6th International Meeting
on
Wind Turbine Noise
Glasgow 20-13 April 2015

Progress Report on Synthesis of Wind Turbine Noise and Infrasound

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Summary

Study of the subjective effects of wind turbine noise in a controlled environment requires the ability to faithfully generate acoustic signatures produced by actual turbines. Field measurements indicate that these signatures encompass a wide frequency range, extending from below 1 Hz to several kHz. Beginning in 2012, the authors have presented conceptual descriptions and preliminary demonstrations of an infrasound synthesizer that is capable of producing turbine-faithful signals at least 10 dB greater than experienced in the field. The basis of the system is a cubic enclosure housing three 18-inch electro-dynamic loudspeakers, driven by a 300-watt DC-coupled power amplifier. At 0.8 Hz (a typical blade-pass fundamental in a modern industrial turbine) the system generates 75 dB sound pressure level in a 60 cubic meter residential room environment. Peak infrasound pulsations up to 97 dB are produced. The system has been expanded to allow simulation of controlled-spectrum steady broadband noise, amplitude modulated broadband noise and periodically excited bursts of coherent multi-tone noise. Details of the design and implementation of the system are presented. In a companion paper, the system is utilized to evaluate the relative subjective effects of audible and inaudible components of acoustic signatures synthesized on the basis of field data.

1. Introduction

In addition to well-established aero-acoustic and mechanical noises, the acoustical signatures of modern, industrial wind turbines has been shown to include spectral components that extend into the infrasonic range, with potentially significant energy as low as the rotor blade-pass frequency (BPF). Although the amplitudes of these infrasonic components are substantially lower than hearing thresholds for the components taken individually, it has been postulated (Schomer, 2013) that vestibular system excitation and/or the relatively high crest factor multiple simultaneous BPF harmonics causes the infrasound to be detectable and potentially a health hazard at sub-audible sound pressures. In one field test, for example (Walker, Hessler, Rand, Schomer, 2012), residents stated unequivocally that they could “sense” the operation of turbines well over 2,000 meters distant from within their homes, while the measured infrasound levels were far below any established thresholds even at a distance of 400 meters.

It became clear that an electro-acoustic simulation of various wind-turbine acoustic components was needed to allow controlled testing and identification of signal properties that contribute to human sensitivity. Laboratory systems have been proposed and implemented (Tachibana and Yokoyama, 2012; Zosuls et al, 2013) that would perform this function. The current system is intended for use in a residential environment.

2. Synthesis of Turbine Noise Signal Components

Numerous individual components of the wind turbine acoustic signature include:

- Steady broadband noise
- Amplitude modulated broadband noise
- Steady tonal noise
- Amplitude modulated tonal noise
- Infrasonic BPF harmonic series pulsations
- Pulsed short-duration mechanical resonances

Synthesis subsystems in Matlab create each of these separately so they can be mixed and adjusted to simulate field conditions. One-minute long segments of each component are created in software and are repeated for extended exposure testing.

2.1 Steady broadband noise covers frequency range 1 to 3000 Hz and spectrum-shaped to an approximate average of a compendium of field data. To preserve continuity of signal and slope for repeated signals, the one-minute of noise is synthesized as a sum of sine waves on 1/60 Hz frequency increments with random phases (i.e., 180,000 separate sine waves with frequency 1/60 Hz to 3000 Hz). Figure 1 shows spectral properties of the synthesized noise as compared to Gaussian noise. Actual spectrum shaping is achieved by appropriate amplitude weighting of the individual sine waves in the synthesis, with final result as shown in Figure 2.

2.2 Amplitude modulated broadband noise is a quasi-swept 1/3-octave band of Gaussian noise that is superimposed on the steady noise. The sweep is intended to mimic the Doppler shift of an advancing blade at a location 45 degrees to side upwind of the turbine. However, the intent for listening tests is to provide a BPF-synchronized fluctuation in audible sound that is suggestive of turbine AM rather than a probably-unachievable full representation. **Figure 3** shows the four spectra and modulation envelopes that are sequenced to synthesize a quasi-Doppler shifted noise from a rotating source. The four spectra are created by filtering four statistically independent synthesized noise signals.

2.3 Tonal noise and infrasound pulsations are spectrally synthesized based as harmonics of the BPF. The amplitude and phase of harmonics 1 to 65 (0.8 to 52 Hz) can be pre-set individual to simulate a multitude of pulsation, steady tone and amplitude modulated tone signatures. Alternatively, modulation windows can be applied to steady individual tones to generate wave packets or fluctuating tome amplitudes directly.

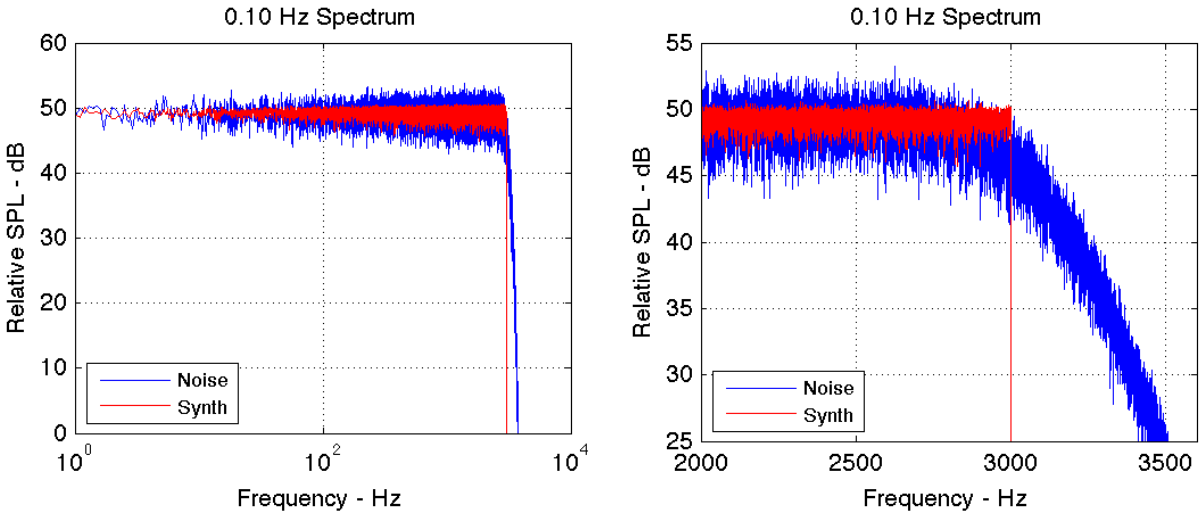

Figure 1. Narrow band spectra of synthesized and filtered Gaussian noise and expanded response near 3 kHz corner frequency

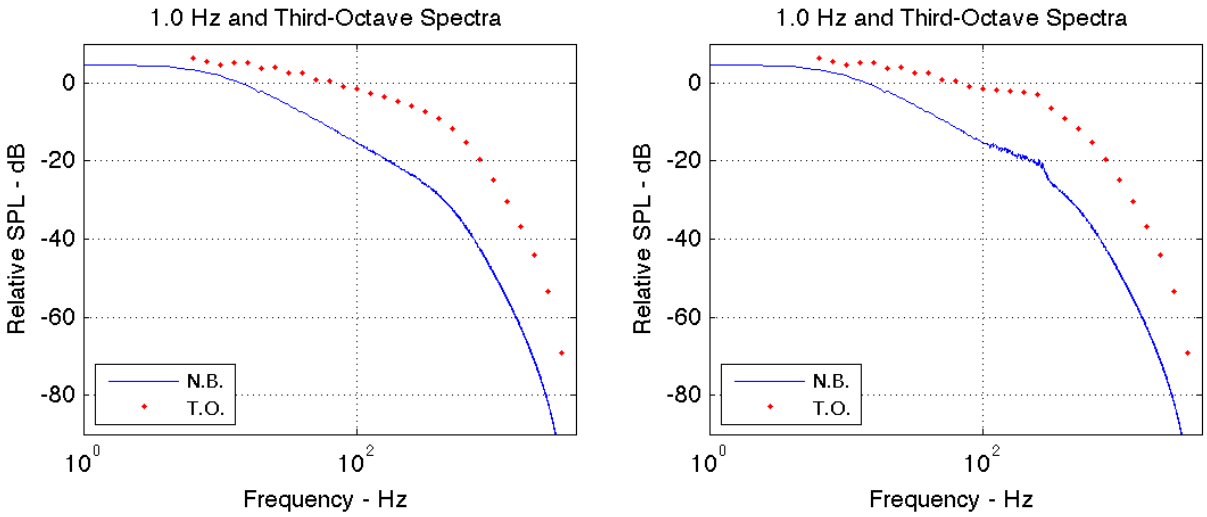

Figure 2. Baseline spectrum of synthesized random noise with and without "Whoosh"

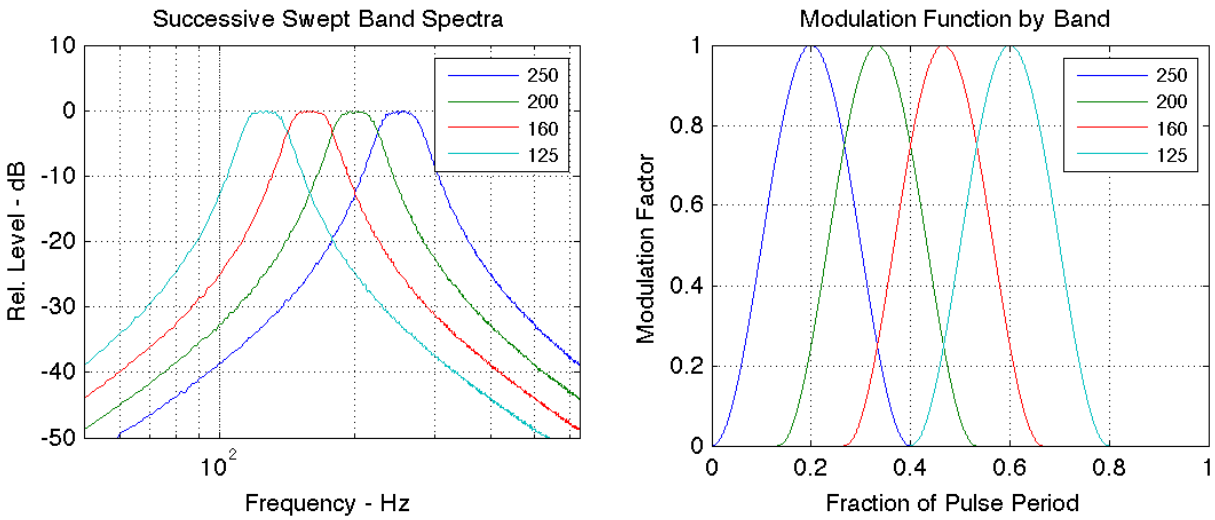

Figure 3. Spectra and modulation sequence for sequenced Doppler shift "Whoosh" simulation

3.0 Data Collection and Monitoring System

To represent the potential effects of turbine noise in noise sensitive (residential) environment, the synthesis system has been set up in a modest-size guest bedroom, approximately 4x5x3 meters. The gravest resonance mode in this space is 37 Hz. The initial intent was that all test signals would have a maximum frequency of 32 Hz so that a relatively simple transfer function from a sealed-enclosure loudspeaker would obtain. The highest SPL of any turbine BPF harmonic observed in the field is approximately 65 dB at 400 meters. The amplitude goal for the synthesis system is 10 dB above this maximum, or at least 75 dB at any frequency over the range 0.8 to 32 Hz.

3.1 Loudspeakers. In a sealed room at frequencies below the gravest resonance, the sound pressure is, per Boyle's law, inversely proportional to the relative variation in room volume. A sealed enclosure loudspeaker modifies the room volume by virtue of diaphragm volume displacement, so a loudspeaker with resonance frequency in the 50 Hz range would operate "stiffness controlled" and ideally provide sound pressure proportional to excitation current.

It was determined that three 18-inch electro-dynamic drivers in a 0.44 m^3 cube enclosure would have a resonance frequency just above 50 Hz and provide linear volume-displacement amplitude of .0036 m^3. In a 60 m3 sealed room, this translates to SPL 106 dB, with significant correction expected at the lowest frequencies due to room leakage and wall flexing. In practice, with full response equalization as described in Section 4, peak infrasound pressure

levels of approximately 97 dB are achieved, nearly 20 dB greater than pressures observed in field measurements.

For audible signal components above 50 Hz, a simple high-quality direct-radiator monitor speaker was set atop the infrasound “cube” as shown in Figure 4.

Figure 4. In-situ photo of synthesis system loudspeakers

3.2 Analog conversion and amplification. Test signals were generated at 8 kHz data rate, with LFIS signals and audible signals on two separate channels. A 16-bit dual channel D to A converter and reconstruction filter were used to generate analog signals, which were then routed to a 5 dB per step ladder attenuator and a dual channel 300 watt DC-coupled power amplifier.

3.3 Monitoring. Four microphones were distributed in the listening room, with the primary position just above the listening seat as shown in Figure 5. The microphones were B&K 4193 with low frequency extensions, having linear response to well below 0.1 Hz. A multichannel simultaneous sampling 24 bit A to D converter was used to capture the microphone signal, the excitation signals and the analog output of an outdoor cup anemometer.

Figure 5. Photo of listening location with monitoring microphones overhead

3.4 System calibration and equalization. In addition to microphone calibration at the beginning of each test day, the output spectrum of the synthesizer had to be adjusted to compensate for room effects. These are primarily leakage losses at very low frequencies and resonances in the range 30-60 Hz.

The first step in the process was a sine wave frequency response measurement, conducted stepwise from 0.8 to 52 Hz in 0.8 Hz increments. The result is shown in Figure 6, which illustrates that room losses are significant below approximately 3 Hz and that room resonances are significant above about 30 Hz. The 7.5 dB drop between 1.6 and 0.8 Hz suggests that both the room and loudspeaker may have leakages that affect the lowest radiation frequencies.

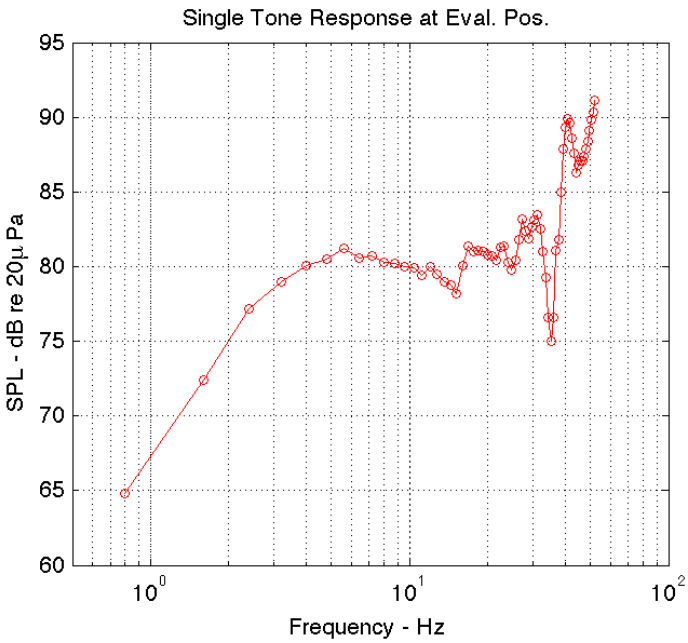

Figure 6. Results of synthesis system frequency response measurement

The second step was to curve fit a 35% over-damped second-order high-pass filter function with 1.9 Hz corner frequency to this data, as shown in Eq.1.

$$Loss = 1 + 1.9i\left(\frac{1.9}{f}\right) - \left(\frac{1.9}{f}\right)^2 \qquad \text{Eq.1}$$

The phase of the model loss function and the inverse of the measured response were used to create equalization factors for the excitation signals as shown in Figure 7.

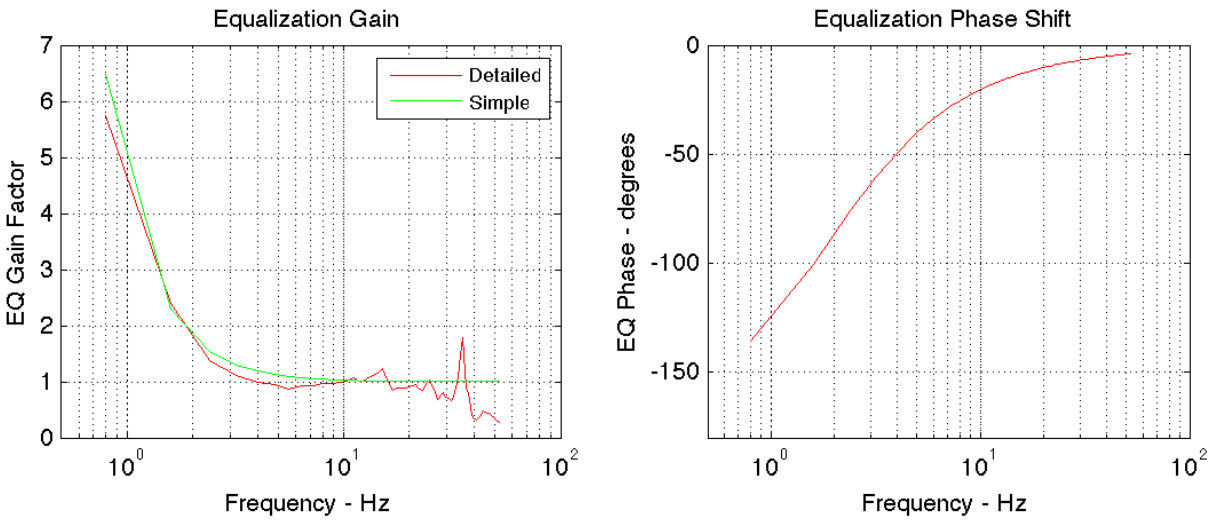

Figure 7. System equalization gain and phase

4.0 Synthesized Infrasound Spectra and Waves

At the onset of the project, two primary infrasound spectra were of interest. This was expanded to include data mimicking interesting field data as well as including audible components as discussed in Section 2.

4.1 N-wave. The first was a classical "N-wave," consisting of a harmonic series

$$Nwave = \sum_{N=1}^{N_{\max}} \frac{\sin(2\pi N BPF\, t)}{N} \qquad \text{Eq. 2}$$

where BPF is the fundamental frequency, which dominates the spectrum, being 6 dB greater than the second harmonic. A useful property of the N-wave is that the maximum slope contribution is the same from each harmonic, so that a slope parameter in the overall wave can be controlled by truncating the spectrum with minimal effect on the total amplitude. An example is shown in Figure 8.

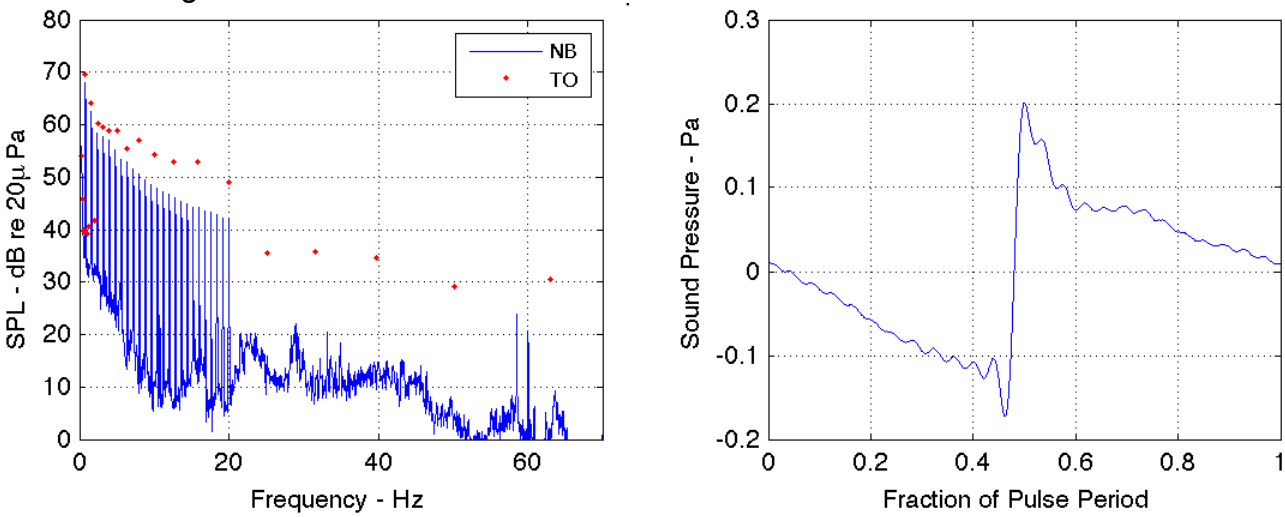

Figure 8. Spectrum and waveform of synthesized N-wave truncated at 20 Hz

4.2 Ch-Wave. Various field tests conducted by the authors and others have shown that the infrasound signature of wind turbines is not as heavily dominated by the fundamental as the N-wave. A more realistic spectrum is approximately flat up to approximately 7 Hz and then drops more rapidly toward higher harmonics, approximately as $1/N^2$ as shown in Figure 9. The Ch-wave has been used for the infrasound component of the preponderance of listening tests conducted with the system.

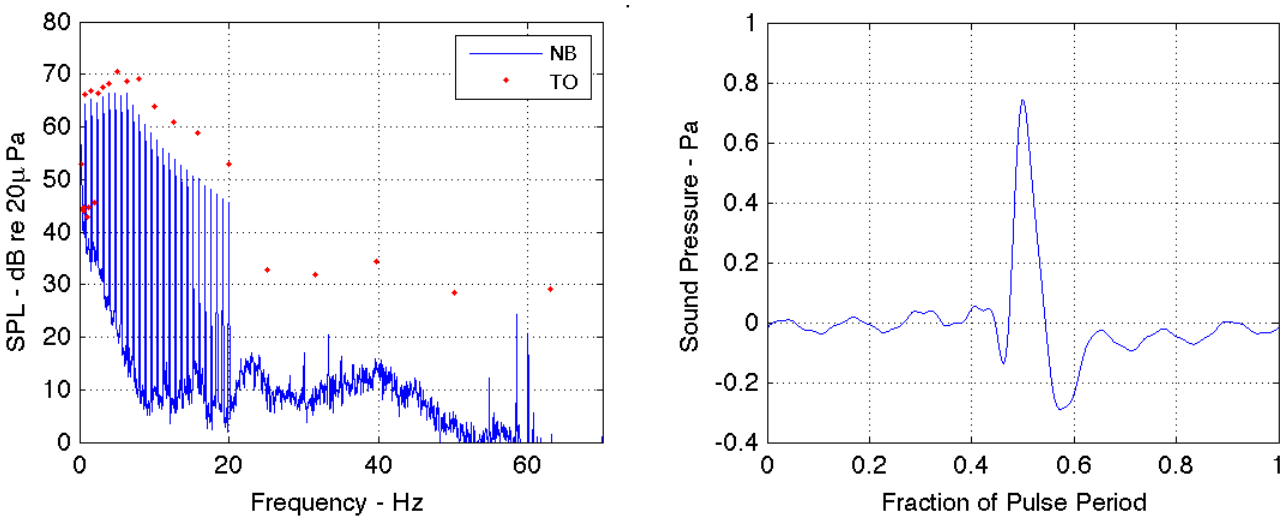

Figure 9. Spectrum and waveform of synthesized Ch-wave truncated at 20 Hz

4.3 Ha(A,H,K,L)-wave. The spectra described above were used for numerous listening tests with evaluators of normal, sensitive and sub-normal hearing acuity. Even with the upper frequency extended to 32 Hz, no evaluator was able to sense the presence of the pulsations at reproduction levels less than 10 dB above those observed in the field.

Hansen, Zajamsek and Hansen (2014), in a study of turbine noise at Waterloo Wind Farm in Australia, observed that in very steady measurement conditions, clusters of BPF-spaced spectral peaks extend into the frequency range 40-50 Hz and above as illustrated in Figure 10.

Analysis of this data is discussed in a companion paper. However, a simplification for synthesis purposes was to simply extend the BPF harmonic series to 52 Hz (65 harmonics or 0.8 Hz BPF) and assign harmonic amplitudes to approximately match power in the measured spectra.

The narrow band spectrum and waveform of the synthesized pulsation signal is shown in Figure 11. It may be noted that the apparent relative spectral levels of the synthesized signal increase with frequency. This is a result of the relative broadening of the measured spectral peaks, presumably due to minor unsteadiness in turbine rotation speed. In one-third octave bands (red dots), the relative spectra agree within approximately 2 dB. The overall spectrum level of the synthesized signal is adjustable as a testing parameter.

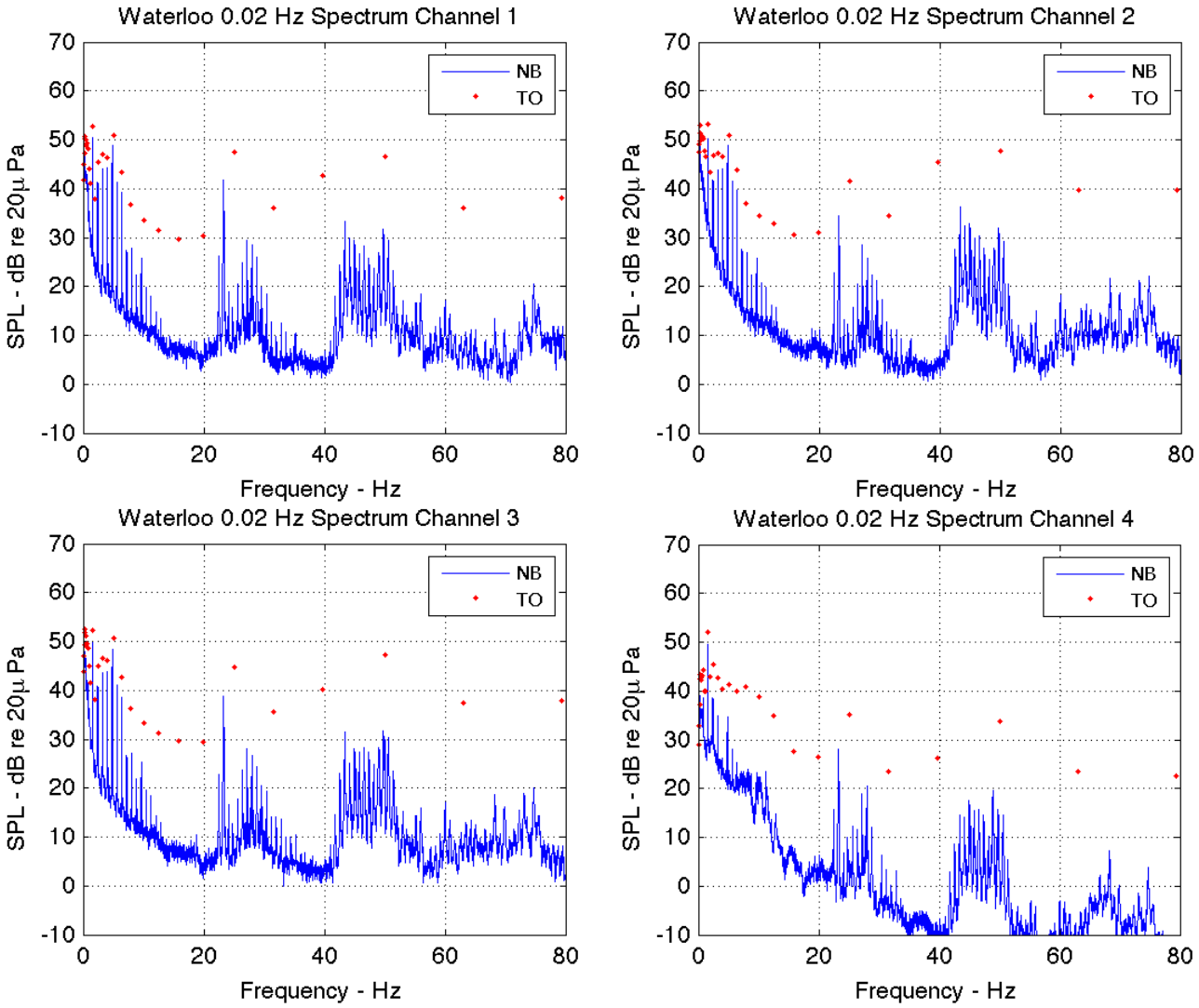

Figure 10. Narrow band spectra from Waterloo Wind Park in quasi-steady conditions. Channel 4 is Indoors.

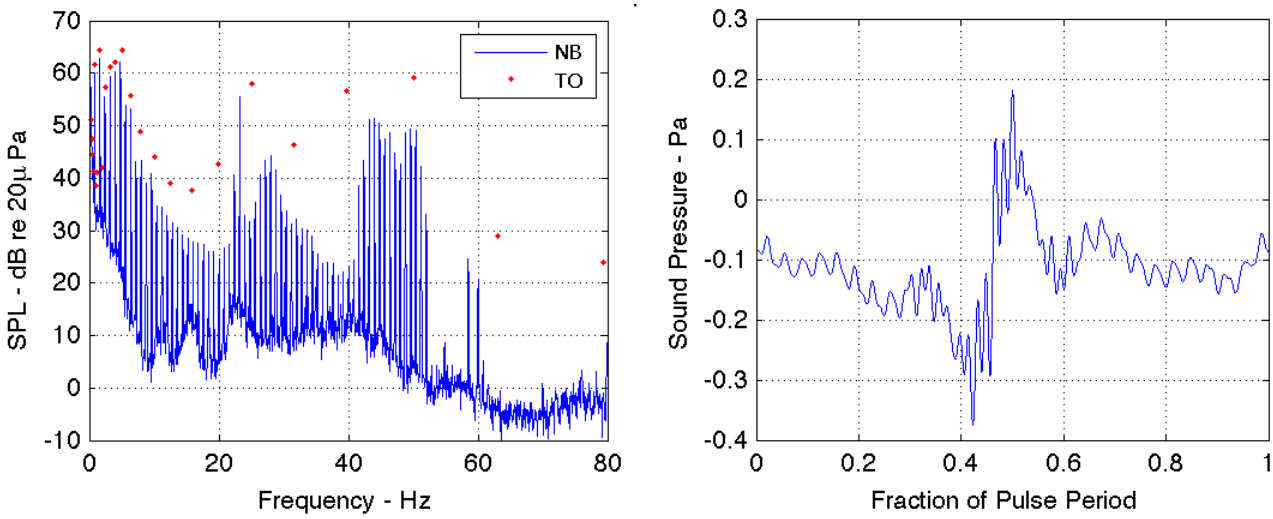

Figure 11. Spectrum and waveform of synthesized HaA-wave representing outdoor Waterloo data

The A,H,K,L designations refer to different portions of the spectrum.

A: All Pass
H: 20 Hz High Pass
K: 30 Hz High Pass
L: 20 Hz Low Pass

These spectra could be selected as test parameters to evaluate the relative importance of the infrasonic, low amplitude tone and pulsating audible low frequency elements in the signal.

4.4 CB-wave. Data published in Nov. 2014 by The Acoustics Group and measured inside a residence near the Cape Bridgewater Wind Farm in Australia showed a particularly high level of infrasound below 6 Hz, together with apparent strong reaction by residents. The published narrow band spectrum and a waveform computed as the sum of sine waves at the six peak spectral amplitudes is reproduced in Figure 12.

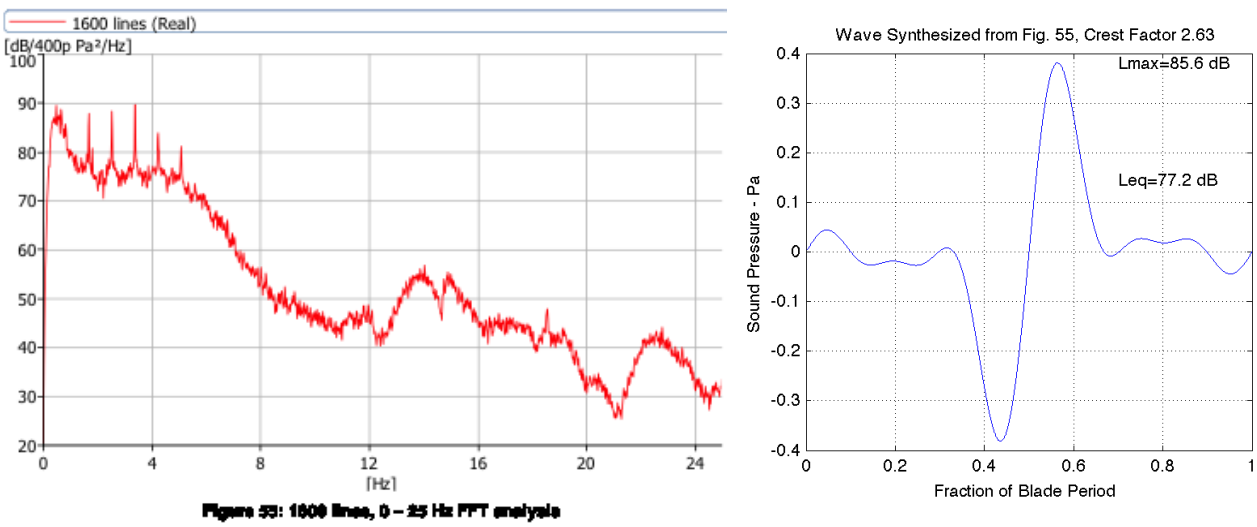

Figure 12. Measured Spectrum from Cape Bridgewater Wind Farm Acoustic Test Report and Computed Pulse Waveform

This wave is essentially Ch-Wave truncated at the 6th harmonic, with peak spectrum levels approximately 72 dB. The result of reproducing and monitoring this wave at approximately 5 dB excess amplitude are shown in the ensemble average recorded wave and its narrow-band spectrum of Figure 13. Although the loudspeaker-reproduced wave is not a perfect duplicate of the computed wave in Figure 12, it only differs slightly and the harmonic distortion manifested above 5 Hz are all over 20 dB below the target harmonics.

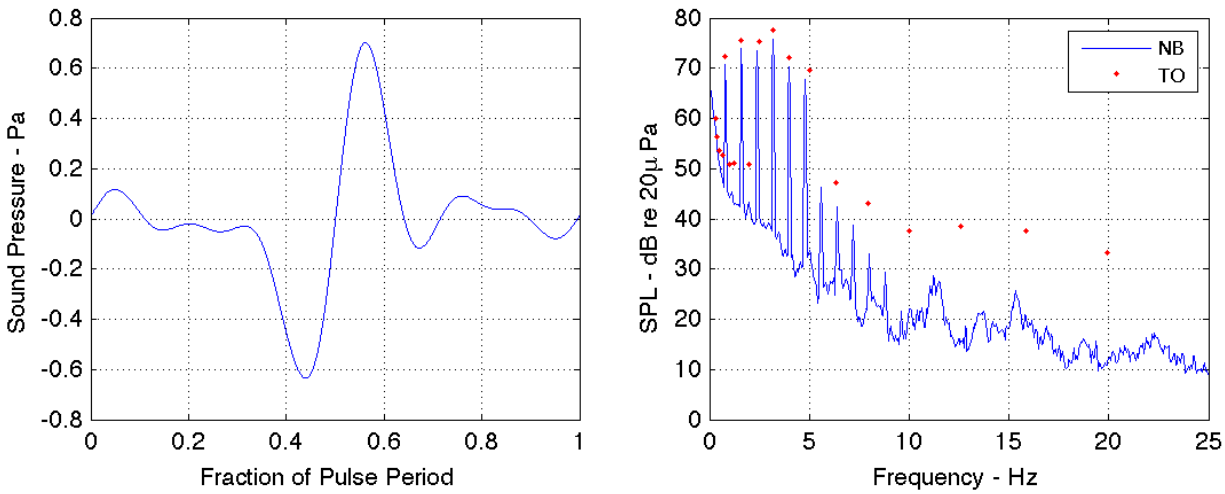

Figure 13. Mean Waveform and Spectrum of Reproduced and Monitored Representation of The Cape Bridgewater data

5.0 Subjective Responses

Three evaluators have been exposed to a wide range of combinations of infrasound, broadband noise, Doppler shift simulated blade "whoosh," amplitude modulated tones and window-gated tones. Four additional evaluators have been exposed to spectrum Ch-wave infrasound (truncated 20 Hz) at peak SPL 92-97 dB. Exposure times ranging from two minutes to one hour have been investigated. Some results of interest are:

> Infrasound alone (spectrum Ch, HaL or CB) has not elicited any response at levels up to 97 dB peak.
>
> Steady random noise with 30-35 dB "Whoosh" and no infrasound on one occasion elicited a nausea response from an evaluator with high sensitivity to low frequency noise.
>
> At 88 dB peak SLP, an evaluator with high sensitivity to low frequency noise reported that presence of infrasound reduced the "roughness" of low-frequency pulsation sound (spectra HaA vs HaH) despite the infrasound (HaL) being undetectable alone.

6.0 Conclusions

It has been demonstrated that simulation of wind turbine noise and infrasound at levels representative of those observed at distances of 100 meters can be accomplished in a typical residential-sized room with a modest array of electro-acoustic actuators. To date, subjective reactions to the synthesized signals are not conclusive due to the small number of test subjects and constrained exposure times. However, no individual thus far has reported any sensation when exposed to infrasound alone at peak levels up to 97 dB.

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