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Correlating very low frequency sound pulse to audible wind turbine sound

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Abstract

Low frequency pulses have been extracted from measured auto-correlations of wind turbine noise. These pulses were observed in about 1/3 of the data sets reviewed and are dominated by the first few harmonics of the blade passage frequency. Higher order harmonics in the audible frequency range are shown to contribute to the characteristic 'swoosh' when propagation effects through a turbulent atmosphere are accounted for. Variability in the shape of the low frequency pulses can be attributed to frequency dependent refraction effects induced by wind and temperature gradients.

Introduction

Sound emissions from operating wind farms frequently give rise to noise complaints. Most compliance based noise audits measure hourly "A" weighted Leq, thereby removing the low-frequency contents of the wind turbine sound. The metric is also insensitive to amplitude modulation and is unsatisfactory when sensitive receptor are annoyed by the low frequency sound and amplitude modulation.

The wind turbine industry and regulators have not vigorously pursued controlled psycho-acoustic research of the kind used to address annoyance of aircraft and traffic noise. It is not surprising that individuals and interest groups opposed to wind farms point to a lack of research on wind turbine sound. There also claims of serious health effects to humans and animals from exposure to wind turbine noise [1,2]. There appears to be no supporting evidence for the latter [3,4].

Steady audible wind turbine sound is generated by the turbulent layer on the rotor blades and the vorticity shed therefrom. The overall spectrum shape and sound power levels correlate reasonably well with empirical models originally developed for propeller noise. Richarz et al. [5] showed that the sound radiated by compact, directional sources located at about 80% of the blade span could explain amplitude modulation.

Amplitude modulation, swooshing and other periodic sounds are factors that influence the loudness and possibly annoyance reported by some listeners. It is relatively straight-forward to document physical parameters such as the sound pressure and its spectrum. For source-listener separations greater than about 300m the infra-sound is well below the level of human perception. This paper explores some aspects of the periodic features of the sound. To this end, spectral analysis is replaced by auto-correlations of wind turbine sound. When propagation through a real, dynamic atmosphere are incorporated another potential source for the 'swoosh' is discovered.

Measurement

Aercoustics Engineering routinely conducts measurements to document sound emissions from wind turbines and to assess noise impact. Previous work with wind turbine noise monitoring led to the conclusion that sound pressures be recorded for short one to two minute intervals, permitting extended un-attended real-time monitoring [6]. Data analysis is performed at the conclusion the session. Sound is measured with a low frequency microphone and preamplifier mounted on a 1m diameter solid ground plane. The microphone is fitted with a 90 mm windscreen and all electrical connections are waterproof. A large hemispherical windscreen affords further protection from wind and the elements. The measured sound was recorded on a Rion DA-20 digital data recorder. The recording equipment low frequency cut-off is at 1 Hz Data from several sites in Canada and the USA was used in this study.

Low Frequency Wind Turbine Sound

The low frequency portion of wind turbine sound (Figure 1) is characterized by distinct tones at the blade passage frequency and its harmonics. There is also wind noise and, in above 10 Hz mechanical sounds from the electrical generator. Above 10 Hz the magnitudes of the blade passage harmonics diminish rapidly and are obscured by the broad-band pseudo-sound of the atmosphere. Betke and Remmers [7] reported similar results using two-microphone cross-spectral densities.

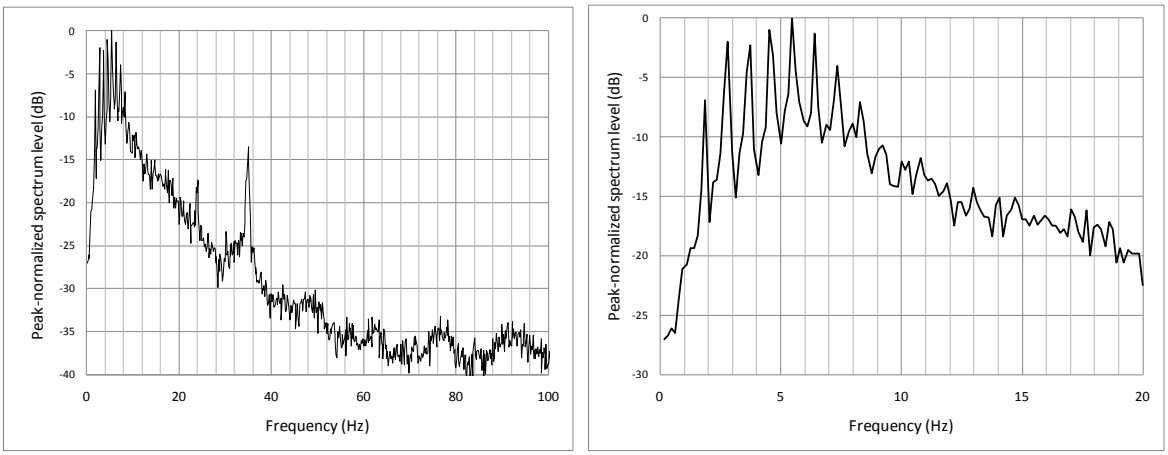

Figure 1. Spectra of wind turbine sound

This pattern is typical for propellers and helicopter rotors [8]. Under ideal inflow conditions the blade passage tone dominates. Here there are many harmonics of comparable magnitude, characteristic of a poor aerodynamic chord-wise load distribution. Non uniform (sheared) in-flow, and ingested atmospheric turbulence can also induce similar harmonic levels. The analytical frame work in Morse and Ingard [9] is an excellent starting point for the interested reader. The load distribution can be modified by a re-designing the turbine blade. There is only very limited scope for controlling shear and turbulence effects with blade geometry.

Autocorrelation of Wind Turbine Sound

Power spectral densities provide only information on the energy contents. The observer in the field hears distinct, periodic sound. This feature is revealed by the auto-correlation:

$$Rpp(t)= 1/(2T)\int_{-T}^{T} p(t)p^*(t-\tau)dt \quad T\rightarrow \text{infinity}$$

The autocorrelation is a measure of the similitude of the signal with itself at another instant in time. Auto-correlations are even functions of the delay time τ. A signal with a distinct period alos has a periodic autocorrelation. The autocorrelation of broad-band sound is concentrated near zero time delay, virtually vanishing for time delays greater than the reciprocal of the spectral bandwidth.

Figure 2 shows the auto-correlation for wind turbine noise where the blade passage harmonics are not obscured by atmospheric pseudo-sound. Figure 1 is the corresponding power spectrum. The time delay between peak and side lobe corresponds to the period of blade passage frequency. Only positive values of τ are shown as autocorrelations are even functions.

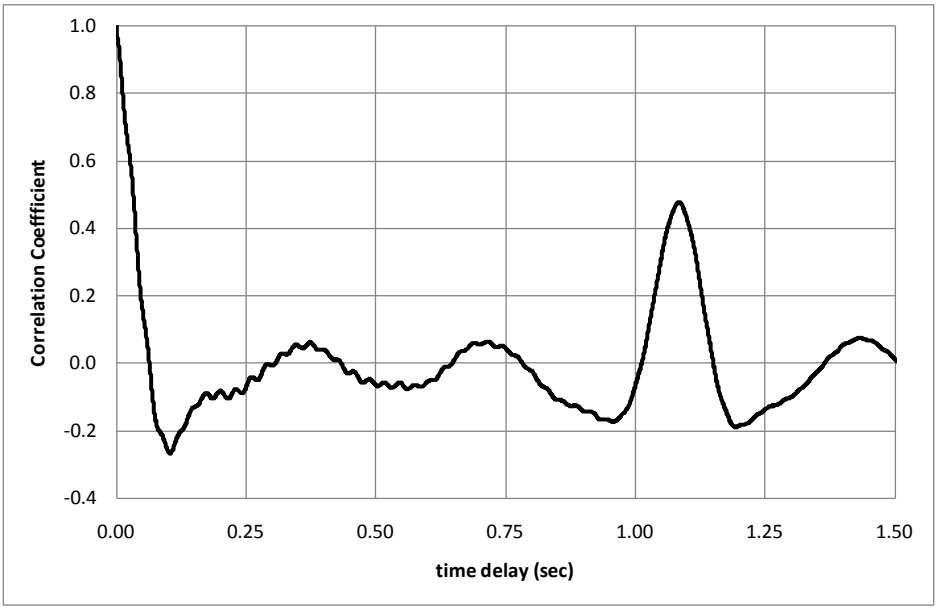

Figure 2 Auto-correlation of wind turbine sound.

The observed pattern shows that a portion of the wind turbine sound is composed of distinct low-frequency pulses. Over 3000 recordings at several wind-farms in Canada and the USA have been analyzed. Over 30% of the recordings have readily identifiable side lobes. There is some variability in the height and shape of the side lobes (Figure 3). Since no simultaneous turbine operating and near field sound data is available, we shall not speculate about the underlying source mechanisms. Nevertheless, there is a good deal of information that can be gleaned from the measured auto-correlations.

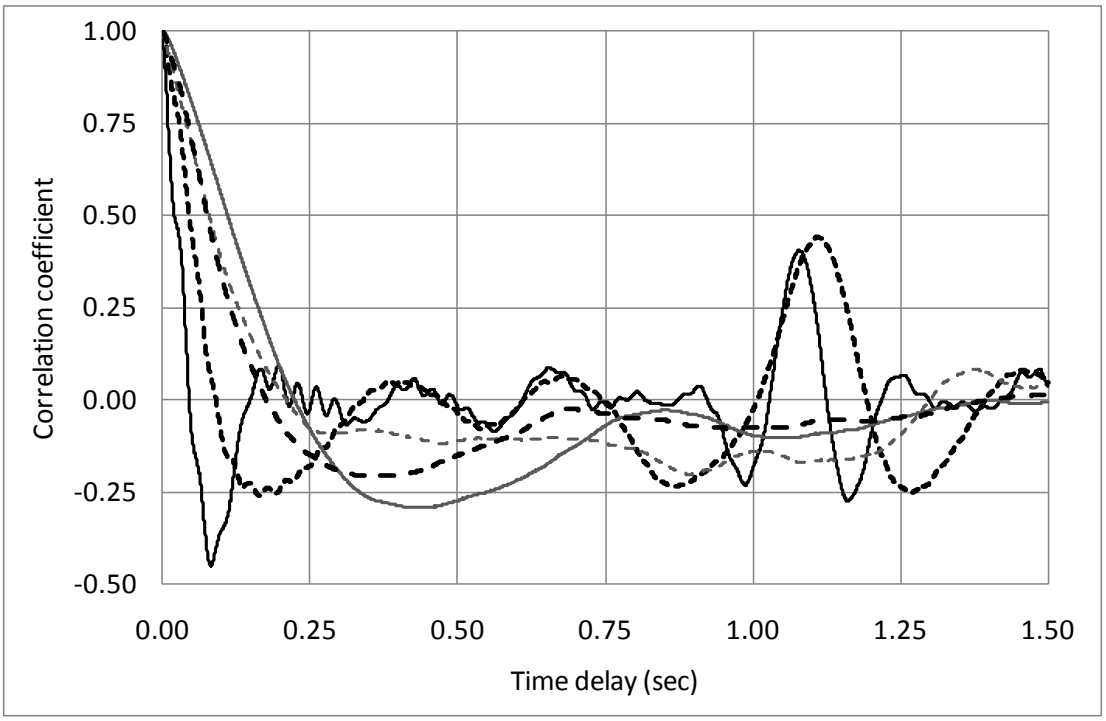

Figure 3. Variability of measured autocorrelations

The sound signal is written as: $s(t)=n(t)+p(t)=n(t)+\Sigma a_m\cos(2\pi m f_1 t+\phi_m)$. Here n(t0) is the broadband noise is the periodic content is a Fourier series. The autocorrelation has the form:

$$R_{ss}(\tau)=R_{nn}(\tau)+.5\Sigma a_m^2\cos(2\pi m f_1\tau).$$

$R_{nn}(\tau)$ has a global maximum at zero time delay (τ=0), and the periodic signal has a periodic autocorrelation with period $1/f_1$. The Fourier series is even, and all the Fourier series coefficients are positive.

The autocorrelation at τ=0 is the mean square: $R_{ss}(0)=\langle n^2\rangle+\langle p^2\rangle$. The maximum value of any 'side lobe' is $\langle p^2\rangle$. Typically $\langle p^2\rangle/(R_{ss}(0)$ is of the order of 0.2 to 0.4. The RMS of the low frequency pulse is comparable to the RMS of the broad-band (i.e. audible) sound.

Figure 4 shows a side lobe in more detail. It has been scaled and shifted in time so that the maximum peak is at zero time delay. In principle, the frequency components can be extracted from narrow band spectra. However, as is seen in Figure 1 only the

first few harmonics can be identified. The remaining harmonics are obscured by the broad-band spectrum.

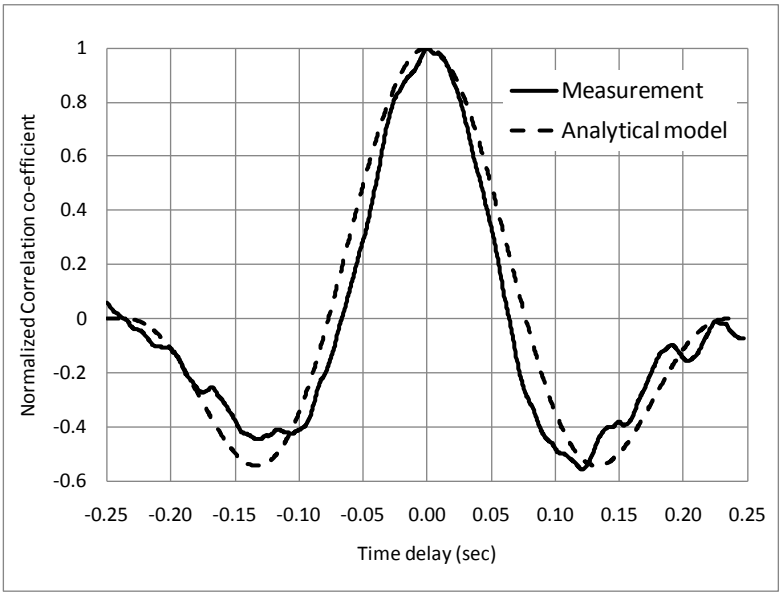

Figure 4 Detailed view of side lobe, time shifted to τ=0

Several analytical models were fitted to the experimental data. This procedure proved unsatisfactory as some of the Fourier series coefficients were negative. For large m the Fourier series coefficients of any of the model functions were found to be proportional to m^{-4}. This then suggests that the sequence

$$a_m=1/((1-m/M)^2)^2+(\alpha m/M)^2)$$

may be used to generate the Fourier coefficients a_m. The parameters α and M were adjusted until the trial waveform (Figure 5) was judged to reasonably match the shape of the measured side lobe.

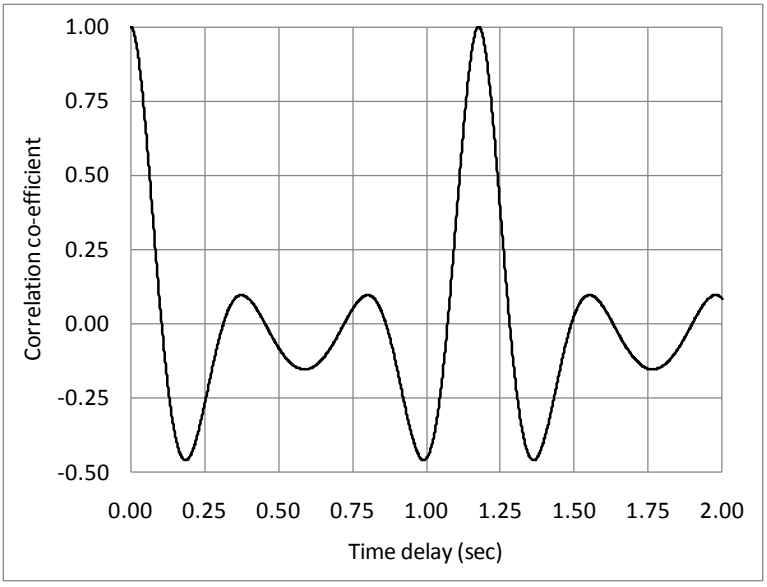

Figure 5 Side-lobe pattern generated by a 100 term Fourier series

The Fourier series coefficients for the periodic portion of the correlation are the squares of the corresponding Fourier series coefficients that describe the periodic low frequency pulses. As the phase information has been lost, one may re-create the general pulse shape by adjusting the values of b_m and c_m in the generalized Fourier series:

$$p(t)=\Sigma(a_m)^{1/2}[b_m\cos(2\pi mf_1t)+c_m\sin(2\pi mf_1t)] \text{ with the constraint: } b_m^2+c_m^2=1$$

Close examination of a short portion of a recording reveals a pseudo-periodic pattern (Figure 6). Selecting c_m=-1 generates realistic low frequency pulses (Figure 7).

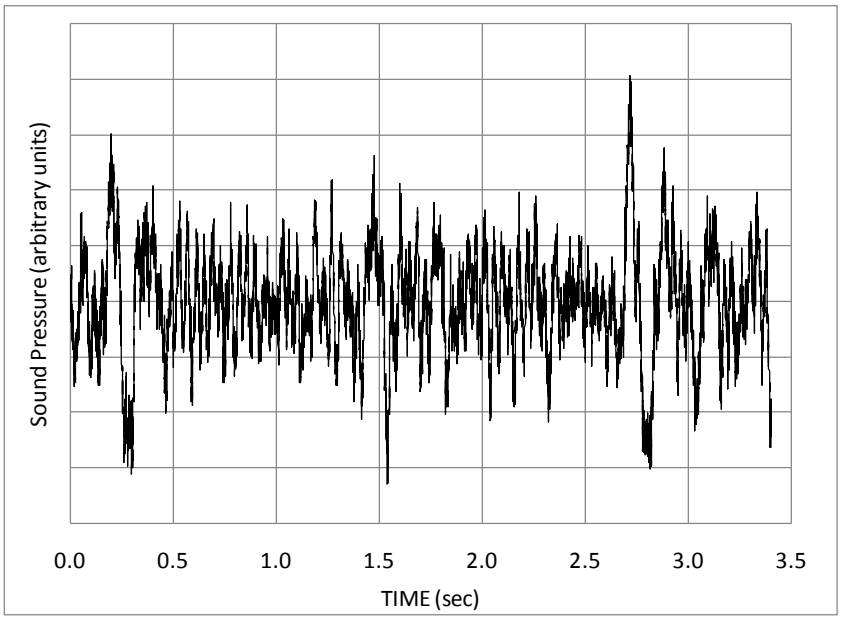

Figure 6. Measured wind turbine sound

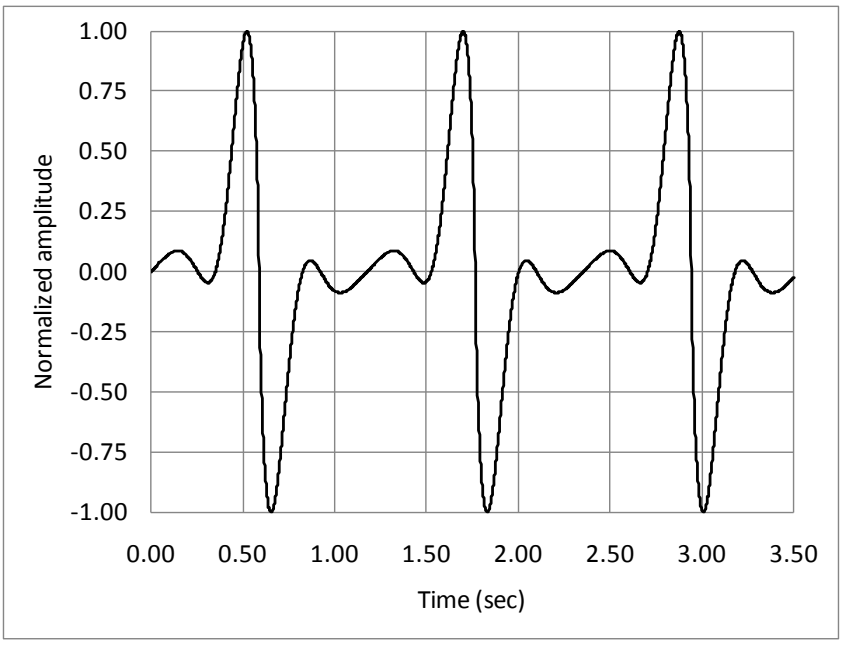

Figure 7. Synthesized low frequency pulses

The characteristic shape of the low frequency pulses are determined by the first ten harmonics. One might suppose that the higher harmonics are not at all important. Careful measurement of propeller and rotor noise show that these higher harmonics are in fact radiated even though they may not contribute significantly to the overall sound pressure level.

The wind turbine sound received several hundred meters from the source does not propagate through a quiescent atmosphere, even though this is implicit in most standardized propagation models [10]. Real atmospheric effects such as steady wind and temperature gradients refract the sound and will introduce a (frequency dependent) shift in the signal transit time. Atmospheric turbulence (both flow and temperature) tends to scatter the sound, so that the signal transit time becomes time-dependent [11, 12]. These features and be simulated by introducing a random, frequency dependent time delay ($TD(t)_m$):

$$P'(t)=\Sigma(a_m)^{1/2}\sin[2\pi m f_1(t+DT(t)_m)]$$

A steady, frequency dependent time delay alters the shape of the low frequency pulse. The effect of a time delay proportional to $DTmf_o(1+mf_0)^{-1}$ is shown in figure 8 for several values of DT. The corner frequency f_0 is 10 Hz.

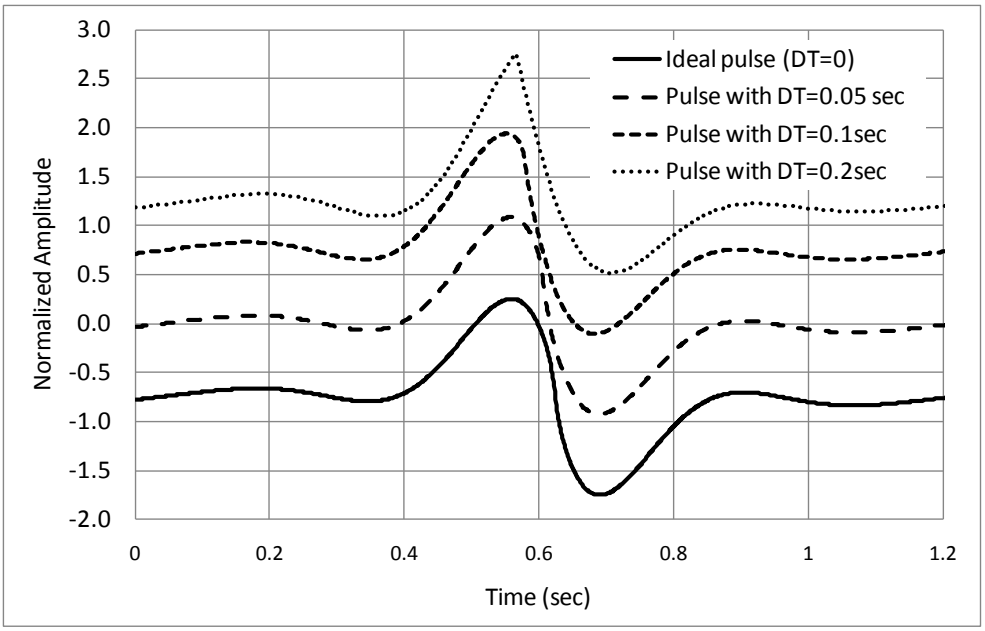

Figure 8. Low frequency pulses with to frequency dependent time delay

'Noise' is added to the low frequency pulse (Figure 9) when DT is a random variable. The signal is confined to bursts that coincide with the pulses. The simulation is approximate owning to the simple statistical model of the time delay.

Plotting P'(t)-p(t) shows that there is significant amplitude modulation of the 'noise'(Figure 10). The time-varying signal is audible, since the instantaneous amplitude is comparable to the broad-band background sound (see Figure 6 for relative amplitudes).

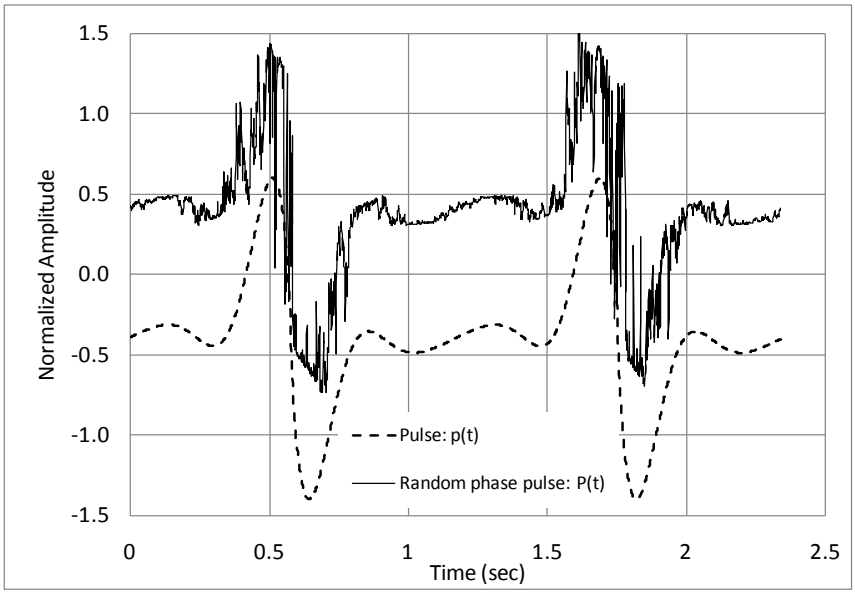

Figure 9. Comparison of low frequency pulse with and without random phase

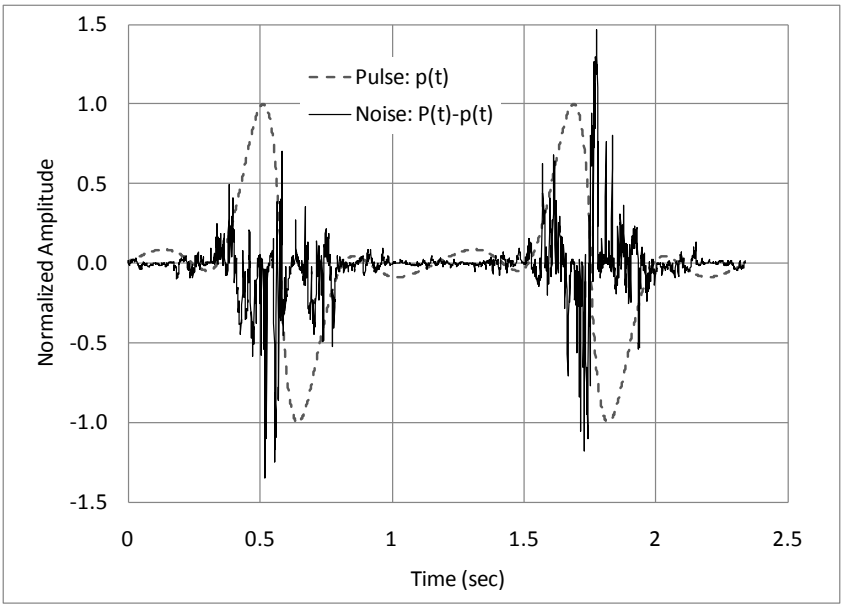

Figure 10. Audible signal from low frequency pulse due to random phase.

Concluding Remarks

Autocorrelations have been used to extract low frequency pulses from wind turbine sound. These pulses occur at the blade passage rate and their dominant energy is confined to the first 10 harmonics. The patterns have been observed for about 1/3 of over 3000 files examined to date. Using a Fourier series description the most likely pressure-time history has been determined. It is shown that propagation through a real atmosphere can distort this pulse shape. In particular, the random effects introduced by atmospheric turbulence destroy the perfect phase relation implicit in an ideal pulse. The result is an audible burst of noise which is perceived as a ‘swoosh’. In effect the infrasound pulse becomes audible.

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