not being a dedicated or specific "carrier" frequency, it is suggested that the correct terminology with respect to general wind turbine noise should be "modulation of the amplitude". Whilst an alternative suggestion could be "periodic fluctuation of the noise level", that concept may not apply to wind farms due to intermittent "beating" because of phasing effects from multiple turbines or limited periods of modulation over the standard 10-min sampling period. Furthermore, in environmental regulatory policies, periodic fluctuation could be taken to mean cyclic operations (which is a different effect).

The use of the term "modulation of the amplitude", when considering the noise signature of wind turbines, permits one to then consider, in psychoacoustic terms, that the impact of the modulation of the amplitude is a special audible characteristic requiring an adjustment to the measured overall noise level for the wind turbine/wind farm.

3.1. Amplitude Modulation as a Sine Wave

The Cape Bridgewater Study identified a unique "turbine acoustic signature" that is different to the natural acoustic environment. The study found the principal effect identified by the specific residents was "sensation", i.e., something that was felt rather than heard.

The Cape Bridgewater Study found certain operations of the wind farm gave rise to greater impacts, with subsequent investigations identifying changes in power output and modulation related to the increases in the perceived sensation. Those investigations have led to question whether there are infrasound sounds present, and question the nature of "amplitude modulation".

The term amplitude modulation (AM) generally refers to the technique used in telecommunications to transmit information (message) using radio frequency electromagnetic waves by modulating the amplitude of a high frequency carrier wave (that is much higher than the frequency of the signal of information e.g., an audio tone of 1000 Hz added to a carrier frequency of 702,000 Hz).

For telecommunications, the information signal is embedded in the carrier wave by modulation of its amplitude using a modulation circuit containing a multiplier to create the resultant signal shown in Figure 3. The embedded signal is extracted using a demodulation circuit.

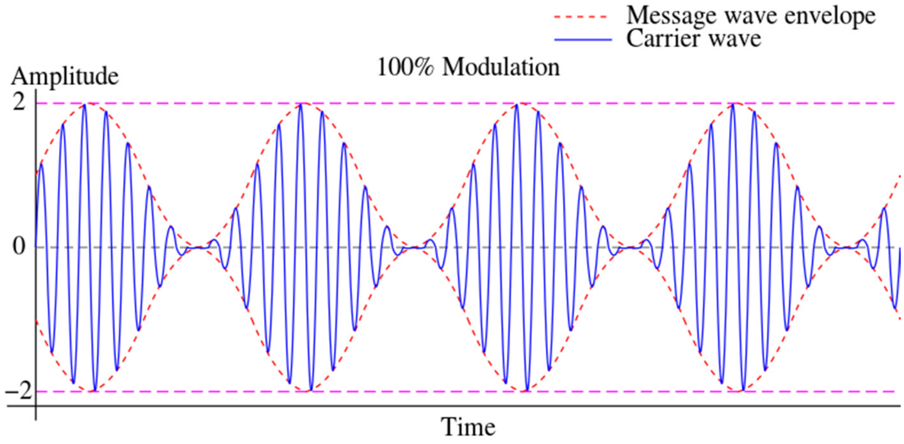


Figure 3. Typical representation of AM for a radio wave [26].

In AM radio, the high frequency carrier wave is modulated by the audio signal (i.e., music and voice) which is demodulated in the AM radio to extract the original audio component that is then generated as sound on a speaker or headphones.

However, the term amplitude modulation in a broad sense can apply to any signal which changes its amplitude (generally on a periodic basis) over time.

For example, if the volume of a pure tone issued from loudspeaker which is turned up and down on a periodic basis over the entire sample time, then the resultant tone could be described as having a modulated amplitude. The rate of modulation would be that set by the pattern of turning the volume up and down.

Common notation for amplitude modulation describes the carrier signal $c(t)$ and the modulation signal $m(t)$ as having the following mathematical relationships:

$$c(t) = A_c \sin(2\pi f_c t)$$

$$m(t) = A_m \sin(2\pi f_m t)$$

where f_c = the carrier frequency
f_m = the modulation frequency
A_c = the carrier amplitude
A_m = the modulation amplitude

The modulated signal is created by adding an offset to the modulation and multiplying this by the carrier wave, where the amplitude modulation signal may be described as:

$$y(t) = [1 + m(t)] \cdot c(t)$$

$$y(t) = [1 + A_m \sin(2\pi f_m t)\ ] \cdot\ A_c \sin(2\pi f_c t) \quad (1)$$

It can be shown that $y(t)$ can be represented by the sum of three sinusoids.

$$y(t) = A_c \sin(2\pi f_c t) + \frac{A_c A_m}{2}[\sin(2\pi(f_m + f_c)t) + \sin(2\pi(f_m - f_c)t)] \quad (2)$$

The resulting frequency content of the AM signal can be deconstructed into a tone at the carrier frequency f_c and two tones at $(f_m + f_c)$ and $(f_m - f_c)$ known as sidebands.

The dB(A) overall noise from wind turbines is an audio signal which in itself is a combination of frequencies that vary across the audio spectrum and is not a steady carrier frequency.

The A-weighted level is derived by the application of a series of filters across the audio spectrum.

The A-weighted sound level represents the overall level of the pressure signal after being passed through multiple frequency filters. A sound pressure level of 40 dB(A) can be obtained for a variety of different noise sources, e.g., a low pitch transformer hum, the operation of a power drill, a washing machine, an electric kettle that is boiling, an air conditioner or a triangle, yet audibly, they have different spectral characteristics.

Accordingly, in an electrical engineering sense, the modulation of the A-weighted value cannot be described as amplitude modulation because the A-weighted signal is not a carrier wave having a distinct single frequency. The A-weighted signal is a resultant sound pressure level of multiple frequencies (after passing through a series of electrical filters).

Considering the above discussion and current usage of amplitude modulation (described in the preceding section), a more appropriate definition for modulation of the amplitude wind turbines would be changes in the level of the dB(A) value where modulation occurs at an infrasound rate (i.e., the blade pass frequency) or modulation of the amplitude.

3.2. Alternative Concepts of Amplitude Modulation Used in Acoustics

Not all acousticians have a background in electrical engineering to understand the nuance of amplitude modulation.

In audiological terms, hearing assessments utilize a series of tones at different frequencies to determine a person's hearing loss, whilst some audiological measurements have utilized broadband high-frequency sounds which are then modulated at a lower rate (where the broadband sound that is being modulated is many multiples higher than the modulation rate). The terminology used for those experiments has also been expressed as "amplitude modulation", but with the specific qualification that it is the modulation of a broadband noise over a certain frequency range, e.g., 1/1 or 1/3 octave bands.

In *Psychoacoustics*, Zwicker and Fastl [8] used both broadband noise and pure tones of 1 kHz which were modulated at a rate that was significantly lower than the frequencies of concern. On that basis, they provided a qualification of their technique which appears in their descriptions for "Fluctuation" and also "Roughness".

It would appear that in acoustics, there has been a "borrowing" of terminology (without an acknowledgement or explanation of the source) to which qualification as to what constitutes amplitude modulation in an acoustic sense is required.

Hence, in consideration of wind turbine noise, it is the author's practice to use the wording "modulation of the amplitude" to convey what is being assessed, to not contradict the general definition, in an electrical engineering sense, of amplitude modulation.

3.3. Specific Turbine Tones—Amplitude Modualtion

In dealing with modulation of audio frequencies including infrasound associated with the turbines, the difference between the signal and the carrier is much smaller (than the radio wave), such that in many cases, the amplitude modulation of the time signal is not obvious.

Appendix V of the Cape Bridgewater study [1] provided a Matlab analysis of infrasound and low frequency spectra from turbines.

For a theoretical application of amplitude modulation, when restricted to the acoustic frequencies of concern for a wind turbine assessment, the following analysis considers the application of a carrier tone of 31.5 Hz and a sine wave modulation tone of 0.8 Hz, as shown in Figures 4 and 5.

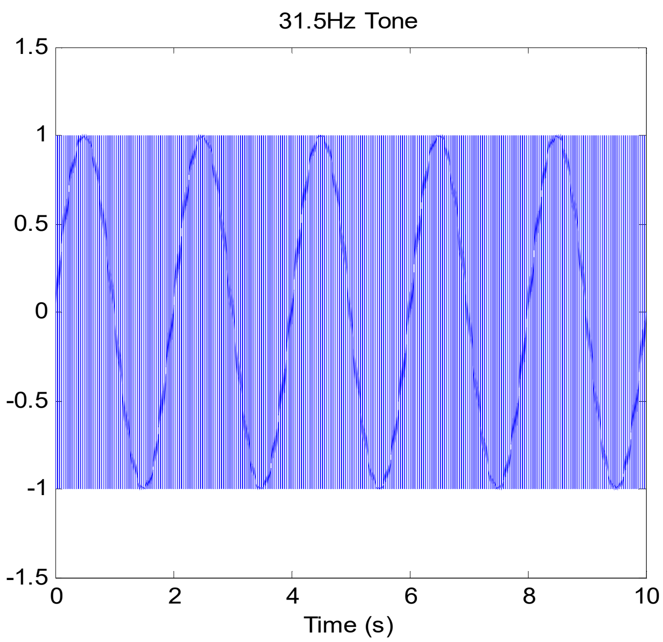


Figure 4. 31.5 Hz carrier tone ($c(t)$:f_c = 31.5; A_c = 1).

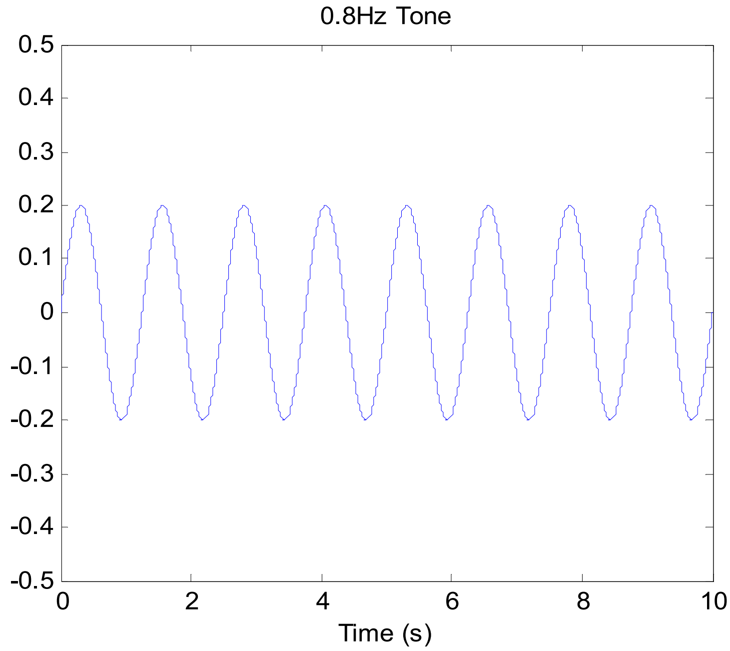


Figure 5. 0.8 Hz modulation tone ($c(t)$:f_m = 0.8; A_c = 0.2).

An analysis of the modulation and the carrier signals in Figures 4 and 5 resulted in the modulated time signal (and the expanded view) shown in Figure 6, with the corresponding FFT in Figure 7.

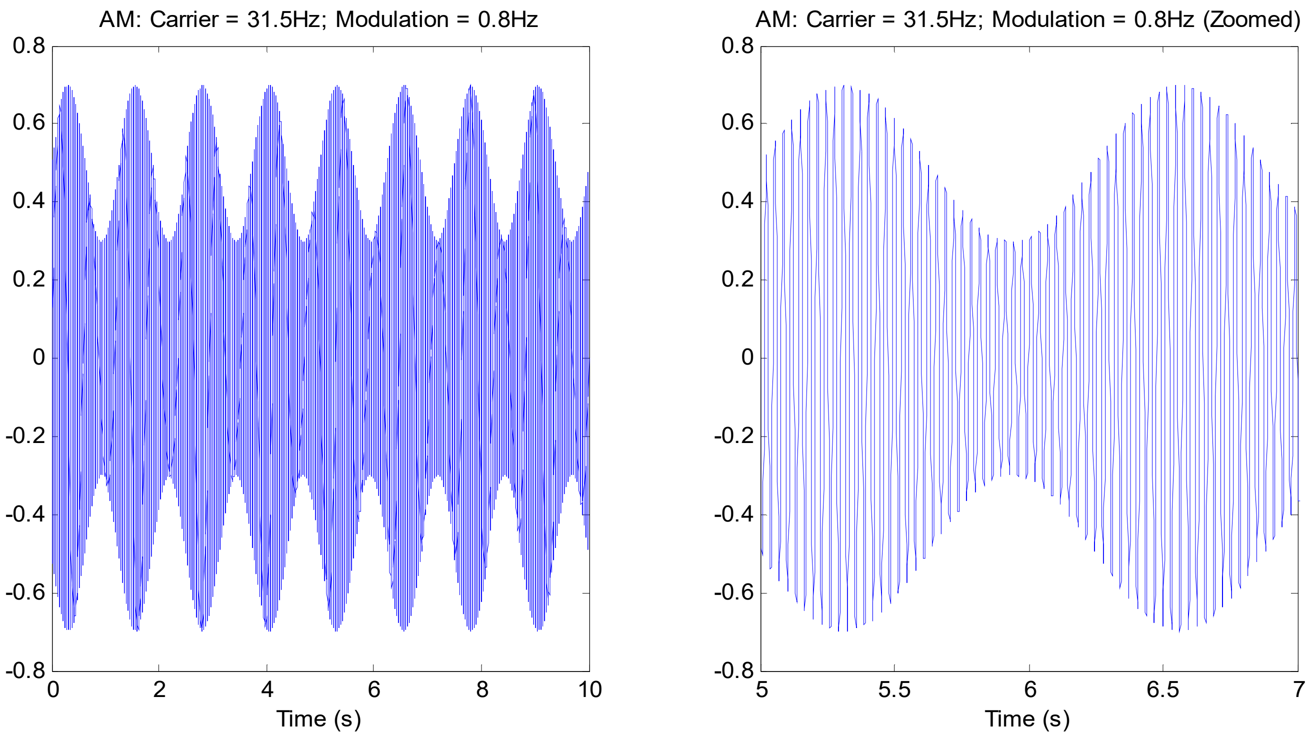


Figure 6. AM signal [$y(t)$: (f_c = 31.5; A_c = 1) (f_m = 0.8; A_m = 0.2).

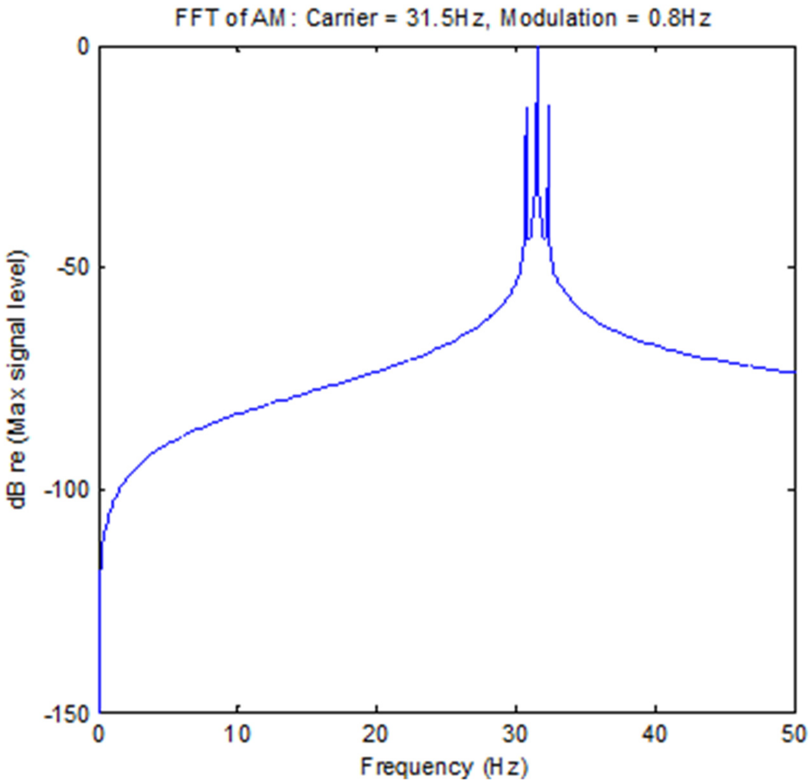


Figure 7. FFT of AM signal $y(t)$: (f_c = 31.5; A_c = 1) (f_m = 0.8; A_m = 0.2).

The 31.5 Hz tone was used as a carrier wave and modulated by the 0.8 Hz tone. This resulted in the time signal shown in Figure 6, which shows that the amplitude of the 31.5 Hz tone had been modulated at the 0.8 Hz rate. This corresponds to the following time signal from Equation (1):

$$y(t) = [1 + A_m \sin(2\pi f_m t)\,]\cdot A_c \sin(2\pi f_c t) = \left[\frac{1}{2} + (0.2)\sin(2\pi(0.8)t)\,\right]\cdot \sin(2\pi(31.5)t)$$

Or by substituting the modulation and carrier signal values into Equation (2):

$$\begin{aligned} y(t) &= \sin(2\pi f_c t) + \tfrac{A_c A_m}{2}[\sin(2\pi(f_m + f_c)t) + \sin(2\pi(f_m - f_c)t)\,] \\ &= \sin(2\pi(31.5)t) + \tfrac{0.2}{2}[\sin(2\pi((0.8) + (31.5))t) + \sin(2\pi((0.8) - (31.5))t)\,] \\ &= \sin(2\pi(31.5)t) + 0.1[\sin(2\pi(32.3)t) + \sin(2\pi(30.7)t)\,] \\ &\mathbf{= \sin(2\pi(31.5)t) + 0.1\sin(2\pi(32.3)t) + 0.1\sin(2\pi(30.7)t)} \end{aligned}$$

This is shown in the FFT result in Figure 7.

The nature of the pressure signal with respect to acoustic analysis could be expressed as repeated transients/pulses. The pressure signal approaches the signature of pulse width modulation where the duty cycle is relatively low.

By taking the fundamental and first three harmonics of the FFT for a pulse with wave at 0.8 Hz (20% duty cycle) and linearly adding those components, one obtains a fourth harmonic approximation to a 20% duty cycle pulse wave trace, as shown in Figure 8.

The above analysis is on the basis that the original signals were sine waves, and that there were no phase differences between the harmonics; it is similar to the derived waveform provided by Walker [26] for digitally synthesizing infrasound.

In [27], Walker utilized Leq FFT results from the Cape Bridgewater study to derive a time signal. A comparison of the derived time signal with the original time signal revealed different results [28].

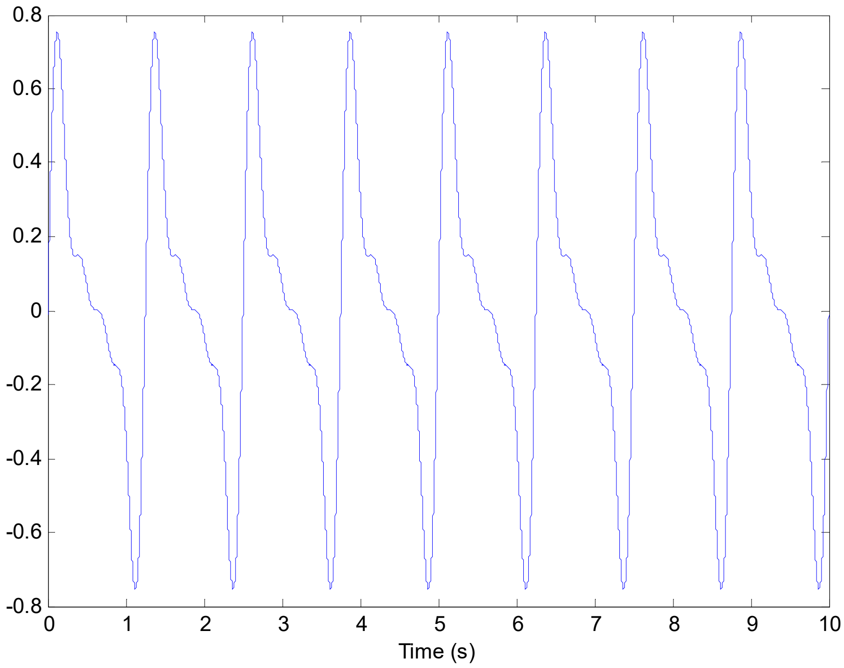


Figure 8. Fourth harmonic approximation to 20% duty cycle pulse wave.

The time signal of the blade pass frequency of a turbine is not a sine wave, but a series of pulses.

Apart from the phase issues and the fact that the wind turbine time signal is not a sine wave modulation, there is also the possibility that for the Cape Bridgewater residential location, the house in question is not influenced by just a single turbine, but by multiple turbines which are not in sync with one another.

There are different opinions as to the source location of significant short-term pressure changes during the swept path of the turbine blades when using acoustic cameras, as shown by Oerlemans [29].

Doolan [30] identified issues with acoustic cameras experiencing different path lengths, and therefore not accounting for phasing.

Zajamsek [31], in investigating the blade-tower interaction for different blade to tower distances, provided both the measured and simulated ensemble averaged acoustic pressure waveforms for an experimental rotor rig. Zajamsek (see Figure 13 in ref [31]) provided acoustic pressure time traces that observed that the pulsations associated with the blade/tower interaction were not sine waves.

Swinbanks [32] noted that the pulsations on the time signature of wind turbine noise cannot be called sinewave modulation. Dependent upon the time weighting of the signal (to depict different rise onset and decay times of the pulse), the pulsations could be called bursts of limited modulation.

Figure 9 shows the time signal of Figure 8 as the modulation of a 31.5 Hz tone. The FFT (Figure 10) shows multiple side bands corresponding to the spectrum of the modulated signal centered around the 31.5 Hz tone.

In the case of AM modulation where a tone is modulated, a frequency analysis will show the spectrum of the modulation signal as side bands around the carrier frequency. This is well described by detailed AM modulation theory, and as analysis is not presented here. However, the result of the outcome is demonstrated by the preceding quantitative analysis.

Translating the theoretical AM exercise of the pulsed signal to the real world, Figure 11 shows the measured modulation in proximity to Turbine 13 at Cape Bridgewater, and reveals multiple sidebands (at the blade pass frequency) around a carrier frequency of 31.6

Hz. This carrier frequency was attributed to the speed of the output shaft of the gearbox in the nacelle of the turbine (REpower MM82-2MW).

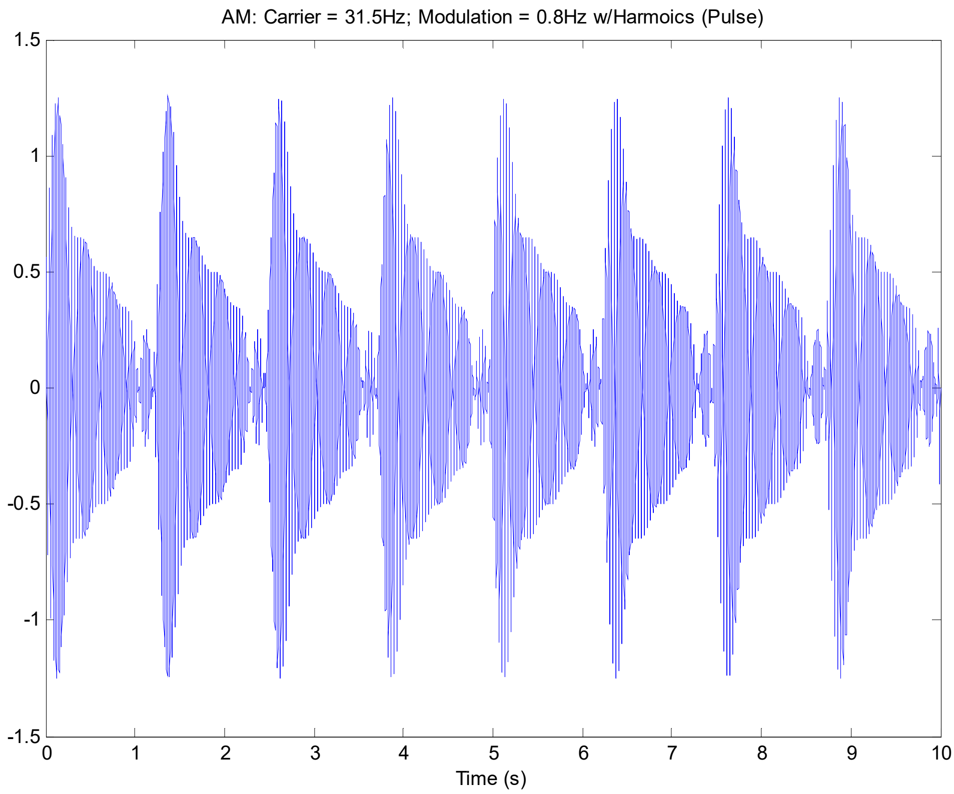


Figure 9. AM signal ($y(t)$; (f_c = 31.51 A_c = 1)).

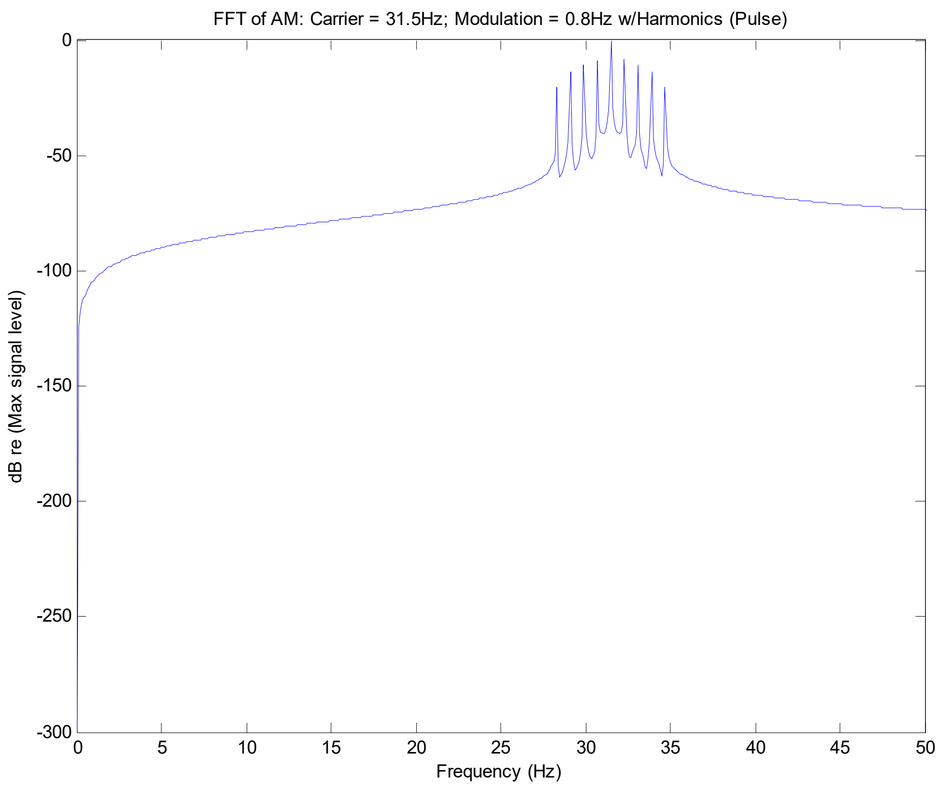


Figure 10. FFT of AM. Signal $fc =$ (modulation using Figure 9).

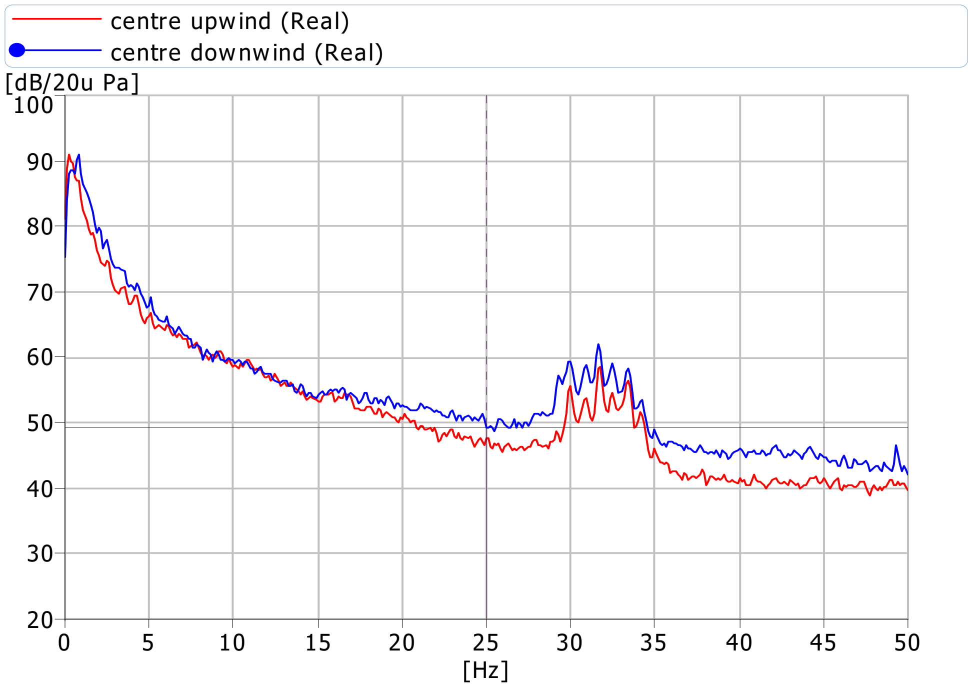


Figure 11. FFT in proximity to Turbine 13 at Cape Bridgewater Wind Farm reference [1].

Other turbine makes/models exhibit similar sidebands but with different carrier frequencies. For example, at the Capital wind farm (in NSW, Australia) the Suzlon S88-2.1MW turbines emit a carrier frequency of around 24.5 Hz and exhibit sidebands around that frequency spaced at the blade pass frequency.

Figure 12 shows the presence of the modulation external to house 87 in the Cape Bridgewater study, but at a distance of 1570 m from the nearest turbine.

The measurement results in Figure 12 are simultaneous Leq FFT 10 min samples for both a ground plane microphone and a microphone 1.5 m above ground level. The measurements on each graph were taken 1 h apart. The 6 AM measurement (blue trace) was with the turbines operating, whilst the 7 AM measurement (bred trace) occurred during a wind farm shutdown (for high voltage cable work at the substation) under similar weather conditions.

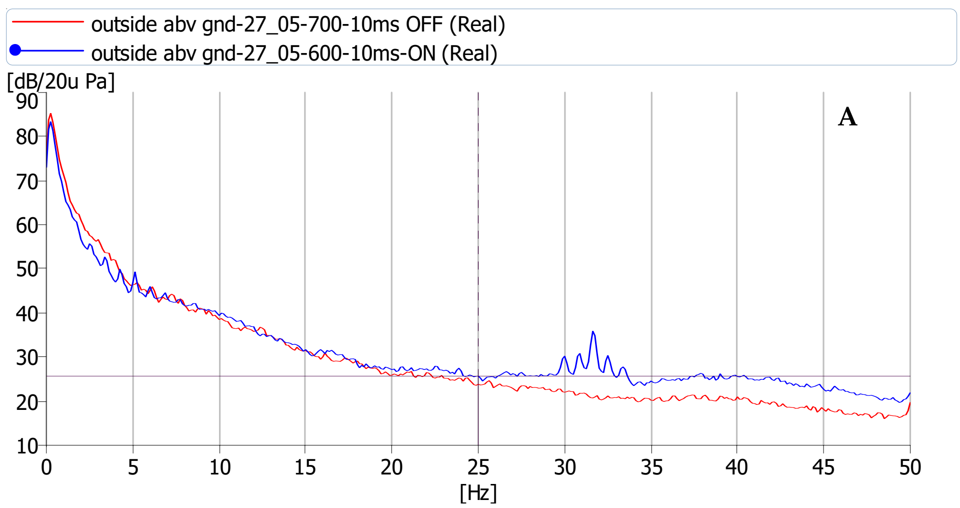


Figure 12. *Cont.*

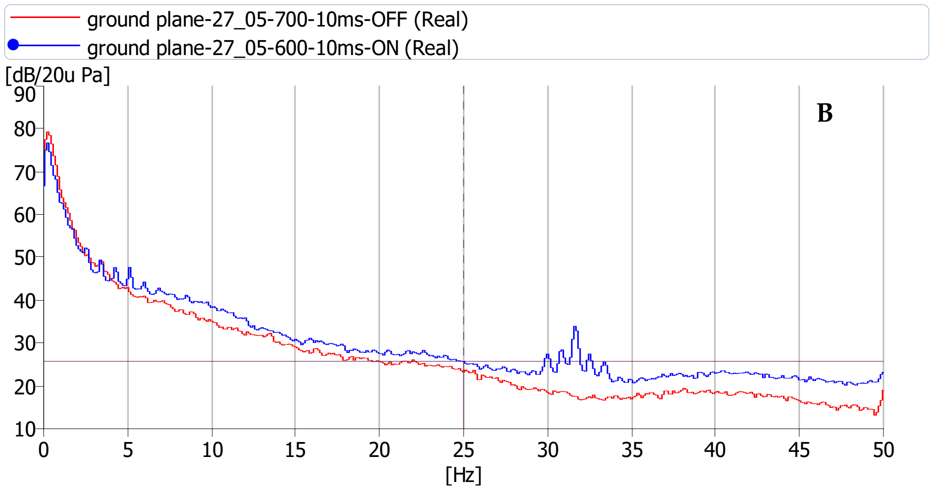


Figure 12. Ground Plane (**A**) and 1.5 m AGL (**B**) external to House 87 at Cape Bridgewater [1].

From the above information, it can be seen that narrow band analyses of the low frequencies have the potential to identify the operation of a wind farm by reference to the presence of amplitude modulation (for this example, around 31.5 Hz) and to identify discrete tonal components at multiples of the blade pass frequency (in the infrasound region) that are not present when the turbines are not operating.

The above frequency spectra are presented using Linear (unweighted) frequency analysis. An issue arises in considering the above amplitude modulation if using the A-weighted spectra, because the attenuation of the A-weighting curve is −39 dB for the 31.5 Hz octave band.

Figure 13 provides the Linear FFT analysis results (for the same time period as Figure 12) for two locations inside the dwelling, and shows the presence of the amplitude modulation and the discrete tonal components at multiples of the blade pass frequency.

Examination of the frequency spectra of turbines in the mid- and high-frequency bands at residential receivers did not reveal discrete frequencies to which the electrical engineering definition of AM would apply. Considering that the use of 1/3 octave band measurements covers a range of frequencies, then whilst amplitude of the mid-frequency 1/3 octave could be modulated (as swish noise), it is incorrect to identify such noise as amplitude modulation because there is no distinct carrier frequency.

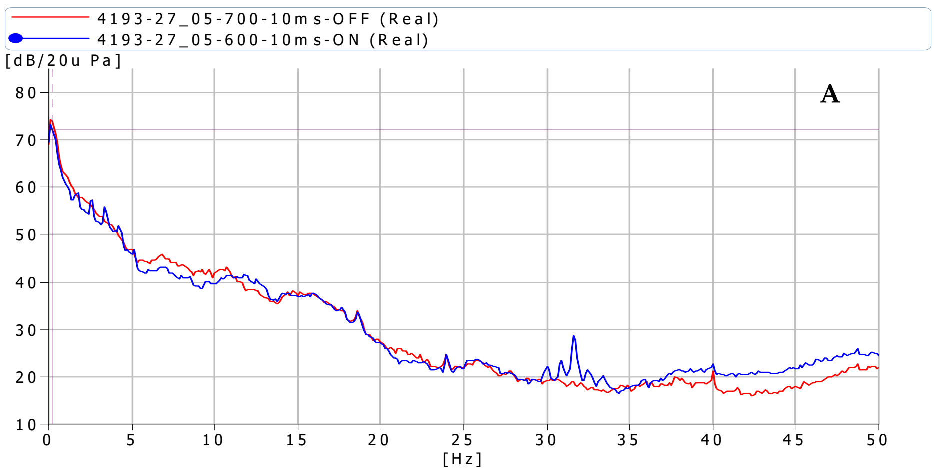


Figure 13. *Cont.*

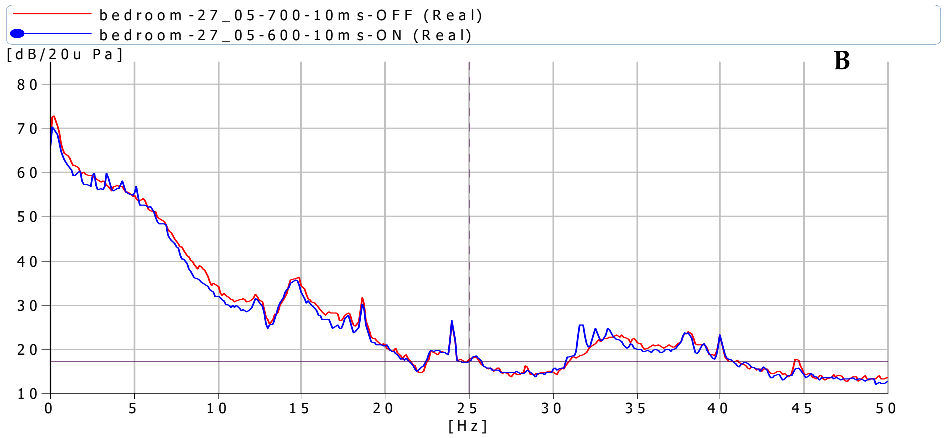


Figure 13. Internal measurements at House 87 corresponding to external measurements shown in Figure 12. (**A**) in living room and (**B**) in bedroom.

Similarly, as 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), then technically, "amplitude modulation" is not 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 low frequency noise, hence the use of the subjective descriptor "whoomph".

In some cases, it has been claimed that infrasound levels in the natural environment are as high (or similar) to that when turbines are operating. This can be the case for 1/3 octave band measurements during gusty winds, near a beach with waves from the surf, or other wind farms (in cases where there are other winds farms that can be detected at a site). However, the natural environment of a remote rural area does not have a periodic time function (i.e., or corresponding periodic function in the frequency domain) in the infrasound region as a result of wind, surf, or the natural environment.

Narrow band measurements that show the presence of amplitude modulation or multiples of the blade pass frequency become a superior tool for the identification of the operation of wind turbines, whereas for locations removed from the wind farm dB(A) and in some cases 1/3 octave band measurements cannot clearly show a discrete signature as a result of the operation of turbines.

The presence of audible modulation of the turbine noise may not necessarily alter the A-weighted level, and generally does not affect the L_{90} level.

Wind turbines generate different levels of fluctuation [17], leading to different perceptions of annoyance.

With respect to the time signals in Figure 1 (recorded in proximity to turbine 13 in [1]), both time signals show modulation of the A-weighted level occurring at the blade pass frequency. As discussed above, the A-weighted level that is being modulated is not a single carrier frequency, and therefore, the variation of the A-weighted sound pressure time signal cannot, in electrical engineering terms, be described as "amplitude modulation", as suggested in NZS 680:2010 [12] or by Hayes McKenzie [5]. However, the modulation of the amplitude in 1/3 octave bands (including the blade pass frequency) can be identified, whilst the presence of modulation of the gearbox output shaft (see Figures 11–13) can be detected as an amplitude modulation, albeit at a magnitude that does not influence the A-weighted level.

3.4. UK "Amplitude Modulation"

The New Zealand Standard 6808 refers to the difference between the maximum and the trough of A-weighted level (or 1/3 octave bands) to determine a 5 dB adjustment for special audible characteristics. There is no specific test procedure provided in the Standard.

As Australia and New Zealand have followed the UK assessment procedures presented in ETSU-R-97, the methodologies used in the UK to describe "amplitude modulation" have been reviewed.

The Independent Noise Working Group [33–35] examined a number of different AM assessment methodologies. The Den Brook assessment method identifies the differences in peak to trough levels of more than 3 dB(A) [34] (page 16).

One means of assessing excessive amplitude modulation [15] is to examine the modulation of the A-weighted level and evaluate the sound pressure levels over 10 s sampled every 100 ms, plot the variation in the amplitude, and determine the depth of the modulation. The exercise is then repeated and arithmetically averaged for multiple 10 s samples for the standard 10 min assessment period.

For defining depth of the modulation with respect to annoyance, the above analysis can be extended to focus on 1/3 octave band peaks in the A-weighted spectrum in the format described above [35].

However, by definition, the above analysis should be termed "excessive modulation of the amplitude".

Other methods discussed in [35] concentrate on the blade pass frequency for discrete 10 s samples, determine the power spectral density function for the 10 min period, and then take the arithmetic mean of the 12 highest AM levels derived from the 10 s periods. Another method is to determine the modulation of the A-weighted value (method not defined) over a 10 min period and add a penalty to the A-weighted value (similar to the New Zealand Standard) [12].

Utilizing the dB(A) measurements in Figure 1, where the parameters of the turbine are known, Figure 14 presents the 1/3 octave band Leq results for the 10 min measurements, both in terms of an A-weighted result and the Linear (unweighted) result. The provision of the Linear weighting permits the identification of the blade pass frequency that cannot be seen in the A-weighted 1/3 octave band spectra due to the frequency response of the A-weighting curve.

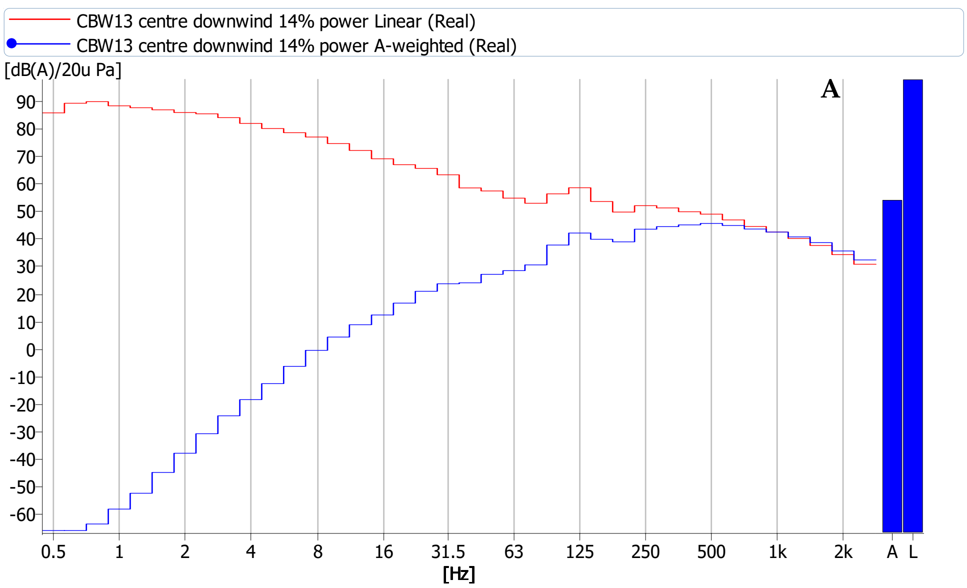


Figure 14. *Cont.*

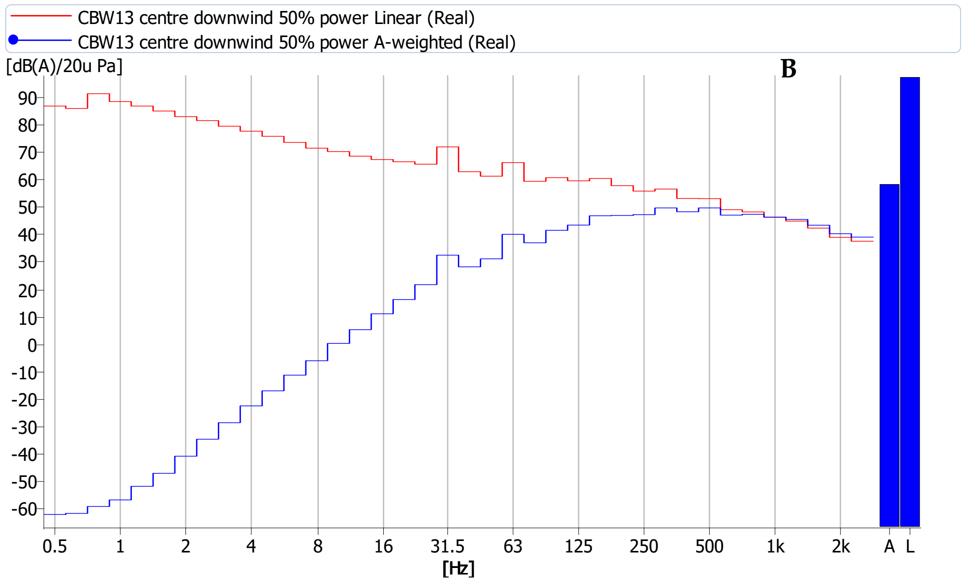


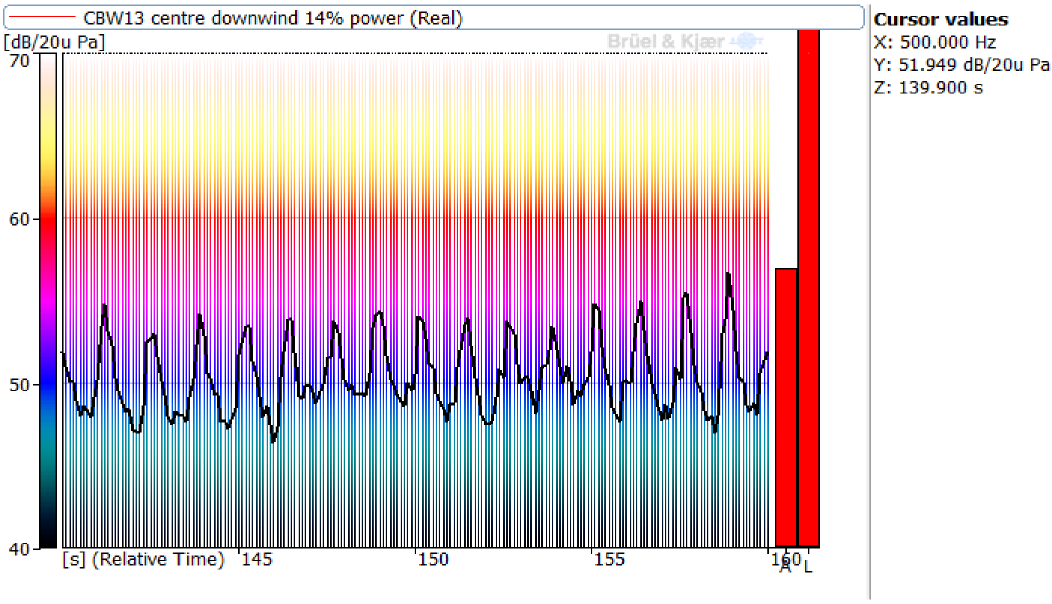
Figure 14. 1/3 octave band Leq levels for the time signatures in Figure 1. (**A**). 14% power, red trace Linear spectrum, blue trace A-weighted spectrum, (**B**). 50% power, red trace Linear spectrum, blue trace A-weighted spectrum.

On reviewing the 1/3 octave band spectra in Figure 14A, for the 14% power scenario, the A-weighted value is governed by a broad peak over the regions of 400–1.6 kHz with a slight peak in the 500 Hz 1/3 octave band. The FFT spectra for the 14% scenario do not reveal any discrete tones in the broad peak described above, i.e., the 500 Hz 1/3 octave band is broad band noise swish noise.

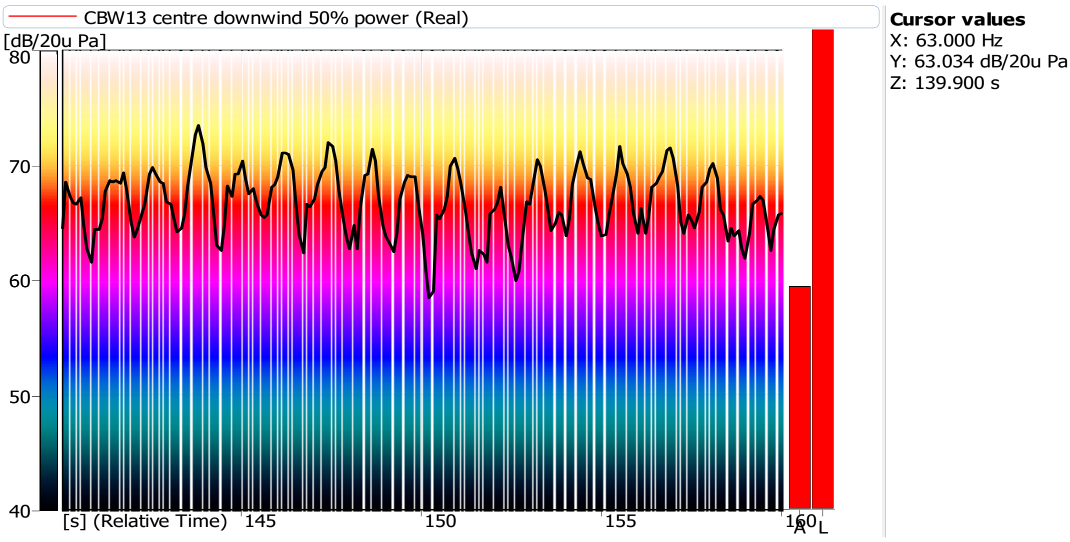
For the 50% power data in Figure 14B, there is the general broad band swish noise at a higher amplitude than expected for the higher wind speed and a higher power output (when compared to the 14% power results). The 1/3 octave spectra for 50% power reveals the presence of distinct peaks in the 31.5 Hz and 63 Hz 1/3 octave bands that is not evident in the spectra for the 14% power output.

From the time trace of the A-weighted levels in Figure 1, the operation of the turbine at 14% power reveals modulation of the amplitude that would require a penalty to the derived A-weighted Leq level, but no modulation correction for the operation at a higher power level of 50%.

However, under the special audible characteristics, corrections in the New Zealand Standard (and if applying an extension to the Den Brook method to assess the peaks in the 1/3 octaves shown in Figure 15) require the identification of the modulation at the blade pass frequency rate in the relevant 1/3 octave bands. This is not just the depth of modulation at the blade pass frequency, which is another method reviewed by the INWG in reference [35].



(**A**)



(**B**)

Figure 15. 1/3 octave band time signatures related to the spectra in Figure 15. (**A**). 14% power, 500 Hz (**B**). 50% power, 63 Hz.

3.5. Viewing the Modulation of a Wind Turbine Signal

The derivation of the depth of modulation of the A-weighted level or relevant 1/3 octave band levels described above is labor intensive and not a straightforward exercise for external locations in view of changes in the A-weighted levels throughout a 10 min sample period as a result of ambient noise (especially wind). How long in a 10 min sample does one require the signal to be modulated to determine that sample to be affected? For example, under the FFT derived power spectral density around the blade pass frequency method, there is a requirement to obtain the arithmetic average of the highest twelve 10 s samples in a 10 min sample, i.e., 120 s out of 600 s (20%).

Narrow band analysis (such as Fast Fourier Transform (FFT)) or Leq 1/3 octave band results for a 10 min sample are not suitable for viewing modulation of the amplitude. To examine the modulation, it is necessary to see the time information as an FFT or 1/3 octave band waterfall analysis (or obtain splices of the waterfall). However, as a starting point, an FFT analysis of the infrasound section of the spectrum is of assistance in identifying the blade pass frequency.

In comprehending the variation in the amplitude, a graphical method was developed showing the change in the turbine signature that highlighted pulsations, amplitude modulation, modulation of the amplitude, and frequency modulation to assist in understanding the dynamics of the acoustic signature and show the failings of just using Leq levels [36].

The graphical method (both in FFT and 1/3 octave bands) analyzes a time sample derived by using a waterfall approach. By orienting the waterfall view to look at the entire spectrum at each point in time, one could progressively scroll through the waterfall (in time) to view the variations. This viewing method can be made into a video that highlights the different frequency components of turbine noise.

A paper presented at the 23rd International Congress on Acoustics provided a simplified method to determine the modulation index of audible and inaudible wind turbine noise [37] and included links to assist the reader in viewing the waterfall results as videos.

For example, the FFT movie view is suitable for infrasound and low frequency (available at http://acoustics.com.au/media/ICA2019AM01.mp4, accessed 31 May 2021). For mid- and high-frequency bands, the 1/3 octave band movie view is a preferred solution, (available at http://acoustics.com.au/media/ICA2019AM02.mp4, accessed 31 May 2021). By use of the waterfall data, one can also view any individual 1/3 octave bands to show the modulation in the time domain to appreciate the UK method in determining amplitude modulation (available at http://acoustics.com.au/media/ICA2019AM03.pdf, accessed 31 May 2021) in relation to time traces at a residential location near the Capital wind Farm in NSW, Australia from ref [37]).

To record the time capture, one obtains a better signal to noise ratio using a Linear (unweighted) parameter when compared with a A-weighted recording, that 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.

Utilizing an exponential FAST response when analyzing the Figure 1 signals in 100 ms increments gives rise to the time traces shown in Figure 15.

The time trace in Figure 15A, for the 500 Hz 1/3 octave band shown in Figure 14A, reveals that a modulation in the 500 Hz 1/3 octave band is occurring at the blade pass frequency for the 14% power operation. Modulation also occurs in the 1/3 octave bands of 630 Hz to 1 kHz. Figure 14A reveals why the A weighted trace in Figure 1 (for the 14% power) shows modulation.

The time trace for the 63 Hz 1/3 octave band in Figure 15B (corresponding to 50% power) shows that modulation at 63 Hz is occurring at the blade pass frequency. Under the NZS 6806:2010, the modulation in this 1/3 octave band would be classified as "Amplitude Modulation", which would be correct as it is the second harmonic of the real Amplitude Modulation identified in the 31.5 Hz 1/3 octave band that is associated with the speed of the output shaft of the gearbox.

Both A-weighted time traces in Figure 1 relate to the occurrence of modulation of the amplitude at the blade pass frequency; yet, on just viewing the A-weighted results for analysis purposes, one would miss the modulation for the 50% power scenario.

Having identified that the time signal in the relevant 1/3 octave bands is modulated (but not apparent using A-weighted time traces), an alternative analysis method was developed using 10-min recordings of the sound associated with a wind turbine and applying statistical analysis.

3.6. Alternative Analysis of Modulation Index

In Australia, for general environmental assessments, acoustic descriptors that are used are L90, Leq, L10 and L1. The L5 or L95 parameter (used in Japan [10]) is not used in Australia by Environmental Agencies. 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 modulation of the amplitude for individual 1/3 octave bands is to conduct a statistical analysis and compare the L1 versus the L90 level. For the purpose of this discussion, the value of the L1 minus the L90 is called the "modulation index".

It is noted that under the UK method (and environmental assessments in Australasia), the analysis is set for an exponential FAST response, and as such, the time constant of the averaging method does not give the true maximum or minimum absolute values that are obtained from using shorter averaging sampling times that would be relevant for an assessment of the subjective impact of wind turbine noise.

The amplitude modulation index using the simplified methodology of the statistical L1 minus L90 for the Capital Wind Farm [37] has, in Figure 16, been superimposed on the A-weighted frequency spectrum to indicate the difference in the degree of modulation.

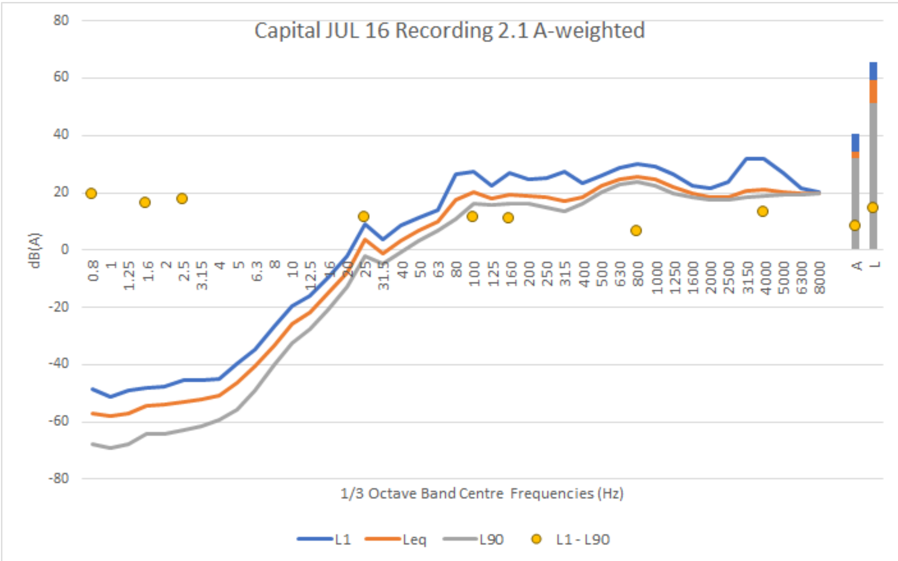


Figure 16. Amplitude Modulation Index derived from alternative method—A-weighted spectra.

Figure 17 presents the same data but using linear (unweighted) statistical spectra. Using linear spectra, the modulation indices for the identifiable peaks in the Leq spectra are slightly different to the values obtained using the A-weighted spectra.

The application of the simplified modulation assessment identified above permits the analysis of wave files in an extremely time efficient manner when compared with the UK methods.

The influence of wind on the measurement of wind farm noise in terms of a dB(A) parameter becomes more significant for increased distances from the turbines.

In the Cape Bridgewater Study [1], there was a strong correlation with the variation of the dB(A) background with the wind, but not the variation of power output of the wind farm.

Cooper [38] raised the issue of wind noise in the overall background level as part of wind farm noise monitoring when deriving the noise contribution of a wind farm and the incorrect use of wake free wind data in regression analysis.

With respect to using the modulation index method, one needs to be aware that the presence of wind on external monitoring locations (despite the use of double windscreens) can give rise to significant variations in the L1 value, thereby requiring examination of the entire 10-min time trace.

Use of internal monitoring locations for assessment of the impact of wind turbines is a relevant matter for assessing disturbance to residents and the difficulty of removing extraneous wind noise for external locations.

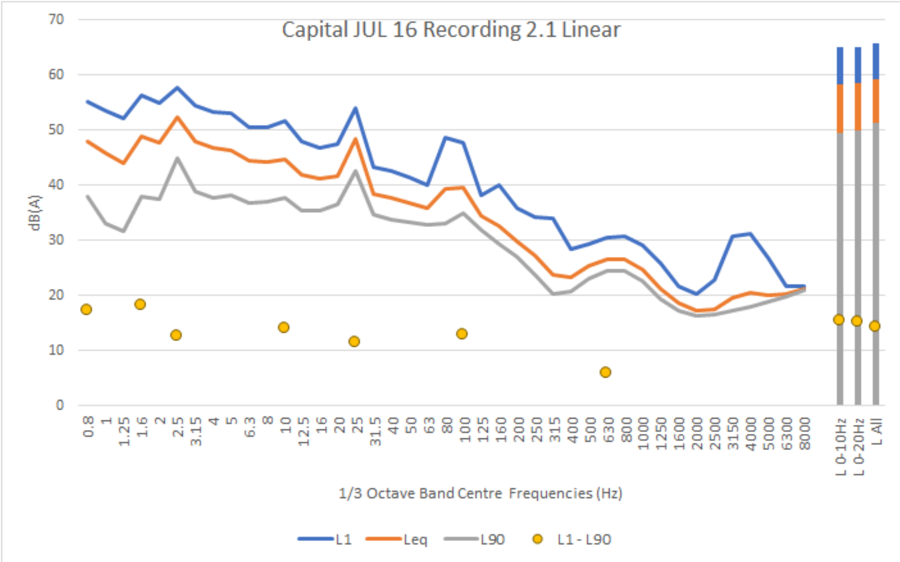


Figure 17. Amplitude Modulation Index derived from alternative method—Linear (Unweighted) spectra.

4. Internal Noise Assessment of Modulation

The preceding analysis of wind turbine sound files is based upon the requirement of the regulatory authorities to utilize noise criteria for external locations at residential receivers.

With respect to noise criteria issued for wind turbine projects, the noise criteria are related to external noise levels that are dependent upon the number of turbines affecting a measurement location and the distance from the turbines, that, in turn, can lead to different acoustic signatures, resulting in significant differences in assessments of modulation.

In Australia and New Zealand, the basis of the noise criteria set down for wind turbine installations is premised on the notion of providing protection against sleep disturbance.

If one is looking to assess the end user, i.e., residents, in terms of sleep disturbance, then the application of any adjustments to the internal measured noise level as a result of special audible characteristics, including modulation of the amplitude, needs to be considered.

An investigation into complaints associated with wind turbine noise cannot be based solely on external noise measurements, but must also consider internal noise levels on the basis of the fact that for the majority of the critical night time period, there is an expectation that people tend to be sleeping indoors, and therefore, are subject to a different acoustic environment that would be occurring external to the dwelling.

The matter of special audible characteristics, as may be assessed external to a dwelling, has no relevance in terms of the actual impact that residential receivers experience inside their dwellings, by reason of the different acoustic environments occurring inside dwellings due to attenuation from the building envelope.

The spectral content of internal environments of dwellings with respect to the matter of intrusive noise from wind turbines is entirely different to that of the external environment, particularly when one is considering the use of A-weighted level which is dominated by mid-band frequencies.

Due to the response of the human ear (with respect to loudness curves used in acoustics), then the nature of the intruding noise relative to a lower background can dramatically alter the subjective impacts of the intruding noise. The general concept of 10 dB representing a subjective doubling of the loudness of the noise may be applicable for external environments, but when placed in the context of relatively low internal ambient noise levels, the relationship in terms of loudness has lower differences in level for a subjective doubling of a sound (to be discussed in next article).

Due to the modulation of the amplitude occurring in the infrasound region, according to the definition of "fluctuation" provided by Zwicker and Fastl [8], the identification of the modulation of the amplitude can be readily sensed by the human ear when it exceeds 3 dB. The depth of the modulation affects the sensing of the fluctuation.

Salt determined that the outer hair cells of the inner ear responded to infrasound [39], and subsequently that broad band noise modulated at an infrasound rate could also be detected by the outer hair cells of the inner ear [40].

Zwicker and Fastl showed that changing the frequency and depth of the modulation of an audible noise led a heightened annoyance when compared to the same signal without modulation. When coupled with the work of Bradley [41] (referred to by Leventhall in [42]), this provides an explanation of why many complaints from residents relate to noise levels that are below or near the threshold of hearing. Bradley indicated that for the critical region of between 2 and 4 Hz (i.e., the rate of modulation of the low-frequency noise) an adjustment for annoyance of up to 17 dB could be required.

In 2004, van den Berg [7] identified the phenomenon of the "beat" of wind turbines being enhanced at night due to increased atmospheric stability. However, contained in that article was the application of Zwicker and Fastl's fluctuation correction for broad band noise modulated at an infrasound rate. This correction appears to have been forgotten in the world of wind turbine noise acoustics.

Several recent investigations have examined the differences between external and internal monitoring locations to identify practical limitations with the identified simplified modulation assessment procedure, or, for that matter, various other modulation assessment procedures discussed in [35].

With respect to noise criteria issued for wind farms, most of the material relates to external noise levels that are dependent upon the number of turbines affecting a measurement location and the distance from the turbines, that, in turn, can lead to different acoustic signatures, resulting in significant differences in assessments of the modulation.

In general, the application of corrections for modulation of the amplitude requires valid data of the noise levels being modulated which, for external environments, can present issues arising from ambient noise masking the relevant measurements and the influence of wind (which, by definition, is considered an intermittent noise source) affecting the measurement results. In many instances, these factors overload the measurement results for the infrasound region. Therefore, the use of automatic statistical analysis to determine the modulation index for external locations is not always applicable in rural acoustic environments due to the presence of "extraneous" noise.

For internal noise measurements, the variation in wind and a significant degree of external masking noise is eliminated due to the building envelope, and therefore, should give more reliable data for subsequent analyses.

To show the limitations/benefits of modulation analysis with respect to wind turbines, the following example is provided.

Testing of disturbance to residents in proximity to a wind farm in Australia utilized simultaneous monitoring at various locations, both in indoor and outdoor settings.

The subject area experienced significant variation in wind, in that the nacelle of the wind turbines in a relative sense were only some 50 to 70 m above the residential receivers.

For the external measurement locations at the residential properties on an A-weighted basis, the modulation of the amplitude occurring at the blade pass frequency, during the night time periods in which the residents reported significant sleep disturbance, was generally less than 5 dB. However, in individual 1/3 octave bands, there were numerous 10-min samples in which, for various individual 1/3 octave bands, the modulation occurring at the blade pass frequency exceeded 6 dB.

Under the criteria utilized in the state of New South Wales (Australia), the occurrence of modulation of the amplitude for the external monitoring locations during the nights in question would be for a small period of time, and as such, could be dismissed by the environmental authorities. However, if assessed in terms of the New Zealand Standard [12] utilized in the state of Victoria (Australia), the majority of those nights would, due to the modulation in individual 1/3 octave bands, require a penalty to be added to all of the A-weighted results attributed to the wind farm.

Utilizing the internal measurements for the same nights, there was a significantly greater number of "deemed" modulation of the amplitude utilizing the A-weighted results, and with respect to the 1/3 octave band results, the majority of the night would be deemed to have been subject to modulation of the amplitude with internal modulation indices significantly greater than 6 dB throughout the entire night.

5. Conclusions

The introduction of wind turbines as an alternative means of power generation commenced with small-scale units upon which various socio-acoustic and environmental studies were undertaken to develop acoustic criteria.

In the absence of detailed investigations into the impact of wind turbines, the acoustic criteria utilized by environmental authorities were "borrowed" from other noise sources without any validation process/precautionary concepts being identified with respect to criteria such as those applied for road traffic noise.

With the proliferation of wind power and significant increases in the size and power output of wind turbines, there has been an increase in wind farm noise exposure to communities and, as a consequence, identification of noise disturbance (and other impacts) to sections of those communities.

The operation of a wind turbine gives rise to a variation in the noise as the blades rotate, such that the noise is not constant, but is subject to changes in amplitude.

The original variation in audible noise from wind turbines was identified as blade swish, which was found to be a modulation of the amplitude occurring at a blade pass frequency. Over time, a general description of amplitude modulation came to be used for one of the characteristics of wind turbine noise, without considering the technical definition of amplitude modulation as used in the field of electrical engineering.

In the area of psychoacoustics, and through examinations of the hearing mechanism, the term amplitude modulation has been used to describe the modulation of broadband noise by a lower frequency rate and in terms of the technical definition of amplitude modulation, which is correct when qualified by the above description of the noise.

The problem that occurs with the general concept of amplitude modulation for wind turbines is its application in some regulatory documents to corrections be applied to the A weighted value of the wind turbine noise subject to amplitude modulation. Due to the A-weighted value not being a dedicated or specific "carrier" frequency, and regulatory authorities utilizing measurements in terms of A-weighted sound pressure levels, it is suggested that the correct terminology for beating, periodic fluctuation of the noise level, or modulation effects with respect to general wind turbine noise should be "modulation of the amplitude".

It has been observed from noise monitoring of wind farms that when turbines are operating and generating power, there is an amplitude modulated signal associated with the output speed of the gearbox being modulated at the blade pass frequency. However, the level of the true amplitude modulation does not affect the overall A-weighted level, because the modulation is related to low frequency noise.

The use of the term "modulation of the amplitude", when considering the noise signature of wind turbines, permits one to consider, in psychoacoustic terms, the impact of the modulation of the amplitude as a special audible characteristic requiring an adjustment to the measured overall noise level for the wind turbine/wind farm.

As the primary function of this article relates to noise criteria utilized by environmental authorities with respect to the operation of wind turbines, the consequence of modulation of the amplitude of wind turbine noise in terms of psychoacoustics, potential impacts on residents, and alternative noise criteria is to be examined in a supplementary article.

The use of the term "modulation of the amplitude" with regard to wind turbine noise permits a focus on the annoyance of the general term "amplitude modulation" or "enhanced amplitude modulation" of wind turbine noise, and permits such noise to be re-assessed with respect to psychoacoustic criteria.

With the need to assess the presence of modulation as a "special audible characteristic", a simplified method of assessment has been developed that can be applied inside dwellings where disturbances are perceptible.

The matter of the turbine signature not being a sine wave modulation, and the response of the ear/brain to a short time response (i.e., shorter than that used for environmental acoustics), together with sleep disturbance are addressed by the author in a supplementary article.

Author Contributions: The article is the work of Steven Cooper. The article utilizes reports undertaken by The Acoustic Group over a number of wind farms. Cooper is the Principal of that organization and the author of those reports. The author has read and agreed to the published version of the manuscript.

Funding: The research for the preparation of this article received no external funding.

Institutional Review Board Statement: Not Applicable.

Informed Consent Statement: Not Applicable.

Conflicts of Interest: The author declares there is no conflict of interest. The author has undertaken assessments of wind farm noise for residents, is the author of the Cape Bridgewater Wind Farm Study and has conducted research into the acoustic signature of wind turbine noise.

Abbreviations

The following abbreviations are used in this manuscript:

dB(A)	Cumulative sound pressure level after passing through the A-weighting filter that approximates the response of the human hearing
ETSU	For the UK guideline ETSU-R-97
L_{A10}	A-weighted sound pressure level exceeded for 10% of the time
L_{A90}	A-weighted sound pressure level exceeded for 90% of the time
L_{A95}	A-weighted sound pressure level exceeded for 95% of the time
$L_{A90,\ 10\ min}$	A-weighted sound pressure level exceeded for 90% of the time in a 10 min sample (840 s)
L_{eq}	Energy averaged sound pressure level
MD	Modulation depth
NASA	National Aeronautics and Space Administration
NSW	The state of New South Wales in Australia
SA	The state of South Australia in Australia
SCADA	Supervisor Controls and Data Acquisition
EAM	Enhanced amplitude modulation

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