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Reproducing wind farm infrasound for subjective testing – Just how accurate is the reproduced signal?

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Apparently on the basis of room modes being excited in residential dwellings one concept has been to ignore high quality field measurement recordings (Wave files) and use the narrow band (FFT) Leq results of a 10-minute sample to create, by superimposing a number of sine waves, a trapezoidal time signal as the source for subjective testing and restricting the bandwidth to only infrasound. Other testing has utilised full spectrum signals but has issues with providing an accurate signal due to the limitation of the speakers. An examination of both methods and the limitations of the results have been examined and will be discussed.

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1.0 INTRODUCTION

In response to investigation of residents' complaints concerning the operation of wind turbines, independent acousticians have identified the presence of a discrete infrasound/low frequency signature associated with the operation of the turbine to be present when such turbines are operating.

The discrete signature of turbines when using narrowband analysis reveals peaks at the blade pass frequency (and harmonics of that frequency) to occur in the lower portion of the infrasound frequency band, generally below 10 Hz and a peak with sidebands around what may be the gearbox output shaft speed.

Attenuation of infrasound over distance occurs at a lower rate than that of normal sound, resulting in the discrete infrasound signature of turbines being recorded up to 7 km from wind farms [1], [2], and in some situations even greater distances [3].

Infrasound measurements of the natural environment in rural areas free from the influence of wind turbines whilst revealing similar broadband levels of infrasound (for example using dBG or even 1/3 octaves) do not experience a discrete periodic pattern similar to that associated with rotating blades on wind turbines when assessed in narrow bands.

In seeking to assess the audible characteristics of wind turbine noise, being different to that of general traffic or environmental noise, laboratory studies have sought to use speakers to generate or to reproduce recorded signals for test subjects in a controlled environment.

Restriction of analysis to A-weighted noise levels or 1/3 octave bands has limitations in examining the impacts of the noise in question.

All of our wind turbine measurements have revealed infrasound levels below the nominated threshold of hearing and low frequency modulated noise as inaudible/barely audible and in some case clearly audible (to sensitised individuals) inside dwellings.

With the (re)identification of the presence of discrete infrasound signatures associated with wind turbines in the last few years, experiments have been conducted on just the infrasound components even though such levels are below the threshold of hearing. Conducting such experiments would confirm inaudibility with conclusions posed that infrasound is not an issue.

Cooper [4] raised the possibility that the infrasound signature, whilst identifying the operation of turbines, may be the by-product of the modern day analysers and that the impact on people could be the result of audible and inaudible modulation of frequencies occurring in the normal range of frequencies associated with everyday sounds.

As the impact of the turbine's inaudible infrasound on people has not been studied in controlled studies, of critical important in the laboratory assessment of wind turbine "noise" is the question as to whether the source signals generated in the laboratory are full spectrum and reproduce the original signal (that includes by narrowband analysis infrasound).

Experiments into wind turbine "noise" have considered just the infrasonic region, audible spectrum only (no infrasound), and possibly full spectrum (infrasound components unknown).

Tachibana [5] used a set of reverberation chambers to evaluate full spectrum sound of wind turbines. However, the primary issue presented in the paper was looking at the A-weighted level with different low pass filtering and modulation. Reference [5] did not examine infrasound specifically but concluded that frequency components below 25 Hz are not audible which is to be expected for the levels that were tested. As a side issue to the investigation of the A-weighted levels and audibility of the modulation, the audible modulation effects were identified as associated with low frequency.

Walker [6] provided results of generating infrasound signals synthesised from narrow band Leq analysis to find no impact. No frequency response was provided to define the output of the synthesised infrasound signal generated by a speaker. There is an assumption the system equalisation curve resulted in a flat spectrum.

Walker [7] started with external wind farm noise samples from the Waterloo wind farm that were then synthesised from the narrow band frequency spectrum to provide the source signal.

Tonin [8] has used a synthesised infrasound signal applied to a pnuematic driver connected to modified hearing protectors.

Crichton [9] & [10] has used single infrasound tones inserted into broad band noise for an assessment of "wind turbine infrasound".

The presentation of synthesised signal of turbine noise as a result of a creating a signal based upon the individual FFT components of a time average (rather than a WAVE file of the original signal) has been used to show the inaudible infrasound frequencies do not impact upon people [6], [7], & [8], by suggesting that the synthesised signal or pure sine waves [9] & [10] is a representation of the signal residents receive as a result of an operational wind farm.

Issues of concern with the use of simulated "infrasound" are:

- Whether the synthesised signal (obtained from adding sine waves) reproduces the actual time signal that occurs in the field.
- "Infrasound" applied as single tones and then attributed as being the signal generated by wind farms
- Testing of synthesised signal and claiming the results apply to wind farms.
- Accurately reproducing the Wave file signal by the use of speakers.

2.0 SYNTHESISED SIGNALS

Cooper [4] identified the original pressure time signal of the full spectrum shows the presence of modulation which is lost by conversion to dB and then A-weighting.

Appendix V of the Cape Bridgewater report [1] discussed the reduction of pulses and modulation into discrete frequency components and the resultant sawtooth time signal derived in Matlab by adding discrete components. Use of a pressure detector (restricted to less than 20Hz) provided results similar to that proffered by Walker. Use of full spectrum signals (obtained at the same time) on an FFT analysis produced similar frequency results in the infrasound region, but produced a different time signal to that of a bandwidth limiter pressure detector, indicating low frequency noise (above the infrasound region) was influencing the time signals.

Walker [6] claims that by taking the amplitude at the peaks corresponding to the blade pass frequency and its harmonics an approximation to the underlying signal can be synthesised.

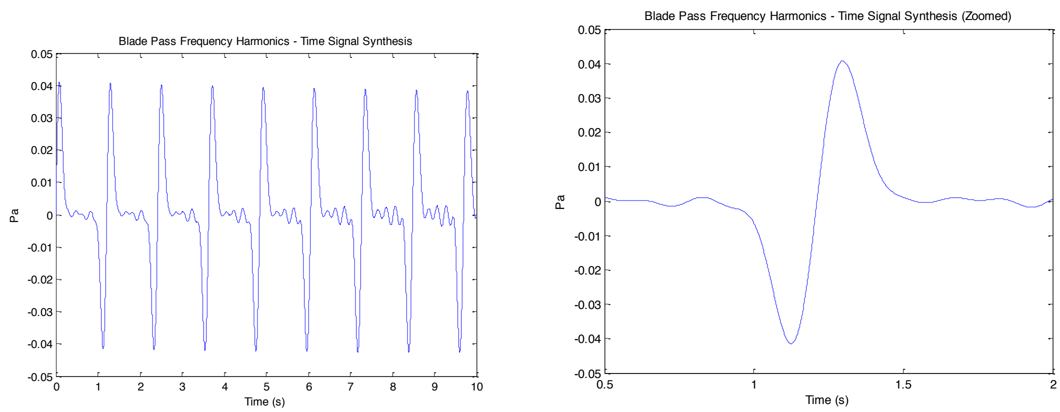

Figure 1: Figure V1 of reference [1] Blade pass harmonics time signal synthesis - House 87 Pressure Detector – 01/06/14 08:20pm

Figure 1 is from the Cape Bridgewater study where the blade pass frequency and the first 4 harmonics from the Leq narrowband spectrum have been added (in Matlab) to produce an approximation of the pressure signal. However, the derived time signal (Figure 1) does not agree with the field measurements in Figure 2 from the pressure detector (limited to 25 Hz).

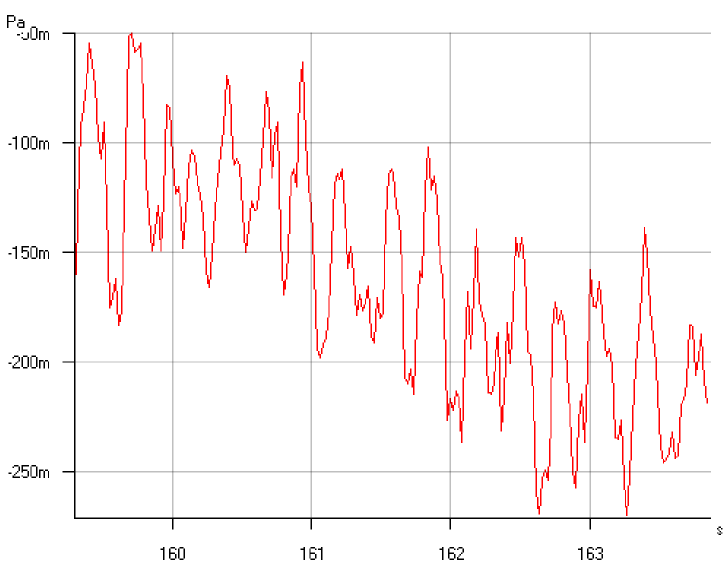

Figure 2: House 87 Pressure Detector – 22/05/14 05:30am (Turbines ON) – Time signal sample

Walker [6] used the sound level Leq FFT results from the Cape Bridgewater Study to derive a similar time signal. The hypothesis for the synthesis method is to add the sine waves at the discrete frequencies obtained by the 10 minute Leq analysis.

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 possibility 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.

Using the dB levels for the internal measurement provided in reference [4], sine waves were generated at the fundamental and the first five harmonics and applied to B & K Pulse Analyser in the ratio of the Leq levels over the 10-minute sample.

Figure 3 shows the summed output of 6 signal generators (multi-channel Bruel & Kjaer Pulse system), with 0 phase difference, to obtain the same spectrum as the field measurements. The time signal shows a profile that is not the same as the mathematically derived signal from Walker, or more importantly the original time signal and a modulation of the entire signal.

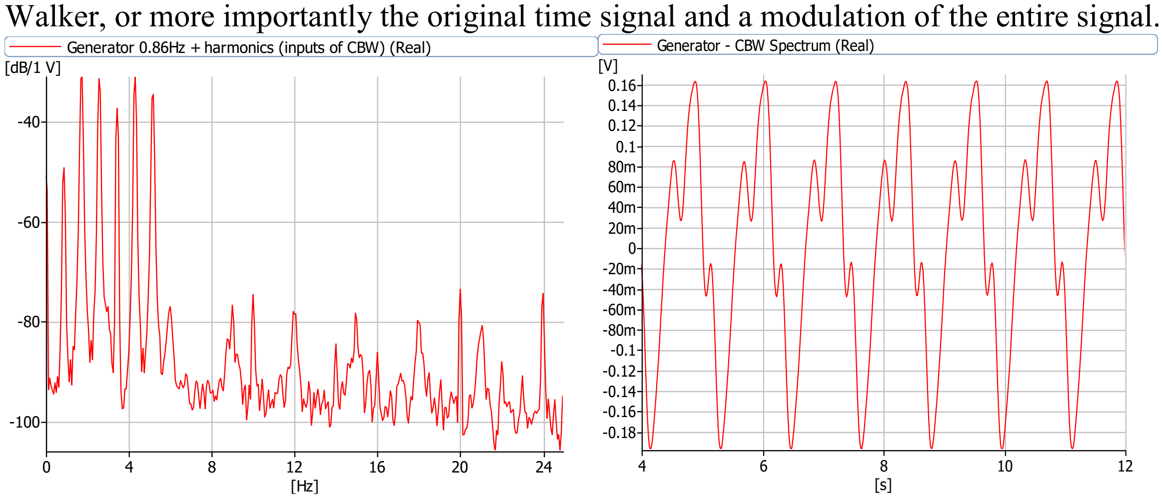

Figure 3: Pulse Analysis of multiple generator outputs

If there are valid and high quality WAVE files recorded in the field, why use a synthesised signal that is different from the original?

3.0 INFRASOUND – SINGLE TONES OR SYNTHESISED INFRASOUND CLAIMED TO BE WIND TURBINE NOISE

Crichton [9] [10] presents an argument for the nocebo effect for "wind farm infrasound noise" by the statistical analysis of the observations, but provides limited information in terms of the qualification of the "infrasound signal". From the advice given to test subjects as to the presence of wind farm infrasound (versus "sham" infrasound) there is a conclusion the nocebo effect is a result the power of suggestion. However, examination of the data reveals that the use of actual wind farm infrasound did not occur. The results of the testing cannot claim and reliance on actual wind farm infrasound.

Reference [9] quotes the use of a Mackie sub-woofer type "HR 150" to generate an infrasound signal at 5 Hz of 40 dB. Reference [10] indicates the generation of an infrasound signal at 9 Hz at 50.4 dB but no information is provided as to the sound system used.

The discrete pattern obtained at operational turbines [1] [11] in the infrasound region is not limited to a single frequency of either 5 Hz or 9 Hz. Nor are the infrasound "tones" constant level but are the result of pulsations.

An examination of the specification [12] for the Mackie HRS 150 speaker (as there is no listing for a HR 150 speaker) reveals that there are multiple limitations in terms of the speaker that was used for the study. The specification sheet for the Mackie HRS 150 indicates that there is an acoustic limitation of 20 Hz in addition to an electrical limitation on the amplifier response of 15 Hz.

Looking at the graphs that are provided in the owner's manual indicate that the frequency response of the system is significantly attenuated below 20 Hz. This is not uncommon for speakers in an enclosure (and also amplifiers) that have difficulty of faithfully reproducing infrasound signals.

Figure 4 reproduces a graph from the main report for the Shirley wind farm that shows the discrete peaks in the infrasound region. The green trace is the external measurement whilst the blue trace is the internal measurement. Both traces show a slight peak at the blade pass frequency with the 2nd, 3rd, 4th and 5th harmonics being clearly evident. The internal levels do not show a distinct single peak at either 5 Hz or 9 Hz used by Crichton.

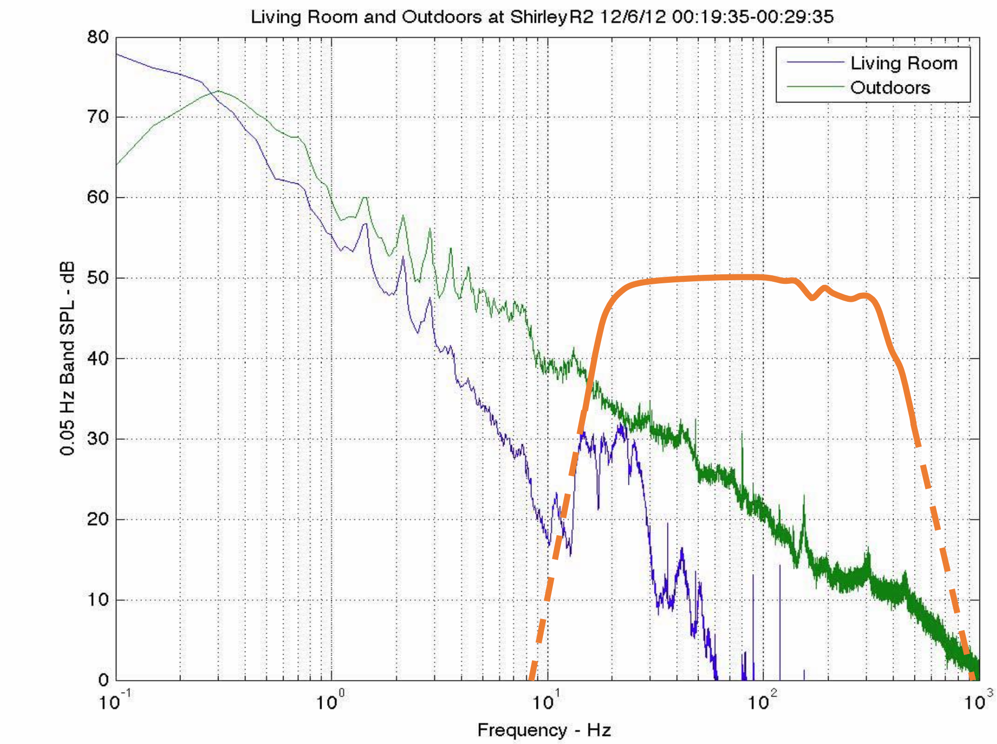

Figure 4: Shirley Wind Farm Test

Superimposed over the measured levels for the Shirley wind farm study is an overlay of the manufacturer's free field response of the Mackie HRS 150 (shown in orange) to indicate the frequency response of that sub-woofer. The dotted lines are an extension of the roll off from the manufacturer's data sheet. Apart from the limitation of the response of the speaker/amplifier combination it can be seen from the result of the Shirley Wind Farm graph that the production of just a single tone at either 5 or 9 Hz cannot be presented as "wind farm infrasound".

The signal chain in the Crichton infrasound test is further compromised by the use of a Presonus Firepod audio interface. The specification for the Presonus FP10 [13] reveals the frequency response at 20 Hz is $\pm$3 dB. This would then provide more attenuation below 20 Hz for the Mackie subwoofer than indicated in Figure 4.

References [9] & [10] do not indicate any calibration check of the response of the system or that the "infrasound" generated for the subject test was a valid signal of 40 dB at 5 Hz. However, as the test signal was not that of windfarm infrasound, then from an acoustic viewpoint references [9] & [10] lead to a study to test the power of suggestion as to wind farm "infrasound", but without providing a control group experiencing actual wind farm infrasound.

Ollson and Ashtani [14], and Tonin [8] have relied upon the Crichton results without identifying the "infrasound" signals are signals that cannot be attributed to wind turbines. The conclusions of the Crichton tests have been the subject of criticism [15], [16] as to the methodology of the analysis without considering the acoustical issues described above.

Tonin [8] conducted a study along the lines of Crichton by using 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 generated by wind turbines.

Tonin's conclusion [8] does not mention wind turbine infrasound, just infrasound. However, the title of the paper *Response to Simulated Wind Farm Infrasound Including Effect of Expectation* implies a different situation.

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 frequency noise, where that modulation occurs as a series of pulses repeated at an infrasound rate.

If the Walker, Crichton and Tonin studies do not use actual wind farm infrasound signal, and have not validated the synthesised signals versus actual signals (in both the time and frequency domains) the application of such testing to wind farm noise impacts must be questioned.

Annex D of ANSI/ASA S12.9-2016/Part 7 [17] expresses caution in the above method by stating the use of "two signals with the same spectrum can sound dramatically dissimilar".

4.0 USE OF SPEAKERS FOR REPRODUCING INFRASOUND

In applying an entire sound field to test subjects that reflects the typical environment of residents near a wind farm (who do not wear ear muffs in the course of daily typical activities) the normal approach in laboratory testing relies upon such sound being accurately generated by speakers in a test environment.

Examination of specification for speakers that are available off the shelf, and are designed to produce low frequencies are typically identified as sub-woofers, reveal that the nominal frequency response for such speakers may not go down to 25Hz and generally do not extend below 20 Hz by reason of the speakers being placed in a physical box that in itself has limitations as to controlling the output of the speaker.

Utilising speakers for testing of the full spectrum of “wind farm noise” (including the infrasound) requires extreme scrutiny in terms of the accuracy of the signal being reproduced.

Basic theory associated with loudspeakers reveals that a speaker sitting in free space, whilst generating satisfactory high frequency noise, will have issues in generating low frequency noise as the movement off the back of the speaker is able to cancel out a portion of the air movement from the front of the speaker. The placement of a speaker in a baffle so as to separate the movement of air behind the speaker from the front dramatically improves the low frequency performance/reproduction of the sound.

Extended large baffles do not lend themselves to normal speaker use, leading to the provision of a box around the speaker to physically hold the speaker and primarily to improve the low frequency response. Folding a baffle into a box so that there are no edges is commonly referred to as an “infinite baffle”.

Furthermore, as part of producing low frequency energy the movement of air behind the speaker may be used to enhance the sound in front of the speaker by the use of ports or ducts inside the speaker box.

Nevertheless, as the majority of speakers are used for the reproduction of music, and music does not normally contain infrasound frequencies, speaker boxes are not designed to produce infrasound.

Is not uncommon to see speaker response curves, such as at for the Mackie HRS 150 showing that below 20 Hz there is a rapid fall off in the low frequency output produced by the speaker for a constant signal input.

Use of high powered sub-woofer speakers provided for rock concerts or nightclubs, whilst having ratings of up to 4000w, do not extend into the infrasound region as they are basically ported and/or horn loaded boxes with cut-off frequencies around 25 Hz.

Testing of a number of speakers for the intended use of evaluating the infrasound/low frequency response found inadequate performance. In addition, there were issues with the frequency response of high powered amplifiers, as high powered amplifiers normally have filters to ensure there are no frequencies amplified below 10 Hz.

Looking at manufacturer’s speaker curves one needs to be aware of frequency responses may be in pink noise, white noise or transfer functions. Our investigations also found that the sweep signal is normally analysed from above 20 Hz using a relatively wide tracking filter, much wider that the discrete individual frequencies of concern for a wind farm infrasound noise assessment.

For this investigation a “speaker baffle” of 38mm MDF with three layers of 16mm plasterboard was installed in the 10.5 square metre opening of our reverberation chambers and used the receiving room of 126 cubic metres that had the ceiling and three of the four walls lined with 50mm thick Martini Absorb XDH50 polyester [18]. In the central baffle are 12 speakers of 15” diameter. No tuning port was provided. The testing started with a set of relatively cheap full range drivers rated at 150w each. However, testing found that that power rating doesn’t apply below 10 Hz, as a number of speakers failed.

The final testing used twelve 1000w (rms) rated speakers being driven by a 2000w Class D amplifier that has a flat response from DC to 50 kHz.

Figure 5: Speakers in 10.5 m2 opening to 126m^2 reverberation room

Free field response curves from speaker manufactures do not give the same result in an enclosed space. Having solid walls (blockwork concrete filled) concrete floor on bedrock does not present typical resonances of the building elements found in dwellings. However, there are some anti-nodes and nodes at certain frequencies as a result of using the multiple speakers mounted in the baffle, acting in this case as a distributed source producing a plane wave.

For the purpose of assessing infrasound from turbines the frequency response from speaker manufacturer’s data is of no assistance. This is because the data uses pink noise or swept sine waves with typically 1/12 octave smoothing of the response. Furthermore, manufacturer’s data normally does not go below 20 Hz.

Very narrow band swept analysis was conducted for locations 1 metre from the EAW sub-woofer (shown in Figure 5), 1 metre from only 1 speaker in the speaker baffle operating, and 1 metre from a speaker in the speaker baffle (with all 12 speakers operating) re 1 watt is shown in Figure 6. The use of narrow band swept analysis without any smoothing (as typically used for audio speaker response curves) provides significantly greater degrees of variation in the response curves in the test room than obtained for individual speakers mounted in free space

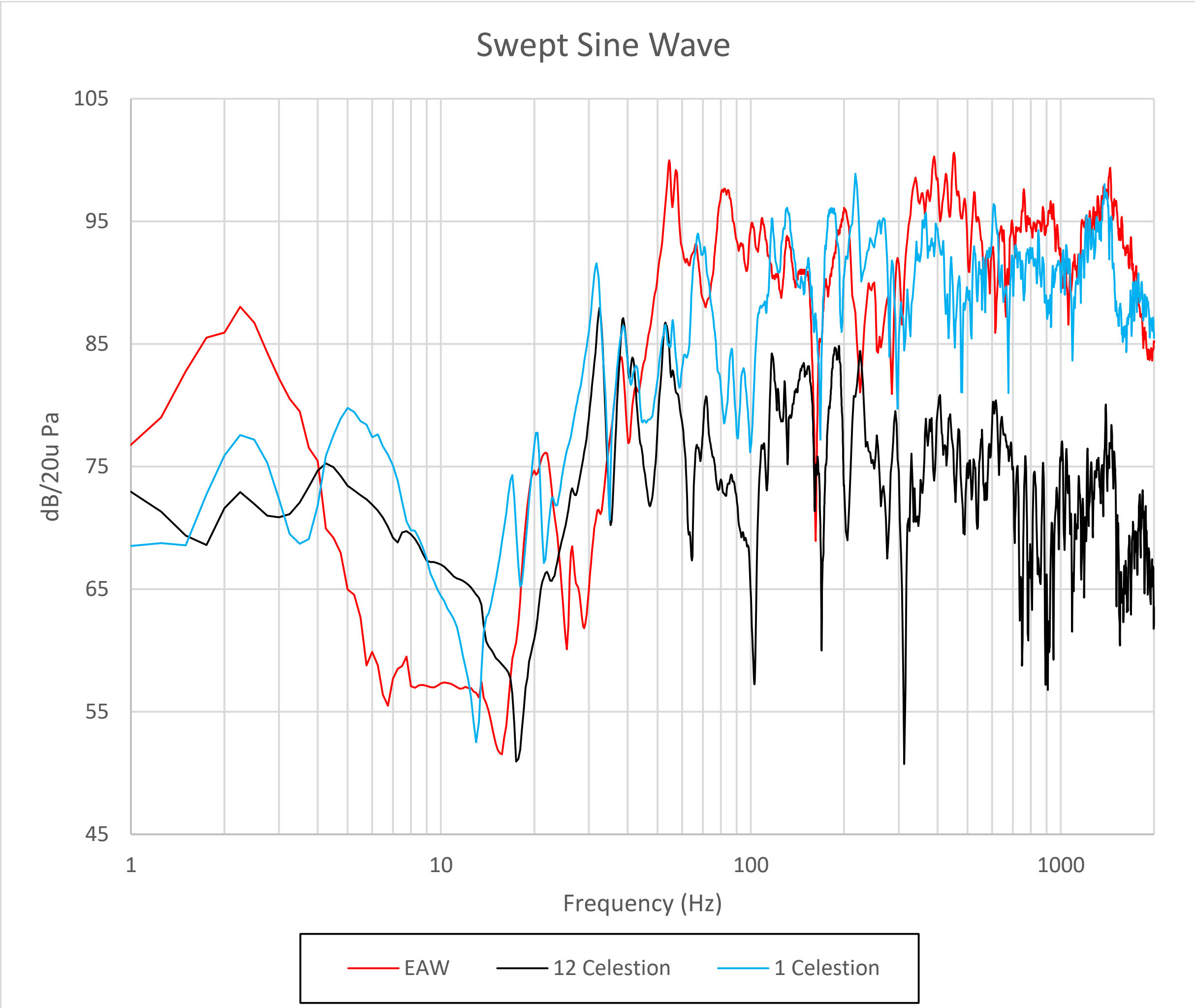

Figure 6: Narrow Band Swept Sine Wave Response of speakers in Figure 5

The different impedances for the speaker combinations will for a single speaker being monitored give rise to different sound pressure levels at a reference frequency of 1 kHz.

In generating sound pressure levels in the test chamber one needs to consider the addition of the 12 speakers when viewing the result for just one speaker as shown in Figure 6.

The multiple speaker arrangement gives a flatter response for frequencies below 10Hz – being the critical area for investigation of the blade pass frequency of turbines.

The typical assessment for turbines noise is to use a sample of 10 minutes duration. The provision of broad band pink noise Linear averaged over 5 minutes for the same speaker/microphone locations (for Figure 6) is shown in Figure 7.

Both Figures 6 & 7 reveal the multiple speaker arrangement gives a flatter response for frequencies below 10Hz – being the critical area for investigation of the blade pass frequency of turbines, thereby requiring less compensation to the signal being reproduced.

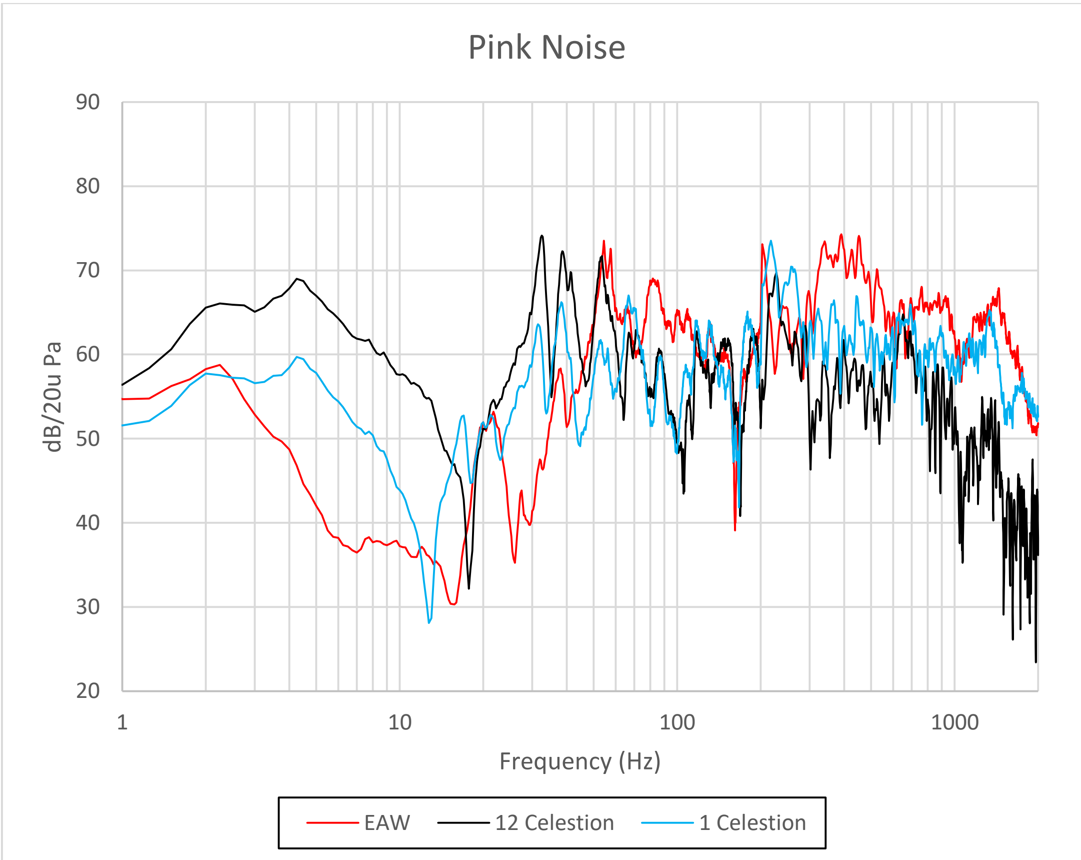

Figure 7: Speaker comparison using pink noise

The system was originally intended for use in a number of experiments with respect to the sound in the infrasound region, separately to the experiments with wind turbine infrasound noise.

For testing hearing thresholds, one 2000w D Class amplifier driving all speakers, can deliver 95 dB at 1 Hz with the GRAS microphone and Pulse revealing a very clear sine wave. The second and third harmonics are more than 35 dB below the fundamental. Similarly, at 10 Hz there was reluctance to push the signal above 107 dB as some of the gear in the adjacent control room was starting to vibrate and complaints from other people in the building were of concern.

The balancing of the spectrum for the proposed acoustic testing requires a complex DSP filter system to address the frequency response (either pink noise or swept noise) and there are also issues with the noise floor of the system.

Preliminary results show challenges in obtaining a balanced spectrum for testing full spectrum wind turbine noise. Restricting the signals to below 10 Hz by using the 12 speakers mounted in the speaker baffle results in an acoustic signal in the reverberation room that follows the input signal (whether wave file or synthesised) as a cleanly reproduced input signal.

Preliminary results have clearly identified the synthesised signal (derived from the original wave file using the Walker method) does not give the same time signal as the original.

5.0 Conclusion

The wind turbine acoustic signal is not restricted to infrasound but provides frequency spectra that covers infrasound and normal audible frequencies.

The time signal of wind turbines show pulses. Due to the variable nature of the acoustic signal over a ten-minute period and the nature of pulses occurring at the blade pass frequency, the Leq result must be lower than the peak levels. Whilst the general assessment of wind turbines is based on the A-weighted Leq level there is a question as to whether people are responding to the A-weighted Leq, peak level A-weighted or linear, bands of sound in the infrasound region or the low frequency region, or responding to inaudible/audible energy.

Some experiments into wind turbine noise have been restricted to just the infrasound components.

The use of synthesised “infrasound” signals from narrow band Leq analysis does not to produce the same time signal as the original signal.

Our testing has found that the original time signal cannot be reproduced by the synthesis method as the Leq narrow band FFT results are an average over time and are devoid of any phase information in relation to the individual frequency components.

If the generation of only infrasound that is inaudible does not produce an impact, then it follows that testing should use full spectrum signals.

If infrasound and low frequency components are a significant factor in the sound field that occurs, then the use of traditional speaker boxes places restrictions on the sound field that is generated.

The presentation of wind farm noise (full spectrum, including infrasound) requires careful consideration, assessment and calibration of the resultant sound so as to reproduce the original signal.

The multiple speaker baffle arrangement has been used for infrasound threshold measurements [20] and subjective testing of wind farm audible noise [5].

As a result of the work to date the generation of a signal for test subjects that is intended to reflect that of wind farms should use WAVE files of actual wind farm and not synthesised waveforms. Obtaining accurate Wave files is relatively straightforward and overcomes the inaccuracies and conflicts that arise by the use of synthesised "wind farm infrasound" signals, or the concept of single tones in the infrasound region and claiming such synthesised signals/tones are "wind turbine infrasound".

The challenge for researchers in the laboratory (separate to measurements in the field) is to be able to reproduce the original signal. Obtaining an audio signal in the laboratory from 0.8Hz up that reproduces the original WAVE file presents many challenges. Obtaining a digital to analogue convertor and amplifier chain with appropriate signal to noise ratio is a limiting factor for laboratory testing of the full spectrum.

The preliminary results reveal interaction of individual speakers and the volume of air behind the speakers affects the linearity of the frequency response from a plane wave, that requires further work.

The transient response of the wind turbine time pulses may be a limiting factor in reproducing the original signal.

The above limitations are subject of further investigations.

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