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The use of synthesised or actual wind turbine noise for subjective evaluation purposes

Steven COOPER[1]

[1] The Acoustic Group, Australia

ABSTRACT

There are technical difficulties in producing an accurate wind turbine noise signal for subjective testing of the noise characteristics for different operational scenarios of wind turbines. There are differences in the subjective response when limiting the test signals to infrasound only versus the use of full spectra. The concept of "nocebo" effect that has been presented has relied upon the use of "synthesised wind turbine infrasound" that does not reflect the signature or pressure pulsations observed in full-spectrum field measurements. The validity of "synthesised wind farm infrasound signals" that have been used in such testing is examined and compared with full-spectrum signals.

Keywords: Wind Turbine, Amplitude Modulation

1. INTRODUCTION

The acoustic signature of a wind turbine in the frequency spectrum encompasses the entire audio spectrum and extends into the infrasound region.

However, the acoustic signature is critical to identify turbines operating under different wind conditions. This is reality.

In the time domain, the overall level is subject to fluctuations occurring at the blade pass frequency, that for modern day turbines is slightly less than 1 Hz.

On a linear (unweighted) spectrum analysis the maximum acoustic energy is concentrated in the low-frequency and sub-audible ranges.

The use of the overall dB(A) level does not account for the low frequency components and tends to be dominated by broadband mid/high frequency noise, sometimes described as a "swishing" sound. The modulation of the overall level of noise emitted by a wind turbine (typically described as "amplitude modulation") can vary from inaudible amplitude modulation, to audible modulation, or excessive amplitude modulation, and is dependent upon the loading of the turbine and the angle of attack of the turbine blades.

Typical acoustic analysis of the noise signal from wind turbines, whether by narrow band (Fast Fourier Transform) analysis or one third octave bands identifies in the spectrum discrete components in the infrasound region being a function of the blade pass frequency and multiple harmonics of that frequency, components associated with the gearbox (that are modulated by the blade pass frequency), and broadband noise. Measurements of the infrasound levels undertaken by such analysis reveal levels well below the threshold of hearing, and such levels are often dismissed as irrelevant.

The high frequency components of the turbine noise are significantly reduced inside the dwelling, due to the attenuation of building envelopes. This results in a frequency spectrum dramatically different to that obtained in the external environment immediately outside the dwelling.

Utilising external dB(A) levels for environmental assessments of wind turbines does not address the noise levels experienced by residents inside their dwellings.

Pioneering work undertaken by Kelly [1] in 1980 in relation to the MOD-1 turbine in North Carolina provided a schematic representation of wind turbine noise spectrum characteristics [2] with structural, room and human body resonances added (see Figure 1).

[1] drnoise@acoustics.com.au

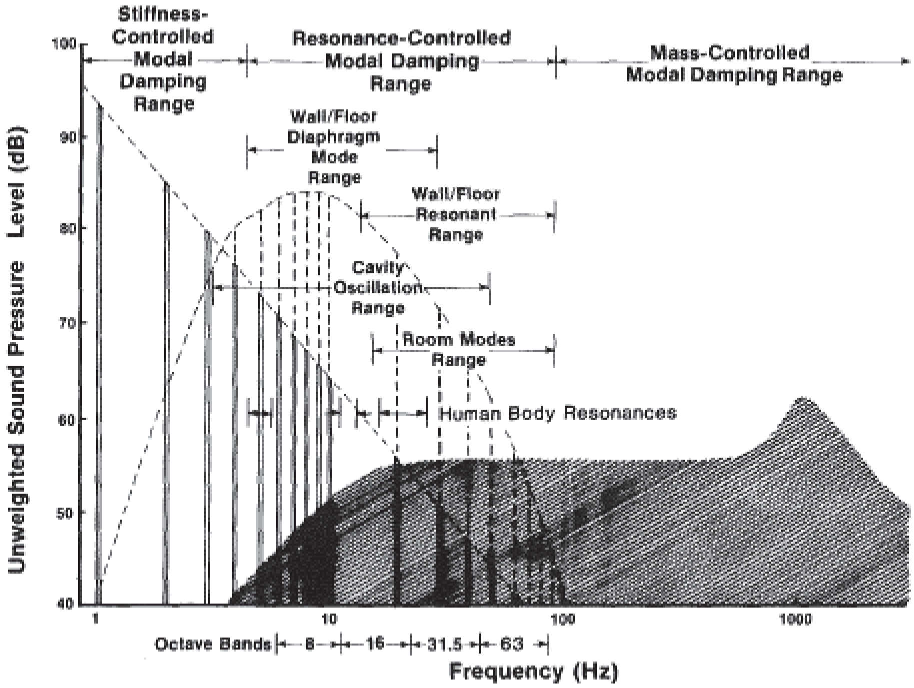

FIGURE 1: Turbine noise emission components with building and human body resonances superimposed. Ref [2]

The MOD-1 turbine was of a downwind turbine (where the blades are downwind of the truss structure). Modern turbines are upwind turbines, where the blades are upwind of the lower support (normally a round tower).

Audible characteristics of wind turbine noise can have different spectrum shapes depending upon the relative distance of the receiver location to the turbines. On moving further away from the turbines, the high frequency noise attenuates. Multiple turbines associated with the wind farm park can give rise to a general low-frequency roar that in some cases is described like the sound of an aircraft that never lands.

Field measurements have identified the presence of discrete peaks in the infrasound region at times when residents have accurately reported sensing the operation of the turbines without visual or audible cues. Testing in South Australia [3] indicated that for narrow band analysis levels in the 4Hz-6Hz region when above 50dB(linear) correlated with the detection of the turbines - even though those frequencies were inaudible. A similar result was obtained in the Cape Bridgewater study [4].

2. AUDIBLE ASSESSMENT

A number of studies evaluating the audible noise of wind turbines have technical limitations in generating a full spectrum by reason of amplifiers, speakers, sampling rates of the recording devices, frequency bandwidth of microphones and whether one is using outdoor measurements versus indoor measurements. The significant differences in transmission loss of building elements, potential resonance effects of buildings, or enhancement of the internal sound levels for different constructions does not provide a uniform transmission loss performance, in terms of subjective testing cannot be related to noise of wind turbines obtained externally to the building.

Such external noise spectrum characteristics can be subject to masking from other sources that in turn do not relate to noise levels experienced inside dwellings. As part of the Acoustical Society of America's Wind Turbine Working Group, a series of papers have been presented to that group in relation to various acoustic tests and investigations to accurately reproduce signals in a test rooms whether restricted to the infrasound region only, full-spectrum, or full-spectrum excluding infrasound.

3. DIFFICULTIES IN REPRODUCING WIND TURBINE "INFRASOUND"

Large areas of speakers, high-powered D class amplifiers and the use of high sampling rates for recorded signals is necessary to be able to reproduce transient signals of wind turbine noise [5] [6]. However, there is a question as to whether infrasound is actually generated by turbines in the same concept as audible noises associated with gearboxes or the "swish" sound from the turning of the turbines.

If one considers for a simple analysis a constant tone of 100 Hz, then under FFT analysis one expects a peak at 100 Hz and say 20 dB lower the second harmonic, and lower still the third harmonic, and possibly the fourth harmonic, to appear in the spectrum because there is a mechanical device (the speaker) used to generate that sound.

If, then one considers that 100 Hz signal is created as a tone burst to run for 900 ms, off for 100 ms, then on for 900 ms, off 100 ms etc, then there would be a periodic function of 1 Hz occurring in the time domain.

Undertake the FFT analysis of that signal (as a pure theoretical exercise) and one would expect a peak at 1 Hz and a peak at 100 Hz because those are the two main fundamental frequencies that are occurring in the time domain. There may be harmonics or multiple harmonics at lower levels of those two frequencies. However, in an acoustic sense, there is no 1 Hz sound that is generated, it is purely a periodic function that occurs in the time domain upon which in the frequency domain there appears a peak at 1 Hz. But there is definitely a 100 Hz signal that is generated.

From the results of Walker, Hessler and Hessler, Rand and Schomer [7] with respect to the Shirley Wind Farm (see Figure 2), there is general frequency spectra shown by high-resolution analysis of the audio signal that identifies a typical pattern in the infrasound region. The question that we need to ask is, is that an audio signal or is it a function of the mathematical analysis of a pulse? I leave the reader to actually look into those components and issues of concern, to ascertain whether there is an audio signal there or not. Hint: One could start with the analysis of a periodic DC Pulse. Then examine the time domain to determine if BT=1 is valid [8] & [9].

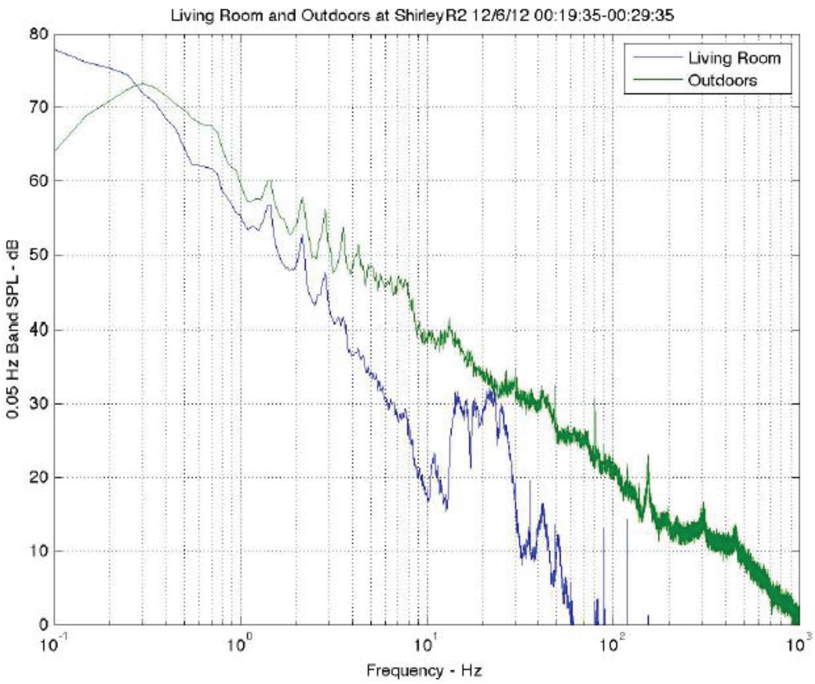

Figure 2: Comparison of outdoor and indoor spectra – Shirley Wind Farm (ref 7)

If an acoustician (or other disciplines) does not understand the mathematical relationship of frequency analysis or the validity of such analysis, then a question arises as to whether they are incorrectly interpreting the data?

3.1 Crichton

In Crichton et al "Can Expectations Produce Symptoms From Infrasound Associated with Wind Turbines?" [10] the title of the first paper specifically refers to wind turbine infrasound. However, the "infrasound" that was used in the experiment was 40 dB at 5 Hz, as was not wind turbine infrasound.

In Crichton et al "The Power of Positive and Negative Expectations to Influence Reported Symptoms and Mood During Exposure to Wind Farm Sound" [11] an "infrasound" signal at 50.4 dB at 9 Hz was introduced with a recording of audible wind farm noise.

If one refers to the spectra set out in Figure 2, it is clearly the case that a constant infrasound signal at a single frequency as used in Crichton's two studies, is not a signal generated by a wind turbine. Neither papers refer to a fluctuating tone as the "infrasound" signal. Accordingly, how can the title of those two papers be correct when wind turbine infrasound noise was not actually used in the experiment?

Furthermore, examining the specifications of the speaker system [12] that was used in the Crichton experiments one finds there would be some difficulty in producing a clean sine wave at those frequencies for the level that has been indicated as it is beyond the specifications of the speaker.

The two Crichton papers have been referenced by a number of acousticians [13] in presenting arguments supporting wind turbine applications. In light of the above one must question whether those acousticians have actually read and comprehended the material in the Crichton work.

3.2 Walker

In investigating the impact of "wind turbine infrasound" Walker has utilised a synthesized signal with a low frequency speaker system and a D class amplifier to demonstrate wind turbine infrasound [14] instead of using actual wave files

Reference 14 includes the results of LAeq FFT analysis of turbines at Cape Bridgewater (Figure 55 in reference 4) to create a waveform computed as the sum of the sine waves at the six peak spectral amplitudes. Walker considered the wave as essentially a Ch-Wave truncated at the 6^{th} harmonic.

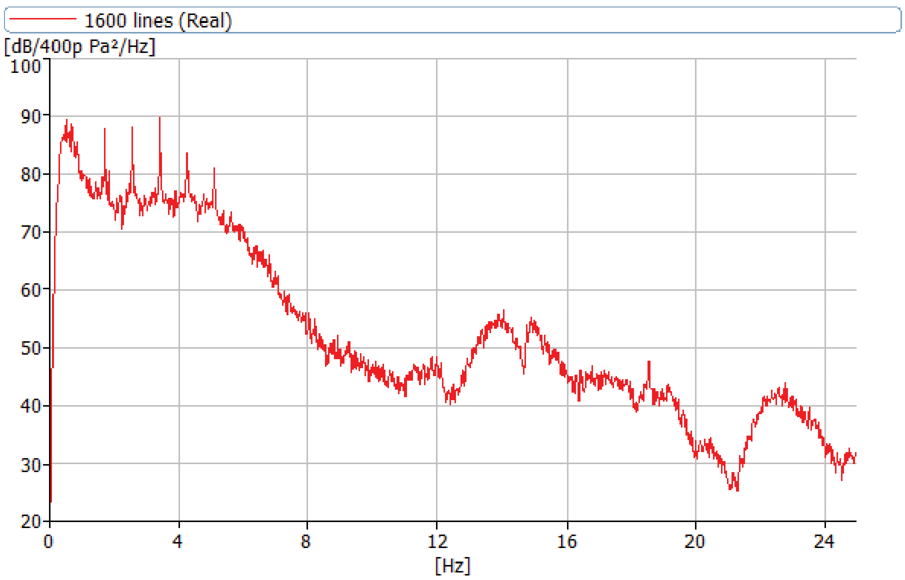

Figure 3: 1600 lines, 0 – 25 Hz FFT analysis – figure 55 from ref 4

However, the signal derived by Walker does not agree with the original time signal that was used to obtain the Leq FFT. The Leq results are the result of squaring the amplitude and then the square root of the result loses all the phase information. Deriving a time signal from an Leq result of individual tones could only fit in with the Walker approach if the original signals were sine waves and all had zero phase difference.

Apart from the phase issues, another possible explanation for the difference between the actual time signal and the Walker derived signal is that the house in question is not influenced by just a single turbine but by multiple turbines, not in sync with one another. Furthermore, the acoustic signals obtained at Cape Bridgewater are not restricted to just infrasound but contain frequencies in the normal audio spectrum[15].

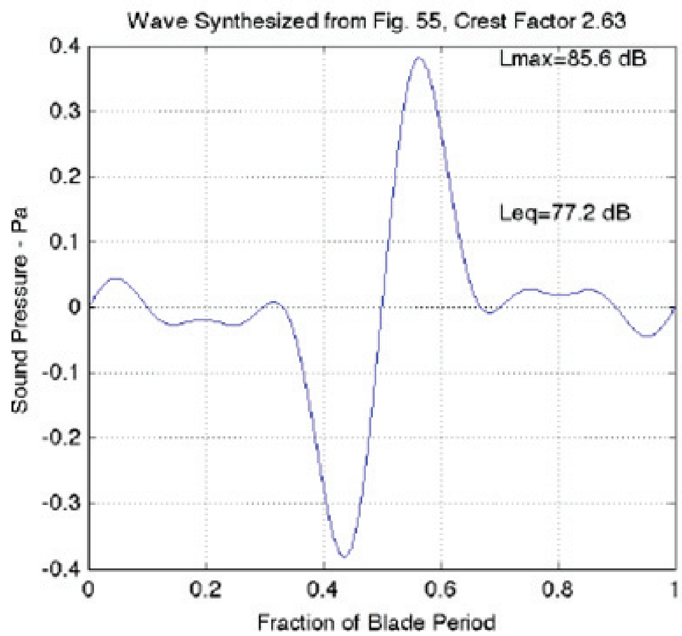

FIGURE 4: Walker synthesis of Figure 3

If one is just restricting the subjective assessment of wind turbine noise to the infrasound region (where the reported levels are significantly below the hearing threshold and the sensation threshold in the infrasound region) then one expects there to be no reported sensation when exposed to infrasound alone.

For subjective testing of wind turbine noise Walker [16] used data from Waterloo wind farm to create a synthesized signal for subjective evaluation and again found synthesised infrasound produced no reaction. Restricting the spectrum of the turbine signal to only infrasound or not the full spectrum, places limits on the validity of the experiment whether using synthesized signals or real wave file data.

3.3 Tonin

Tonin [17] conducted a study along the lines of Crichton but used a Walker synthesised signal applied to headphones using a pneumatic driver. Tonin acknowledges that the signal would be deemed to be inaudible in light of the levels being below the nominal threshold of hearing in the infrasound region.

Tonin concludes that the infrasound had no statistically significant effect on the health symptoms reported by the volunteers and suggested the results support the hypothesis that a nocebo effect may be the cause of the reported symptoms. The Tonin study did not use WAVE files of actual turbine noise restricted to the infrasound range, but used an inaudible synthesised signal with no verification that the signal was the same as measured in the vicinity of wind turbines. Similarly, the Tonin study did not consider inaudible or audible low frequency noise, or mid band noise generated by wind turbines.

Tonin's conclusion [18] presents the concept that infrasound is perceived by some people to affect the health of people and as no effect was observed supports a hypothesis of a nocebo effect. But if the synthesised signal is inaudible, and not actual wind turbine noise, then the results of the Tonin study cannot apply to the full spectrum of wind turbine noise.

Tonin acknowledges that his study can only apply to the application of the "infrasound" to the ears in an enclosed space (ear muffs) and therefore does not address other potential paths (excluding the ears) that may impact upon individuals. Tonin does not discuss the possibility the wind turbine infrasound signature (obtained from narrow band FFT analysis) is the result of the modulation of the amplitude of the low/mid frequency noise, where that modulation occurs as a series of pulses repeated at an infrasound rate.

If the purpose of the above acoustic experiments is to evaluate the perception and annoyance of wind turbine noise, then apart from restricting the testing to signals that may not even be there, there is also the issue as to the relevance of the Crichton/Walker/Tonin signal with respect to Annexure D of ANSI/ASA S12.9-2016/Part 7 [18].

Annex D to the ANSI document "advanced signal processing techniques" provide specific advice in Section D1:

It has been observed (Bray, Swinbanks, Walker, et al) that for complex low-frequency signals (those comprising multiple frequencies), the temporal relationship between the components can have a significant influence on their subjective assessment. (Indeed, al one needs do is listen to the difference between a gun-shot and an extended Galois sequence signal to observe the two signals with the exact same spectrum can sound dramatically dissimilar.) There is reference to figure D1.

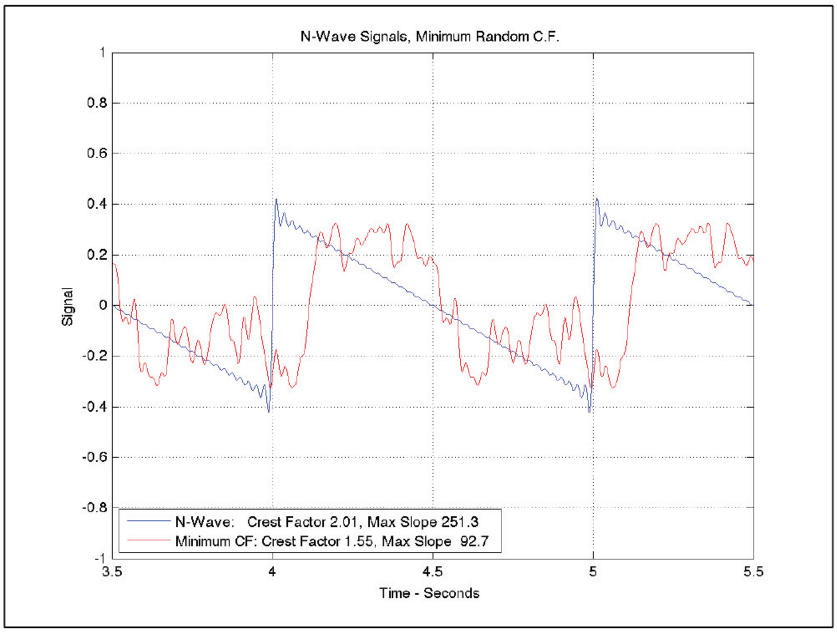

Figure D.1 – Two signals with exact same power spectrum and (therefore) autocorrelation function

Figure 5: Figure D1 from ANSI/ASA S12.9-2016/Part 7

Tonin used a sawtooth signal similar to above that does not agree with the actual time signal from wave files for the Shirley wind farm. If Tonin utilised a digitised infrasound signal which is not an actual wind turbine signal, and produced infrasound levels that are inaudible, then the likely result of such a study is that there would be no impact.

3.4 Cooper

In contrast to the approached of the three researchers above, our research has used as a starting point the full spectrum noise wave files of actual wind turbines applied as a complete sound field. I then investigated the subjective whole-body response to this sound reproduced in a laboratory setting.

It is difficult to comprehend from just an LAeq frequency analysis of a time signal how one can reconstruct the original time signal. In any event, why would you need to use a digitised signal when it is much easier to use the actual wave files that are available from recordings? This digitised concept has always perplexed me as the instrumentation for the Shirley wind farm study went down to the low infrasound region. If Walker's field measurements had data recording capabilities at a high sample rate to be able to reproduce the signal, then why couldn't those signals be used? Due to space limitations the following link http://acoustics.com.au/media/ICA2019SS01.pdf provides additional material with respect to Section 3 of this paper

How does one verify the audible characteristics of an infrasound signal? If we take the original recorded wave file signal and put a low pass filter to only have 0 to 20 Hz from the original signal as signal 1, and then utilise 6 generators all set to 0 phase to reconstitute an analogue signal (below 20Hz) as per the Walker concept (signal 2) then two wave files can be obtained. When both signals are then sped up 100 times we find that in terms of the sped up “infrasound” signal, they do not sound the same and therefore would be invalid under ANSI/ASA S12.9-2016/Part 7, as a test signal for subjective testing of infrasound.

Reference 15 identifies limitations we experienced in creating full spectrum signals in our laboratory.

Having examined the issues of analysis of short-term burst signals and finding that frequency analysis of these frequency analyses can produce infrasound “signals” that are not actually present then the issues in terms of the frequency response, timing rates and bandwidths of frequency analysis must be looked into, to ascertain the validity of the signals. We presented the concept of ghost frequencies that are not valid and may be considered a similar concept to the issues of digitisation requiring anti-aliasing filters.

Just as ghost frequencies associated with vibration in gearboxes lead to further developments such as Cepstrum analysis to reveal patterns that relate to faults in the gearbox, we proposed that the FFT of wind turbines that give rise to infrasound spectra is just simply a tool to identify that the turbines are operating and generating pulses.

From Hansen/Walker’s observations contained in reference 16, and the analysis identified in reference 16, our research investigations into the subjective assessment of wind turbine noise ignored infrasound [19] [20] and utilized testing with a high pass filter to eliminate frequencies below 20 Hz. Therefore, it became a simple task of using actual wave files of wind turbine noise which could be simply validated.

Our double blind pilot study presented to the ASA Wind Turbine Working Group in December 2017 [20] and Euronise 2018 [21], used inaudible wind turbine noise from field measurements recorded on a high sample rate data recorder to which as a double blind study of 9 persons sensitised to wind turbines were able to detect with 100% accuracy the signal containing the operation of the turbines.

The two additional papers presented in this session utilise wave file recordings presented to the test subjects as an entire sound field (not headphones) that can be validated with the field measurements as to the accuracy in both frequency and amplitude as the source data to then be used for audible subjective testing or inaudible subjective testing.

4 CONCLUSIONS

In the past the use of traditional acoustic analysis of wind turbine noise has revealed a time varying noise that by way of 1/3 octave bands and narrow band analysis has revealed infrasound and low frequency signatures, commonly referred to as ILFN (Infrasound and Low frequency Noise).

The author has never claimed there to be infrasound as the concept of a noise but has identified the presence of the narrowband signature (blade pass frequency + harmonics) in the infrasound region.

With respect to wind turbine noise much discussion has been made in relation to wind turbine “infrasound” without qualifying the basis of what is the infrasound signal – that in any event is below the threshold of hearing.

Subjective evaluation of pseudo/sham/synthesized wind turbine infrasound has revealed there to be no impact leaving some researcher to claim such testing supports a nocebo effect, despite the data also identifying the power of suggestion is important.

A fundamental problem exists with such studies as to why actual wind turbine noise (in the form of high quality wave files that extend down to the infrasound region) could not be used as the test signal?

Using actual wave files, we have ascertained that there is no perceptible difference with or without infrasound in the signal when creating an entire sound field in which the test subjects are immersed.

Reference 22 presents the results of further work with wind turbine wave files set at an inaudible level to show that limiting the spectrum to be between 20Hz and 1kHz produces less of an impact than using 20Hz to 16 kHz.

Having reproduced the acoustic signature of wind turbines in a laboratory and finding changes in the EEG of the brain now permits the assessment of wind turbine noise (inaudible and audible) to be extended by the appropriate medical studies.

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