5th International Meeting
on
Wind Turbine Noise
Denver 28 – 30 August 2013

Infrasound Measurement, Interpretation and Misinterpretation

Bruce Walker Channel Islands Acoustics 676 W Highland Dr, Camarillo, CA 930101 USA . E-mail: bwalker@channelislandsacoustics.com

Summary

A portable measurement system comprising three low-frequency microphones, a turbine tachometer and dedicated time-domain signal analysis has been used to collect and evaluate infrasound emissions from large wind turbines. Field measurements of a 2-3 MW range turbine taken with this system indicate that acoustic energy at frequencies below the turbine blade-passage rate is unrelated or weakly related to turbine operation. "Thump" waveforms produced by turbines were shown to be asymmetric and dependent on relative measurement and wind directions. At 100 meters, peak-to-peak amplitude is on the order of 0.5 Pa and peak rate of change of pressure is on the order 7 Pa/second.

The data acquisition portions of the system were deployed in late 2012 on a field test to investigate indoor/outdoor infrasound levels at three homes abandoned by residents objecting to the location of eight 2.5 MW turbines within two km. At one residence, located approximately 400 meters from a turbine, outdoor to indoor coherence was observed for blade-pass harmonics 1-10 (0.7 – 7 Hz), with peak-to-peak thump amplitude approximately 0.26 Pa. Overall sound pressure in the frequency range 0.1 - 10 Hz fluctuated up to ±7 Pa.

1. Introduction

In response to growing concern that sub-audible components of wind turbine acoustic emissions can adversely affect a portion of the exposed human population, an effort is underway to determine parameters of very-low-frequency (infrasonic) wind turbine emissions relative to potential human sensitivity. This requires a data acquisition system capable of capturing amplitude and phase accurate acoustic signals ranging to well below the blade-passage frequency. However, because atmospheric pressure variations of high amplitude are known to be present in windy environments[1,2], signal post-processing must be capable of separating the turbine-emitted infrasound from unrelated signal components, without affecting the potentially important wave-shape related parameters of the turbine emissions. A relatively simple system satisfying these requirements was developed and initial test results were reported at Low Frequency Noise 2012 in Stratford Upon Avon, UK[3].

In parallel with the measurement system development, a reproduction system capable of adjusting various wave parameters including fundamental frequency, overall amplitude, peak to rms ratio, maximum wave slope has been constructed that would allow rating subjective response to likely combinations of parameters and to guide efforts to reduce sensitivity potential.

The elements of the infrasound measurement system have been recently employed in two interesting studies. First is a detailed investigation of turbine noise emissions conducted by University of Minnesota in June, 2012, and the second was a field investigation of infrasound immission at a community near Green Bay, Wisconsin in December, 2012. In the emission test, special instrumentation on the test turbine allowed a much better implementation of the signal processing concept that had been possible under field conditions reported at LFN2012. In the immission test, three residents had abandoned their homes, putatively as the result of intolerance to the low frequency acoustical environment that commenced with the installation of

eight large turbines, distributed around the community. Extensive broadband acoustic data extending down to 0.1 Hz indoors and 0.4 Hz outdoors was collected and analyzed. It was determined that turbine infrasound was detectable at approximately 76 dB peak SPL in one of the residences and that failure to implement high-pass filtering of acoustic signals below 0.5 Hz would result in high measurement levels that were unrepresentative of infrasound emitted by turbines.

2. Test methodology

2.1 Concept The basic idea behind the infrasound measurement system is a relatively large (10 meter diameter) sparse array of low frequency microphones, the signals from which are delayed-summed and synchronously ensemble averaged to extract periodic blade-rate harmonic signals from ambient infrasound.

2.2 Data Acquisition Three Bruel & Kjaer type 4193 microphones and signal conditioning amplifiers with 0.1 Hz – 10 kHz frequency range were used to record acoustic emissions from a large wind turbine as part of an intense investigation of turbine noise directivity at University of Minnesota in June, 2012. The microphones were located on ground boards in a 10 meter diameter array as shown schematically in **Figure 1** and illustrated In a photo from the turbine nacelle in **Figure 2**. Several hours of turbine run and turbine park condition recordings were collected over a three-day period, spanning wind speeds 2 – 14 meters per second and multiple wind directions. In addition to the acoustic data, turbine tachometer signals at 1 and 48 per revolution were recorded simultaneously. Wind and other non-acoustic parameters were recorded on the turbine's data logging system.

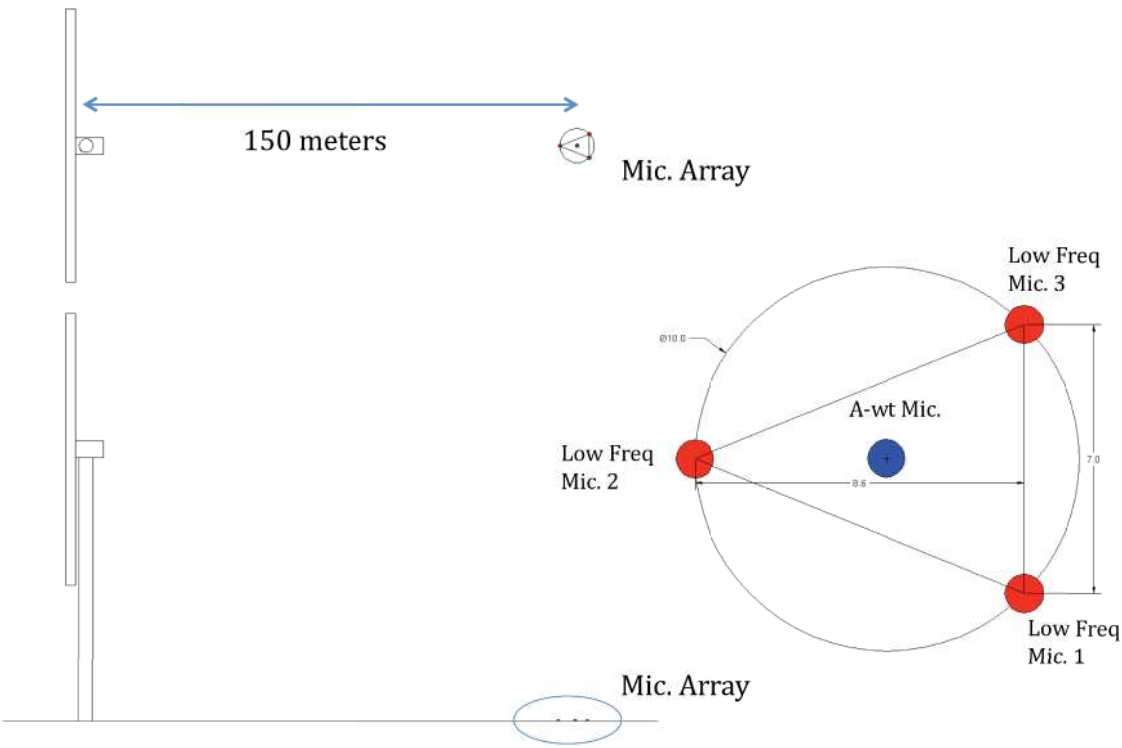

Figure 1. Schematic Layout of Low Frequency Data Acquisition Array

Figure 2. Photo of Low Frequency Array from Turbine Nacelle

2.3 Microphone Calibration The microphones at each test were calibrated using standard acoustic calibrators at 1 Pa rms (94 dB), 1 kHz. To ensure reasonable results in the infrasound range, a simple manual test was conducted. Near sea level, the static vertical atmospheric pressure gradient is approximately -10 Pa per meter. The data acquisition system was used to record microphone output as it was moved slowly and quasi-sinusoidally in a 1 meter peak-to-peak traverse, vertically, laterally and again vertically. The results of this simple test are shown in Figure 3. Although the 0.1 Hz high-pass signal conditioning and residual atmospheric infrasound cause some baseline wandering, the 10 Pa P-P (105 dB) wave is well captured.

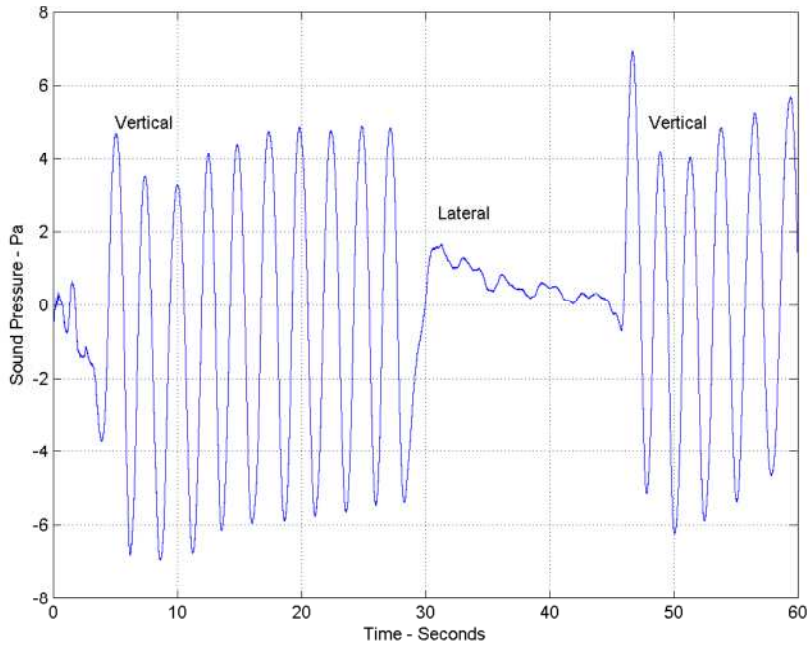

Figure 3. Results of Manual Microphone Movement Calibration Check

2.3 Post Processing The recorded data was analyzed in ten minute blocks, in a manner reported at LFN2012. The signals were decimated to retain low-frequency information and phaseless[4] high-pass filtered at 2/3 the turbine blade-pass frequency to reject excessive very low frequency ambient infrasound. Cross correlations were computed and used to determine

time-offsets for the three microphone signals. The signals were appropriately time-aligned and summed as the second step to suppress random ambient and wind-induced noise. The resulting composite signal was re-sampled to a fixed count per turbine revolution, using the 1x tachometer pulses as time reference. The turbine-synchronized signals from 150 ± revolutions were averaged to educe the periodic infrasonic wave emitted by the turbine. The Fourier transform of the ensemble average wave was computed to determine the amplitude and phase of the shaft-order spectrum components.

2.4 Microphone Adaptation for Indoor Measurements The indoor acoustic environment lacks microphone wind exposure and an unambiguous propagation path. However, as shown in Figure 4, there is substantial infrasound present, even with no wind turbines in the area. The low frequency microphones were distributed to representative rooms or room locations in subject residences. A reference low frequency microphone, with lower limit frequency 0.4 Hz, was located outdoors on a ground board with primary and secondary wind screens in the direction between the subject residences and nearest turbines. Data was recorded in 10-minute blocks with simultaneous monitoring of ground level winds.

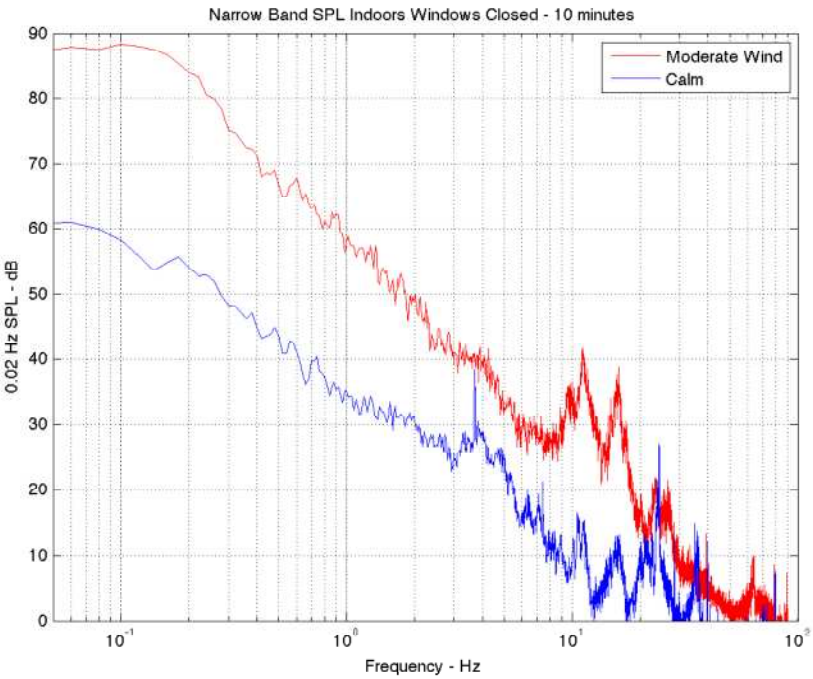

Figure 4. Very Narrow Band Spectra Measured Remote from Turbines

2.5 Indoor Measurement Processing To establish a relationship between turbine noise outdoors and infrasound exposure indoors, cross-spectrographs were computed with 0.1 Hz frequency resolution and 20 second time resolution. Narrow band spectra and coherences were computed for each 10-minute measurement block. To assess an upper-bound turbine infrasound exposure, the recorded signals were high-pass filtered at 0.5 Hz, low-pass-filtered at 24 Hz and plotted as decibels in 20 ms blocks. Power spectra for periods identified as having significant coherence between outdoors and indoors were used to synthesize acoustic waves, based on a harmonic phase relationship that maximized either wave peak amplitude or wave peak slope.

3.0 Emission Measurement Results

In this section, representative results from each stage of the data processing and analysis are presented and discussed briefly.

3.1 Spectrum and Cross Spectrum Analysis The Run and Park 1/3-octave band frequency spectra for a representative pair of measurements at approximately 11 mps wind speed are shown in Figure 5 and Figure 6.

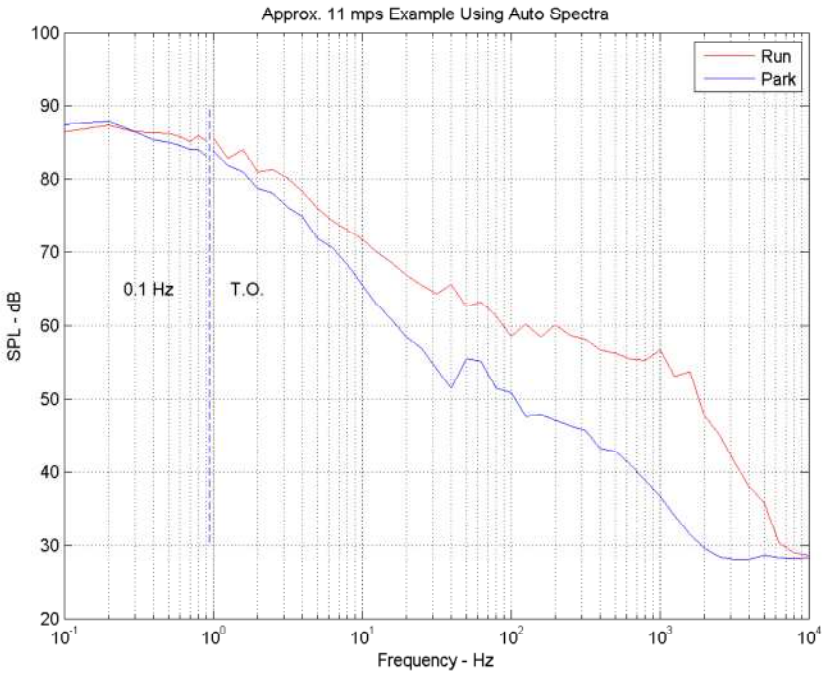

Figure 5. Run and Park Mean Auto-Spectra

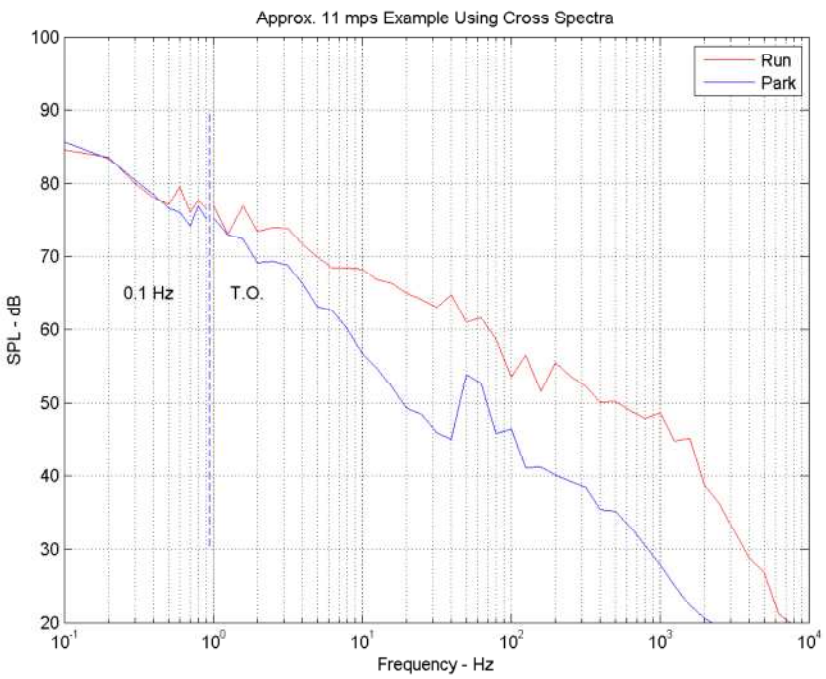

Figure 6. Run and Park Mean Cross-Spectra

The third-octave spectra are computed from 0.1 Hz power and cross-power spectra. Below 1 Hz, the plotted values are the measured 0.1 Hz spectral levels corrected to T.O. bandwidth by 10 $\log_{10}(0.26\ f)$. The graphs indicate that the SNR is very good above 10 Hz for the cross spectra and above 20 Hz for the auto spectra. At the higher frequencies, cross-spectra appear to suppress measurement system noise, but loss of coherence in the turbulent propagation medium causes a systematic reduction of level above 100 Hz. The graphs hint at spectral peaks at blade-pass harmonics from 0.7-10 Hz and show that below 0.5 Hz, there is essentially no difference between Park and Run.

3.2 Cross-Correlation Analysis The delay between noise emission and microphone positions is estimated from cross-correlation of high-pass filtered pairs of microphone signals. A typical example is shown in Figure 7. The upper graph shows ±6 seconds of delay, with blade periodicity at 1.4 seconds evident. The lower graph is an expanded picture of the central peak, which shows that signals at the two rear microphones in the array (1 and 3) are

synchronous from the source and delayed 20 ms from the front mic (2). These delay factors are used in an align-and-sum creation of a composite low frequency acoustic signal.

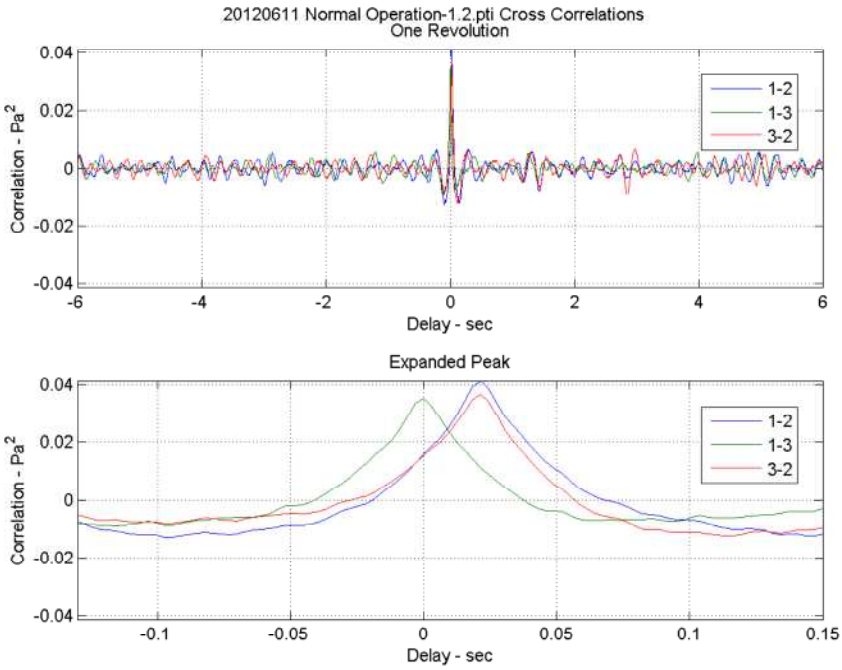

Figure 7. Example Cross-Correlation Result

3.3 Synchronous Ensemble Averages Modern large turbines do not turn at steady speed, but rather are allowed to adjust rapidly to wind speed fluctuations. To allow ensemble averaging over multiple turbine revolutions, the three-mic composite signal was re-sampled at 12,500 samples per revolution. The nominal 150 revolution blocks were averaged to educe shaft-synchronized signal components. Representative results are shown in Figure 8 and Figure 9.

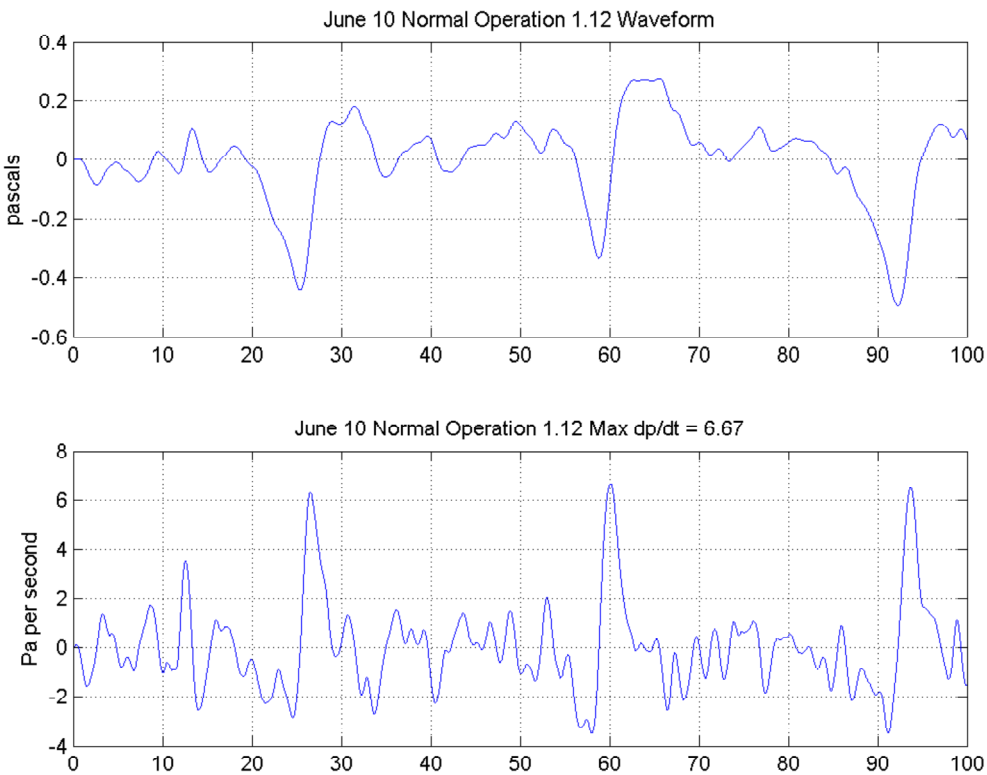

Figure 8. Example Waveform and Time Derivative for Day 1 with Wind Direction approx 140° re Mic Orientation

The figures show example waveforms truncated at 50 shaft orders and their nominal time derivatives for two days with approximately opposite wind direction relative to the microphone orientation. On day one, the emphasis is on the negative-going pressure and on day two the emphasis is on positive-going pressure. In both cases, the maximum wave slopes occurred at roughly 27, 60 and 93 percent of the rotation.

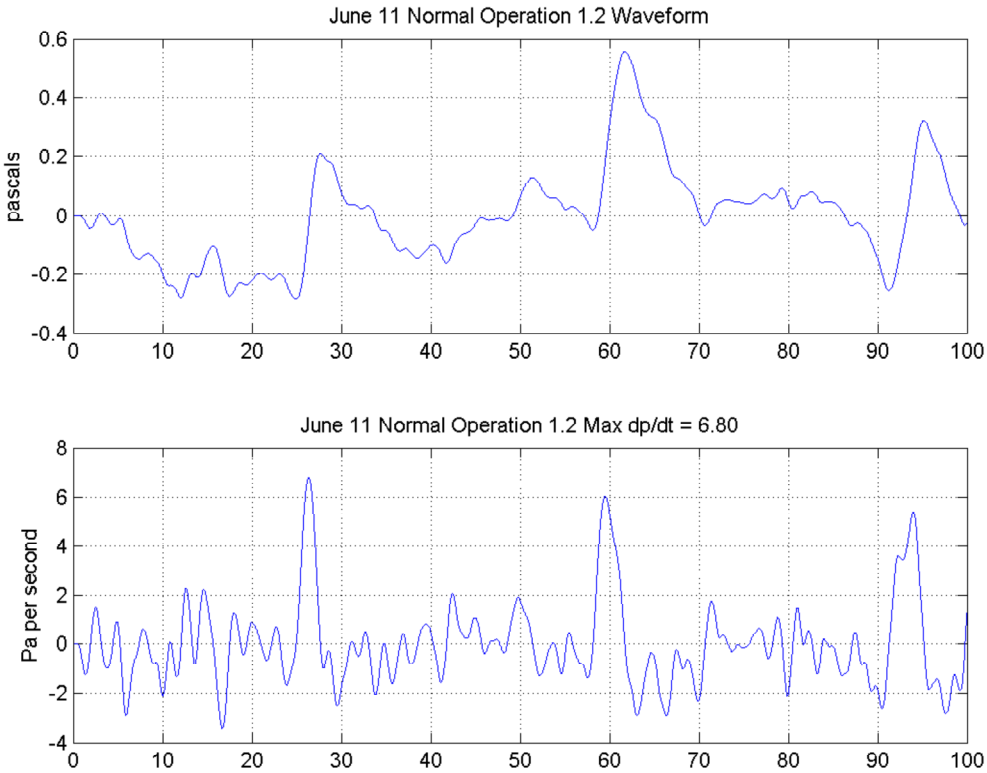

Figure 9. Example Waveform and Tine Derivative for Day 2 with Wind Direction approx 60° re Mic Orientation

3.4 Spectral Analysis of Synchronous Waves The synchronous waves were computed as ensemble averages from data re-sampled to 12,500 per rotor revolution. The Fourier transforms of these waves were computed for 111 ea. 10-minute measurement blocks. Figure 10 shows a representative example.

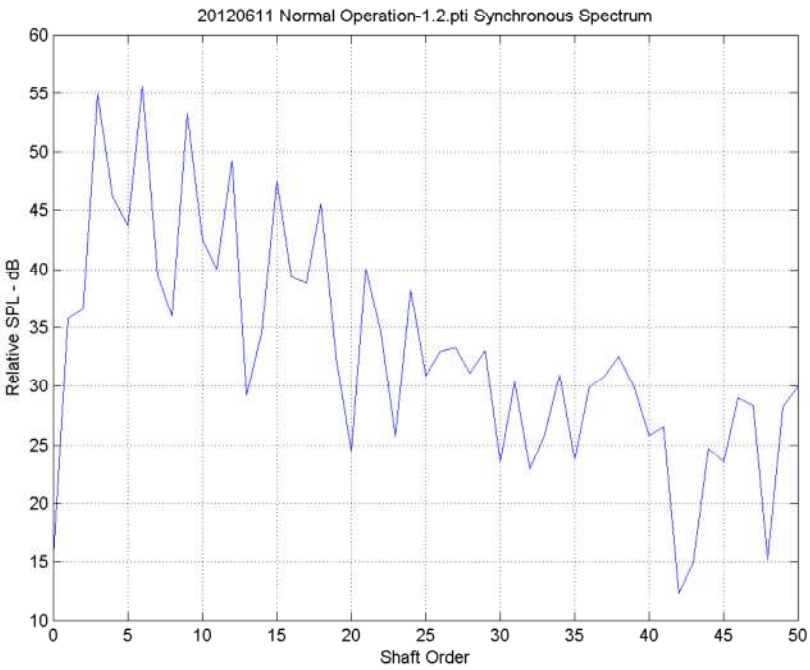

Figure 10. Shaft Order Spectrum for Wave shown in Figure 9

Spectra were computed and averaged for 52 and 59 10-minute measurement samples on Day 1 and Day 2, respectively, with some key results shown in Table 1. In addition, the complex amplitudes of the Shaft Order and Blade Order harmonics were plotted as shown in Figure 11. It may be noted that the mean rms amplitudes of the fundamental shaft order (SO1) and blade-order (SO3) components are similar, the variability of the shaft order component phase is large, resulting in a low correlation to rotor rotation. The Blade Order complex amplitudes (phasors) show clear trends the shift with the wind direction shift, whereas the Shaft Order phasors are essentially random. When the phasors for SO1 and SO3 were averaged over the 50+ measurement samples, SO1 was 12 dB lower than SO3 on Day 1 and 25 dB lower on Day 2. This is consistent with the very low difference between Run and Park sound levels in the 0.2-0.3 Hz range as indicated in Figure 6.

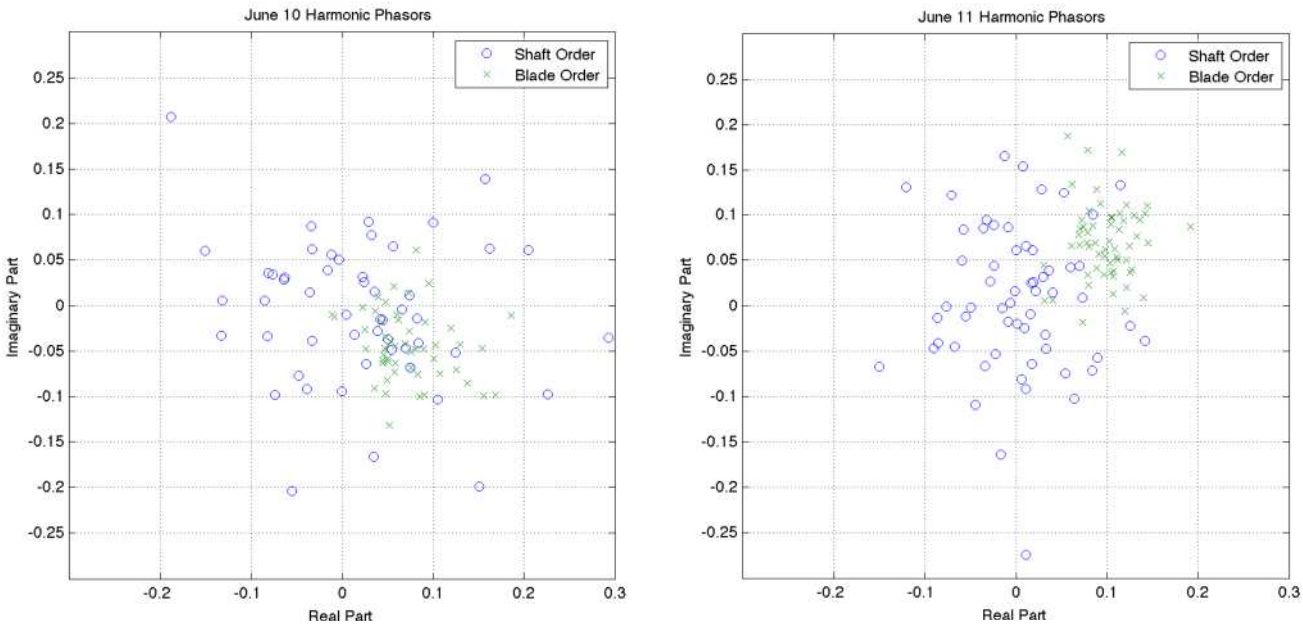

Figure 11. Complex Harmonic Amplitudes for Shaft and Blade Order Components of Ensemble Averaged Waves

Table 1. Summary of Thump Overall, Shaft Order 1 and Shaft Order 3 (BPF) Amplitudes (Pa) and Phases

Test Day		Thump P-P	Max dp/dt	SO1 RMS	SO3 RMS	SO1 deg	SO3 deg	SO1 Phasor	SO3 Phasor
1	Mean	0.47	6.74	0.11	0.09	13	-34	0.021	0.084
	S.Dev.	0.09	1.68	0.07	0.04	96	31	0.126	0.056
2	Mean	0.51	7.51	0.09	0.13	-7	33	0.007	0.121
	S.Dev.	0.04	0.92	0.05	0.04	102	17	0.101	0.051

Figure 12 a and b show the individual 10-minute block values of Thump P-P and Max dp/dt versus the average hub wind speed for the two measurement days. It may be noted that the range of wind speeds was somewhat greater on June 10, partially resulting in the larger standard deviations shown in Table 1.

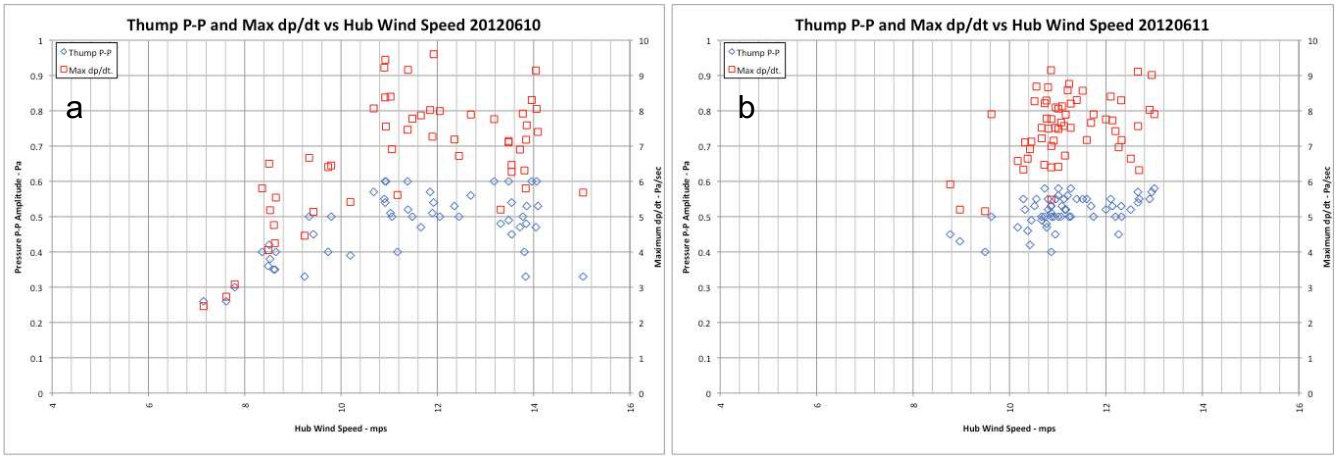

Figure 12. Scatter Plots of Thump P-P and Max dp/dt vs Hub Wind Speed

4.0 Immission Measurement Results

Figure 13 is an illustration the division of acoustic energy indoors. Only infrasound is included, with data low-pass filtered at 24 Hz. The red curves represent 20 ms block averages of all energy below 24 Hz for a minute encompassing a near-maximum signal event. The green curve shows the result of high-pass filtering the data at 0.5 Hz and the blue curve is the date low-pass filtered at 0.5 Hz. The blade-pass rate of the turbines to which the residence was exposed is 0.7 Hz. Two important inferences can be made from this (and many other similar) curve. First, over 90% of the acoustic energy in the data is below 0.5 Hz and therefore highly unlikely to be related to turbine emissions. Reporting the levels from the red curve as “turbine infrasound” is inappropriate. Second, even the energy represented by the green curve is generally not well synchronized with the turbine BPF and therefore also not reportable as “turbine infrasound.”

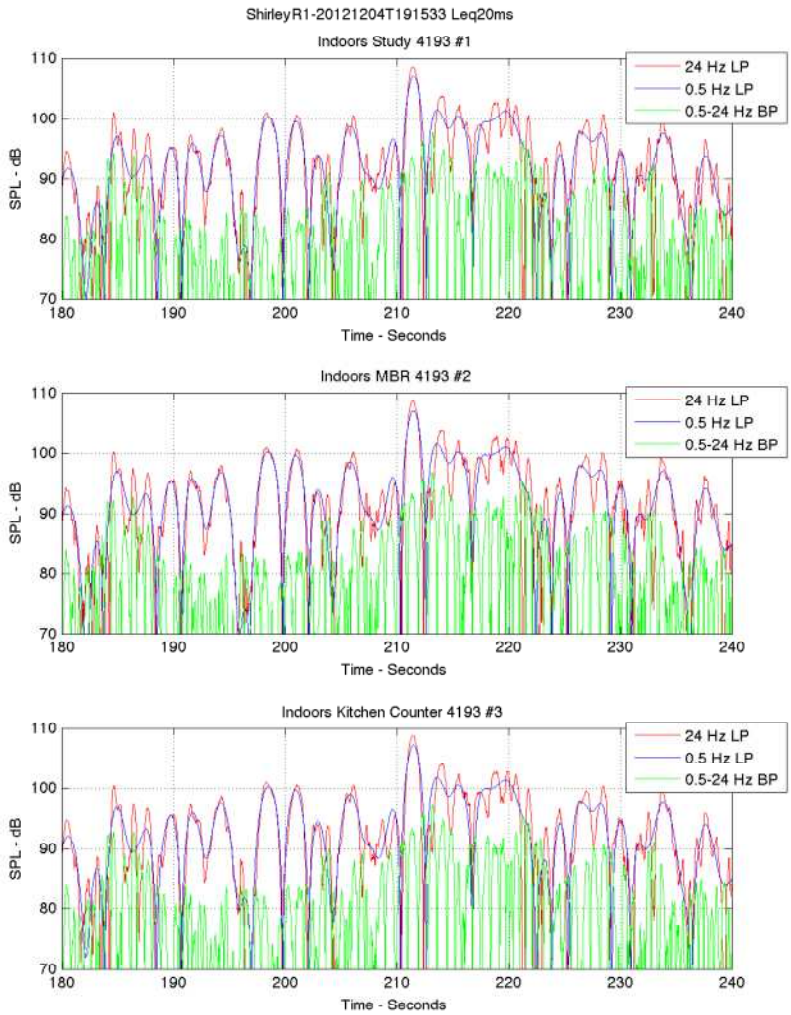

Figure 13. Examples of Low-Pass vs Band Pass Data from Residence 1 in Moderate Wind

Figure 14a shows narrow band and third-octave spectra measured outside (red) and inside (green) a residence exposed to four wind turbines approximately 1,000 meters distant. The outside microphone rolls off at 0.4 Hz. The final (blue) graph shows the coherence between the outdoor and indoor measurements. This indicates that although infrasound above 90 dB is present in the residence, there is very little correlation between this signal and the outdoor signal, particularly at the blade-passage harmonic range. There is a mechanical tone of about 28 dB at 300 Hz that transmits into the residence and shows substantial coherence.

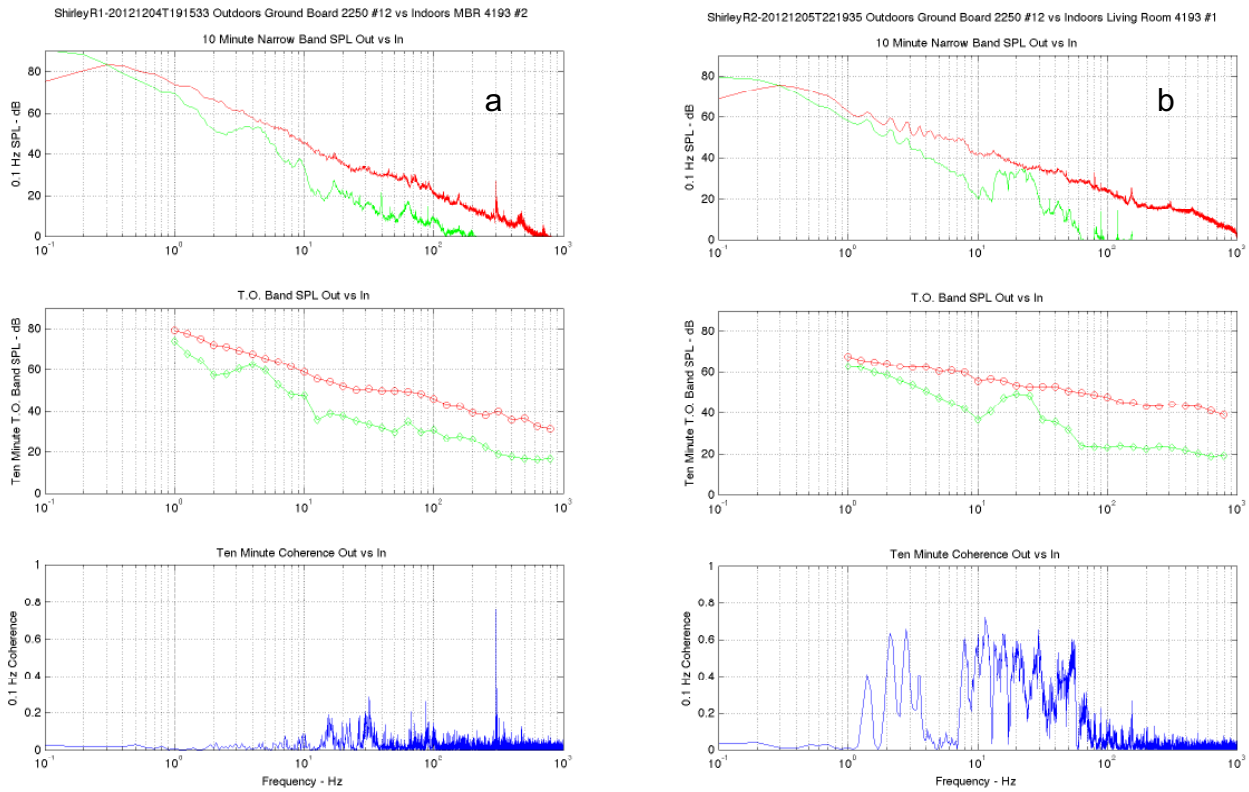

Figure 14. Example of Narrow Band Spectra Inside and Outside a) Residence 1 in Moderate-High Wind and b) Residence 2 in Low-Moderate Wind

In contrast, Figure 14b shows the spectra and coherence for Residence 2 at approximately 400 meters from two turbines. In this case, the turbine blade-pass harmonics are seen both in the narrow band spectra and in the coherence. Note that the spectrum levels are in the 60 dB range.

As a final example, Figure 15 shows an infrasound event caused by a helicopter overflight at Residence 3, roughly 2,000 meters from the nearest turbines. The spectra and coherence show very little evidence of turbine blade-pass effect, while the cross-spectrograph shows the helicopter Doppler effect quite convincingly.

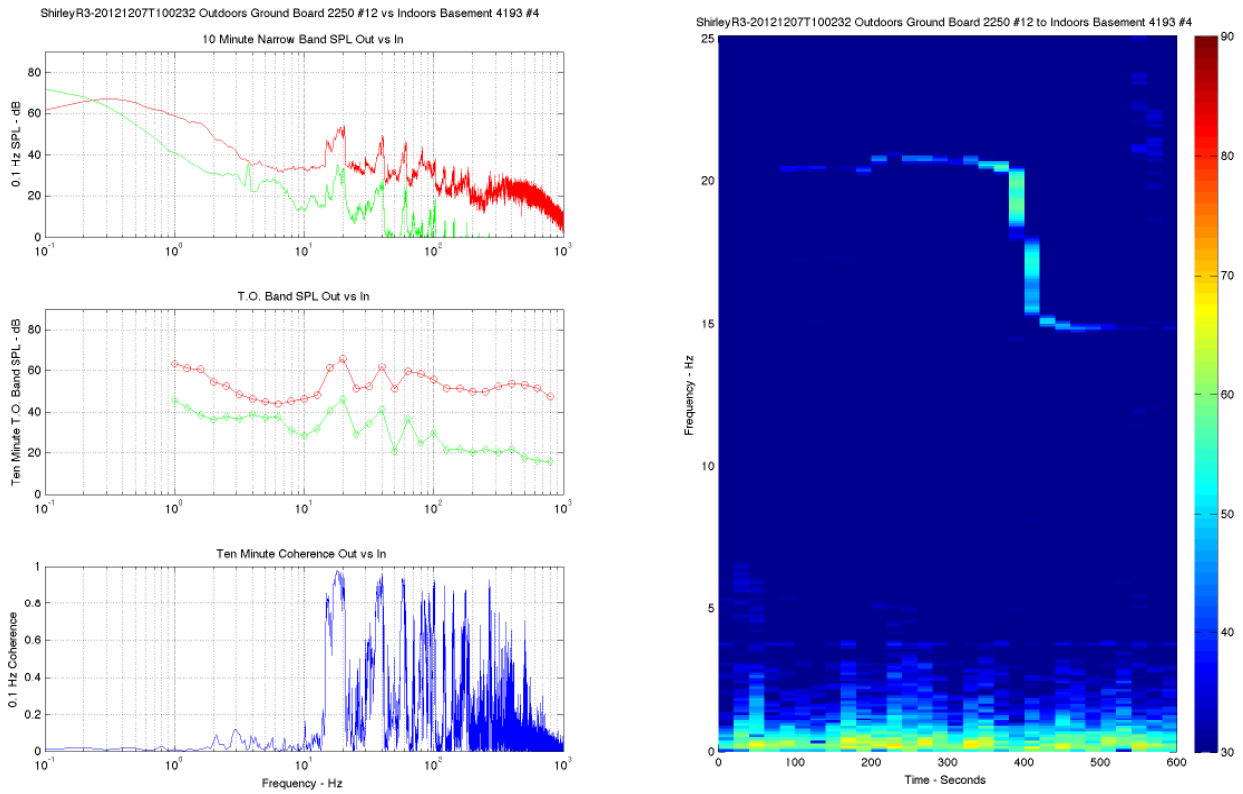

Figure 15. Spectra and Cross Spectrograph of Residence 3 Basement with Helicopter Flyover

In order to assess the turbine BPF related infrasound at the one residence where clear evidence of measureable levels was observed, the cross spectrum was computed in 20-second blocks and the clearest one selected for analysis. Spectral peaks from 0.7 to 8.4 Hz were estimated from the spectrum shown in Figure 16 and a composite wave was synthesized, assuming harmonic phases would combine to maximise the wave slope. The synthesized wave, with peak SPL 76 dB and maximum slope 2.1 Pa per second, is shown in Figure 17. This is in reasonable agreement with the single turbine slope around 7 Pa/sec measured for a single turbine at 100 meters.

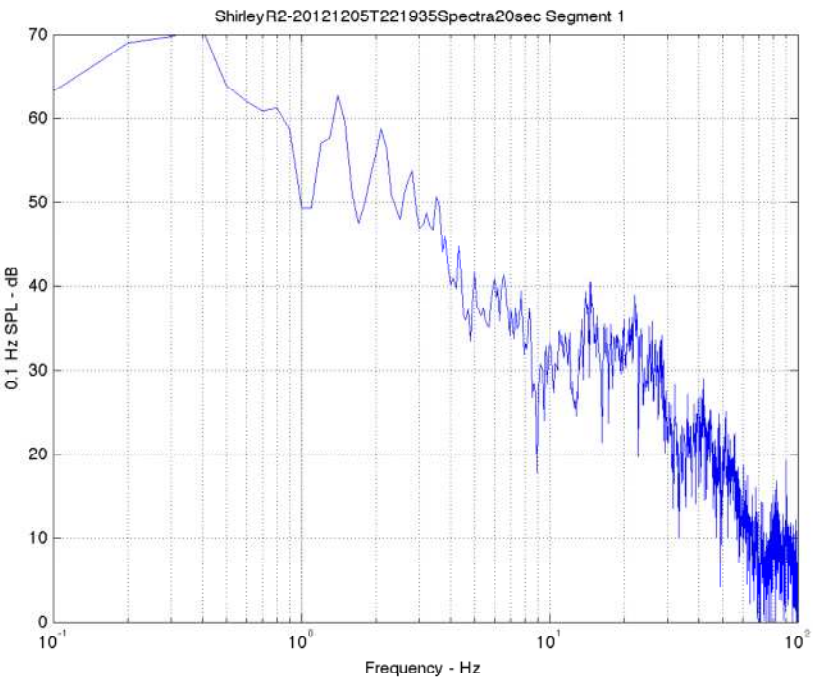

Figure 16. Clearest 20-second spectrum displaying Turbine BPF Harmonics at Residence 2

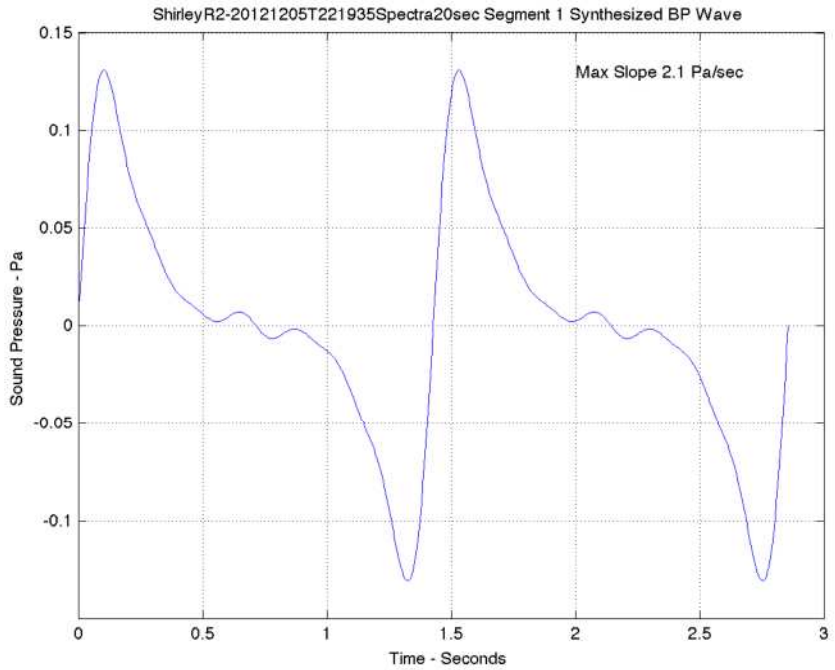

Figure 17. Waveform synthesized from the harmonic series shown below 10 Hz in Figure 16

Figure 18 shows the recorded time history from which the prior synthesis was derived. Signal components below 0.5 Hz have been filtered out. At least eight repetitions of a pattern similar to suggested by Figure 17 are evident. There is also evidence of unrelated transients.

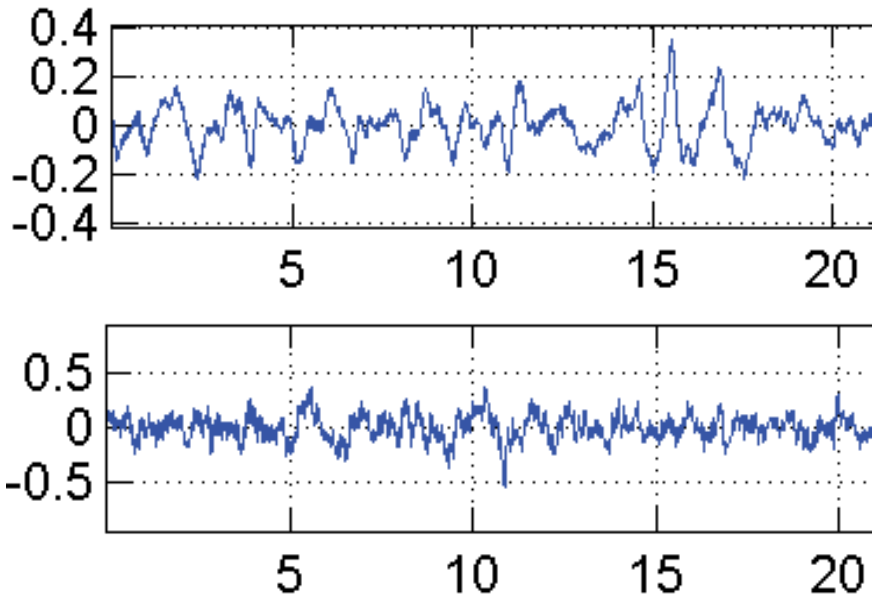

Figure 18. 0.5 Hz Phaseless High-Pass Filtered Waves Indoors (upper) and Outdoors at R2 corresponding to Spectrum of Figure 14.

4.0 Turbine Thump Simulator Progress

The simulator consists of a 0.8 meter cube enclosure designed for installation in the corner of a sealed room and with high-power 0.46 meter diameter electro-dynamic transducers on the three exposed faces. The fundamental resonance frequency is 50 Hz, so that response is defined by transducer displacement per ampere of excitation current. In a sealed room with dimensions smaller than ½ wavelength of the lowest frequency of interest (24 Hz – 7 meters), the sound pressure in the room is therefore proportional to the excitation current.

Excitation is provided by a 450 watt amplifier with response to below 1 Hz. The excitation signal is a truncated harmonic series of fundamental frequency 0.8 Hz, with harmonic

amplitudes and phases individually controlled. A wide variety of spectra, crest factors and maximum wave slopes can therefore be presented for evaluation. An example output for a series of harmonics truncated at 20 and with phase 0 degrees is shown in Figure 19.

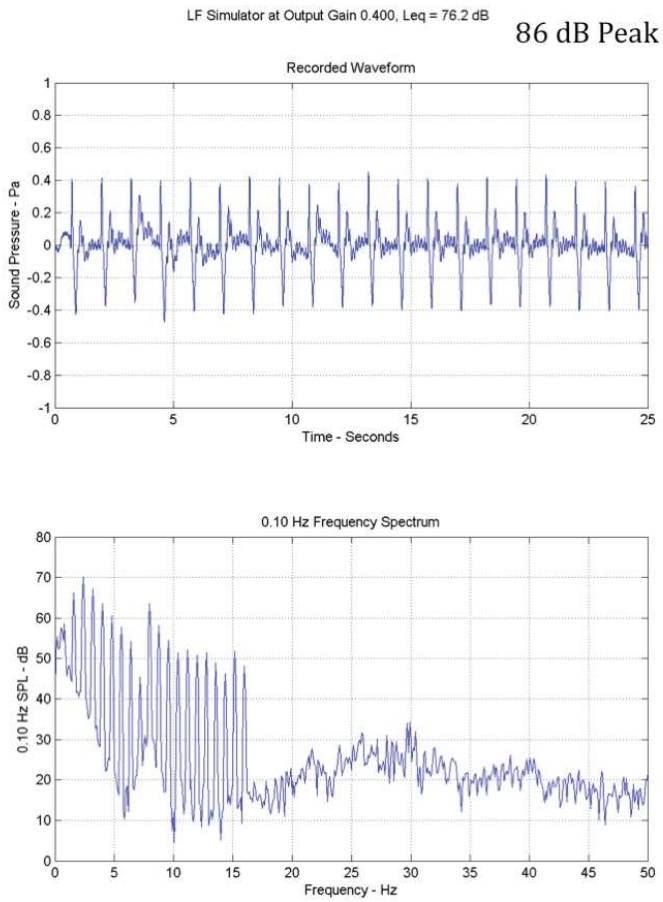

Figure 19. Example output of Thump Simulator in a large room at maximum undistorted excitation

5.0 Conclusions

Measurement of infrasound radiation and reception from large wind turbines has been achieved with good success, with results that confirm the need to examine more than the power spectrum or LG_{eq} to evaluate potential human response. Emitted periodic waves appear to be characterized by a relatively steep wave-slope and moderately high crest factor. The amplitudes of observed wave harmonics appear to be well below known sensation thresholds.

The author's *conjecture* is that perhaps the periodic sequence of relatively sharp time-derivatives of pressure may in some individuals circumvent the evolved rejection of naturally occurring infrasound.

Reporting of low-pass filtered, un-weighted sound pressure levels as turbine infrasound has been shown to exaggerate the magnitude of the issue by 10 dB or (much) more if microphones adequate to accurately record turbine emissions are employed.

References

1. T Hauf, U Finke, J Neisser, G Bull, JG Stangenberg, "A Ground-Based Network for Atmospheric Pressure Fluctuations," Journal of Atmospheric and Oceanic Technology, V 13 p 1001, October 1996
2. FD Shields, "Low-frequency wind noise correlation in microphone arrays," JASA 116(6) p 3499, June 2005
3. B Walker, "Time domain analysis of low frequency wind turbine noise," 15th International Meeting on Low Frequency Noise and Vibration and its Control, May 2012
4. Matlab Technical Manual, filtfilt() function

Acknowledgements

Robert Dougherty
Delores Walker
George Augspurger
Joseph Celano
George Hessler
Bruel & Kjaer Instruments