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How frequency response influences measurement and audibility of periodic wind turbine sound

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Summary

Harmonics of the blade passage frequency dominate the low frequency sound from large wind turbines. They extend well into the audible range. To capture the periodic signal with any fidelity, the frequency response of the measurement system must extend down to at least 0.1 Hz. Instruments lacking this performance significantly modify pressure-time history. This has implications for the interpretation of measured data as well as audibility.

The periodic wind turbine signature was described with over 400 Fourier series components whose amplitudes were deduced from measured auto-correlations and narrow band spectra of wind turbine sound. The periodic signal from each wind turbine was then 'propagated' to a set of listeners on the periphery of the wind farm. Propagation through a turbulent atmosphere was not been accounted for.

Sound pressure time histories reveal both slow and rapid changes. The influence of in-adequate low frequency response was examined by high pass filtering the computed time history. Even a lower frequency limit of 4 Hz introduces significant deviations.

When several wind turbine contribute to the sound at a point of reception, the signal, even though periodic being to resemble a random collection of waves, arriving at different times.

Introduction

It is now well established that autocorrelations of wind turbine sound have periodic structures at the blade passage frequency (1,2,3). The energy therein can contribute up to 50% of the overall signal energy. Contributions from the first few harmonics of the blade passage frequency define the general pattern of the waveform. Higher harmonics have much lower acoustic energy, but have the potential to contribute to audible sound. Previous analysis (3) showed that propagation through a turbulent atmosphere introduces random phase shifts rendering the high frequency portion of the harmonic signal audible. This paper examines the influence of limited low frequency response as well as contributions from several wind turbines on the audibility of the higher harmonics.

When wind turbine sound is measured with conventional equipment, the lack of low frequency response influences the wave form. This may not be an issue if spectra in the audible range or *A* weighted sound levels are of primary interest. The high-pass filtering introduces phase shifts that alter the pattern of the periodic structure of wind turbine sound. As the human ear is also a (non-linear) high pass filter, these effects may also play a role in the perception of wind turbine sound.

Periodic low frequency wind turbine sound

Figure 1 illustrates a measured autocorrelation function of wind turbine sound. It has been normalized by the mean square sound pressure. There is a large central peak at zero time delay and secondary peaks at time delays that correspond to multiples of reciprocal of the blade passage frequency.

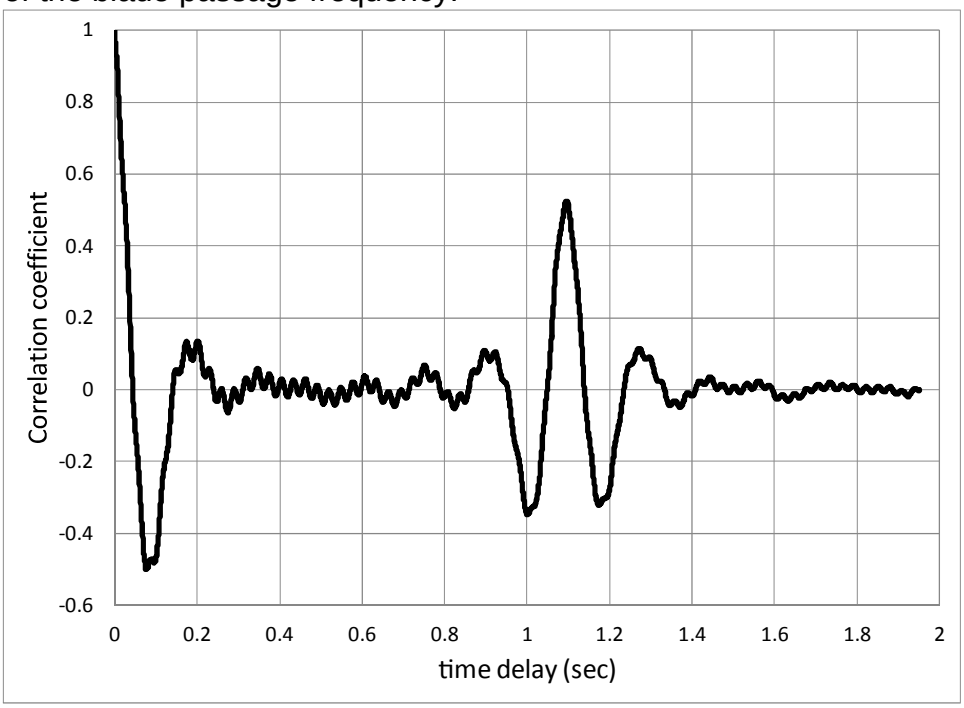

Figure 1. Measured autocorrelation of wind turbine sound

This can be modelled by assuming that there are at least three distinct sounds: naturally occurring background noise ($f(t)$), random ($g(t)$), and periodic ($s(t)$) wind turbine sound:

[1] $$p(t) = f(t) + g(t) + s(t); \;\; s(t + 2T) = s(t)$$

Broad-band signals attributed to the wind turbine and the environment (e.g. wind) are uncorrelated so that the autocorrelation of the pressure is:

[2] $$R_{pp}(\tau) = R_{ff}(\tau) + R_{gg}(\tau) + R_{ss}(\tau)$$

The autocorrelation of the background noise and random wind turbine sound is non zero only for small time delays. Only $R_{ss}(\tau)$ persists for larger time delays, as it is a periodic function. Writing $s(t)$ as a Fourier series:

[3] $$s(t) = \sum_{n=1}^{\infty} a_n \cos\left(\pi n \frac{t}{T} + \emptyset_n\right)$$

The corresponding autocorrelation has only positive Fourier coefficients (a_n^2):

[4] $$R_{ss}(\tau) = \sum_{n=1}^{\infty} 0.5\, a_n^2 \cos\left(\pi n \frac{\tau}{T}\right)$$

Normally, random signals obscure the periodic waveform. The Fourier series coefficients a_n can be obtained from the autocorrelation; however, the phase terms $\emptyset_n$ are unknown. Under favourable field conditions only the first few harmonics can be resolved unambiguously. Extrapolation to higher harmonics is to some extent governed by the choice of a 'best fit' function $\mathrm{R}_{ss}(\tau) = \sum_{n=1}^{N} A_n \cos(n\pi t/T) \sim R_{ss}(\tau)$.

As pointed out above, one requirement is that all A_n be positive. This restricts the selection somewhat, as many Fourier series are alternating. Previously (3) it was assumed that $s(t)$ was an odd function. Walker (1) employed ensemble averaging to enhance the periodic signals which, for the most part, are even about their local maxima or minima.

The autocorrelation provides a good estimate of the period ($2T$). This allows ensemble averaging of digital recordings of wind turbine sound without an external trigger. The procedure is straightforward. The record is reformatted into segments of duration $2T$:

[5] $$f_{n,m} = f(ndt_s + 2mT)$$

$dt_s = (sampling\ rate)^{-1}$ and n an integer ranging (0, M-1). Averaging over m segments enhances the periodic signal while reducing random noise. The *RMS* contribution of the latter diminishing by $1/\sqrt{M}$. The duration of the records used herein were relatively short, so noticeable random noise remains in the ensemble averages in Figure 2. There is a good deal of variability. Records with high correlation peaks yielding reasonably smooth traces. Many possess multiple, similarly shaped pulses. This is expected when

the sound levels from several wind turbines are comparable. Even under these circumstances the major side lobe of autocorrelation is located at the delay time $2T$.

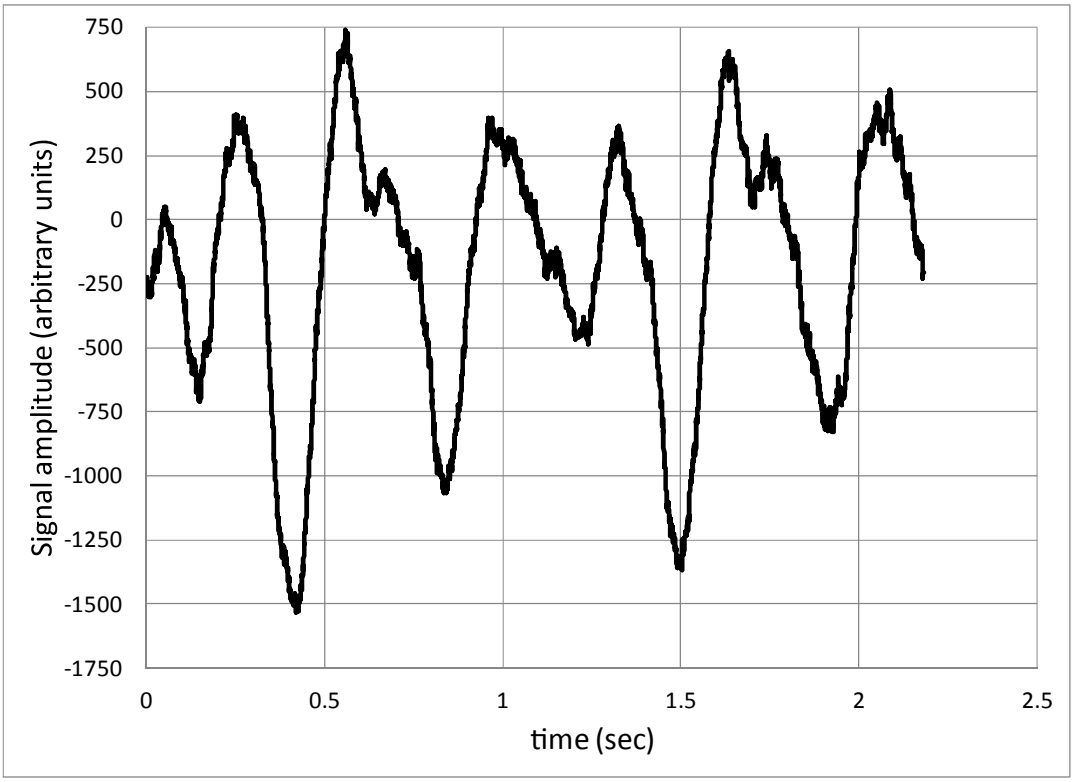

Figure 2. Ensemble averaged wind turbine sound. At least three wind turbines contribute to signal. $2T = 1.09\ sec$. Figure 1 shows the autocorrelation of this data set.

From equation [2] one may deduce that the fractional contribution of $s(t)$ to the overall mean square pressure is $R_{ss}(2T)/\ R_{pp}(0)$. Observed magnitudes of this ratio ranges from zero to about 0.4. Since there are also non-wind turbine sounds, it is seen that the periodic portion of wind turbine noise, for the most part, makes a non-negligible contribution.

The ratio $R_{ss}(2T)/R_{ff}(0)$ is a measure of the contribution of the periodic signal to the overall means square. Figure 3 shows a histogram of measured $R_{ss}(2T)/R_{ff}(0)$ that exceed 0.2. This represents about 43% of the all data analyzed.

The cumulative probability distribution is estimated by treating the ratio as a random variable: $F(x) = 1 - \int_x^1 \gamma q(x)dx$; γ is chosen to so that $F(0.2) = 0.57$. In Figure 4 a linear extrapolation extends $F(x)$ to small values of. It follows that the corresponding probability density function is $0.3\delta(x) + 1 - H(x - 0.7)$. This suggests that the low frequency tones are obscured for about 1/3 of the observations. A larger data base is needed to improve these approximate statistics.

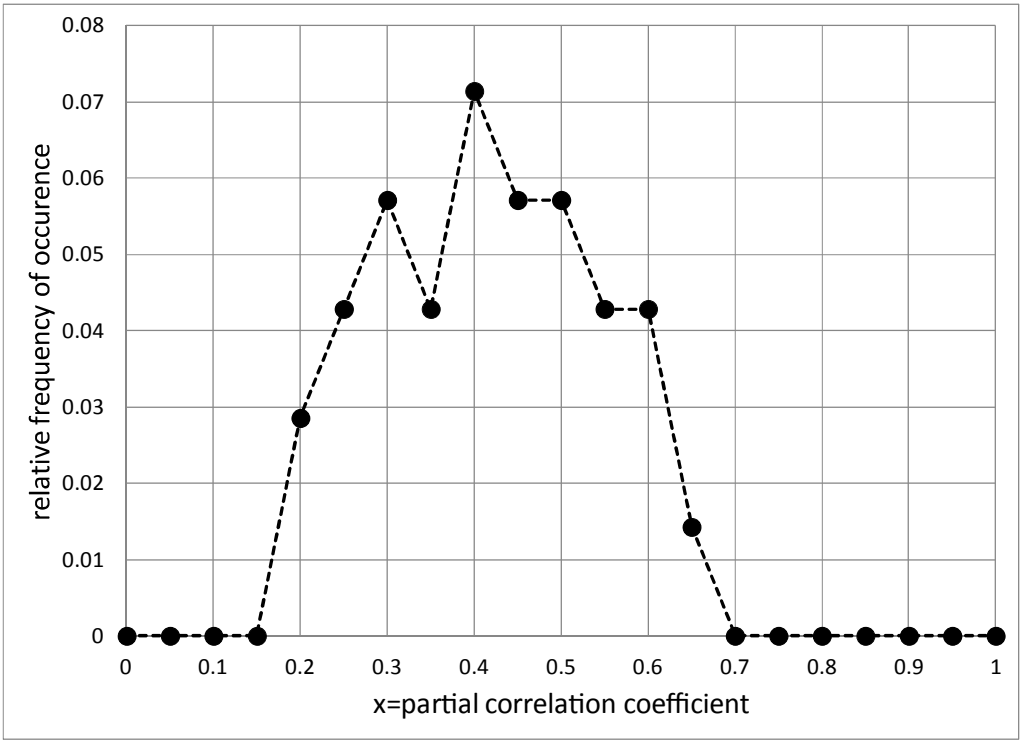

Figure 3. Scaled histogram of x=$R_{ss}(2T)/R_{ff}(0)$

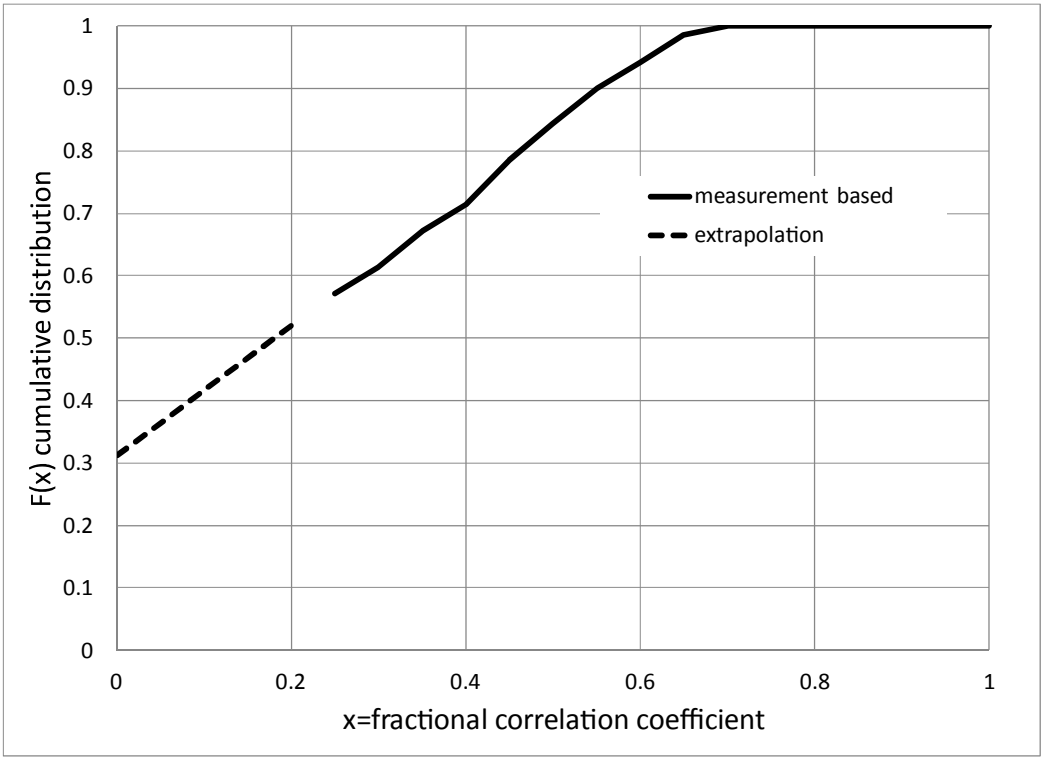

Figure 4. Cumulative distribution of x= $R_{ss}(2T)/R_{ff}(0)$.

Influence of High Pass Filtering

A good deal of data has and continues to be obtained using instrumentation that has inadequate low frequency response. Listening tests conducted in loudspeaker driven environments are another example where in-adequate low frequency response of the equipment alters the stimulus. One example is loudness of a sonic boom. Controlled listening tests in a special simulator showed that removal of low frequency components had negligible impact on loudness (4). It may well be that audible sound from wind turbines is a psychological trigger, even if the sound pressure are substantially lower.

A model low frequency pulse was constructed from Fourier components whose frequency distribution resembles measured narrow band spectra (Figure 5). The signals are contain 400 harmonics. For simplicity the blade passage frequency is 1Hz, and the sampling rate was 8000Hz. The corresponding time and autocorrelation signals are shown in Figure 6. The similitude of the model and measurement is good.

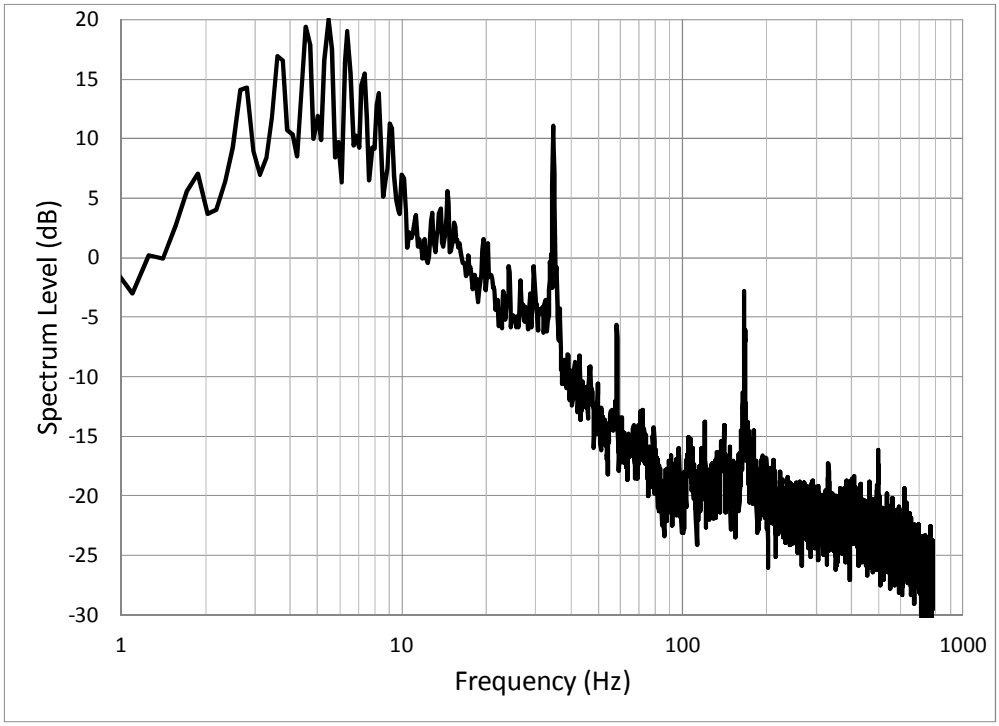

Figure 5. Narrow band spectrum of wind turbine sound. Figure 2 shows the ensemble average of this data set.

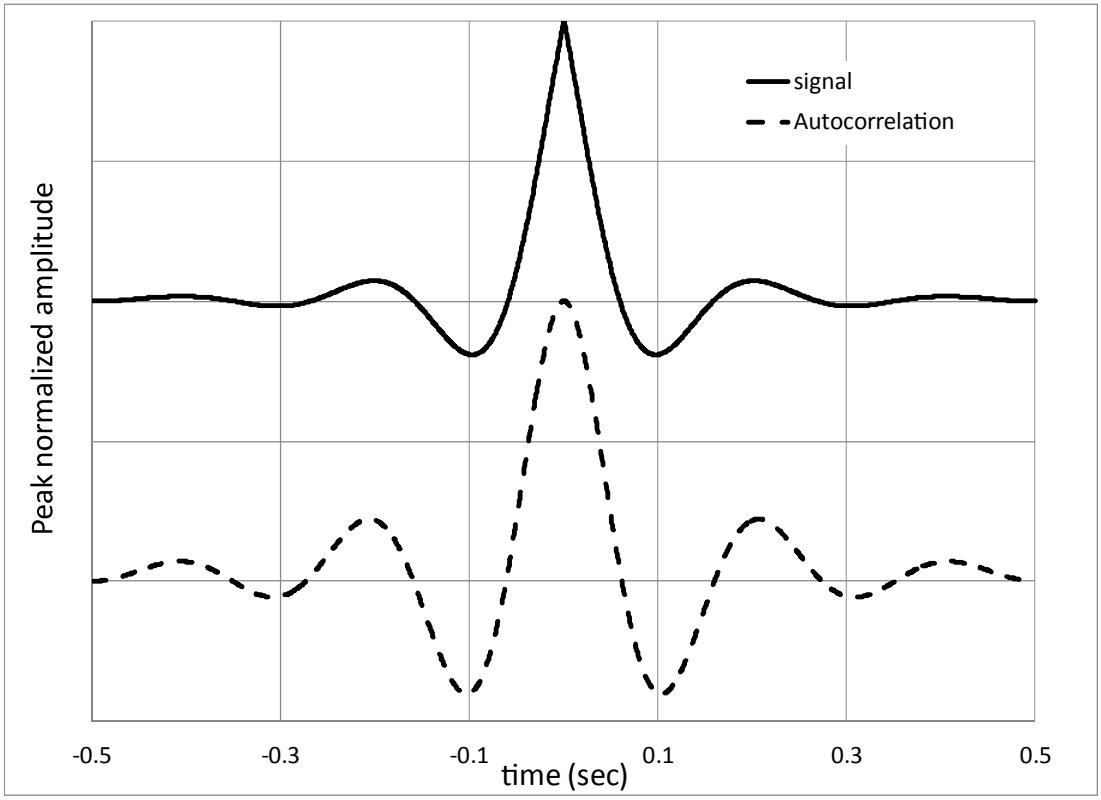

Figure 6. Time series and autocorrelation function of model pulse.

The analysis presented here is concentrates on linear second order filters with constant coefficients. Under these constraints the general response takes the form:

[6] $$y(t) = \sum_{n=1}^{N} a_n \{B_n cos\left(\frac{\pi n t}{T}\right) + C_n \sin\left(\frac{\pi n t}{T}\right)\}$$

The filter transfer function magnitude is $\sqrt{B_n^2 + C_n^2} = \frac{f^2}{\sqrt{(f_0^2 - f^2)^2 - (\alpha f_0 f)^2}}; f \rightarrow \frac{n\pi}{T}$

Figure 7 illustrate the responses at selected corner frequencies (f_0). Even for moderate values the effect is quite dramatic. The *RMS* level of the output signal is reduced; still, the periodic structure may render it audible. The repetition rate also provides a consistent trigger or cue as the patterns repeat at the blade passage frequency whose period is of the order of 1 second for large modern wind turbines.

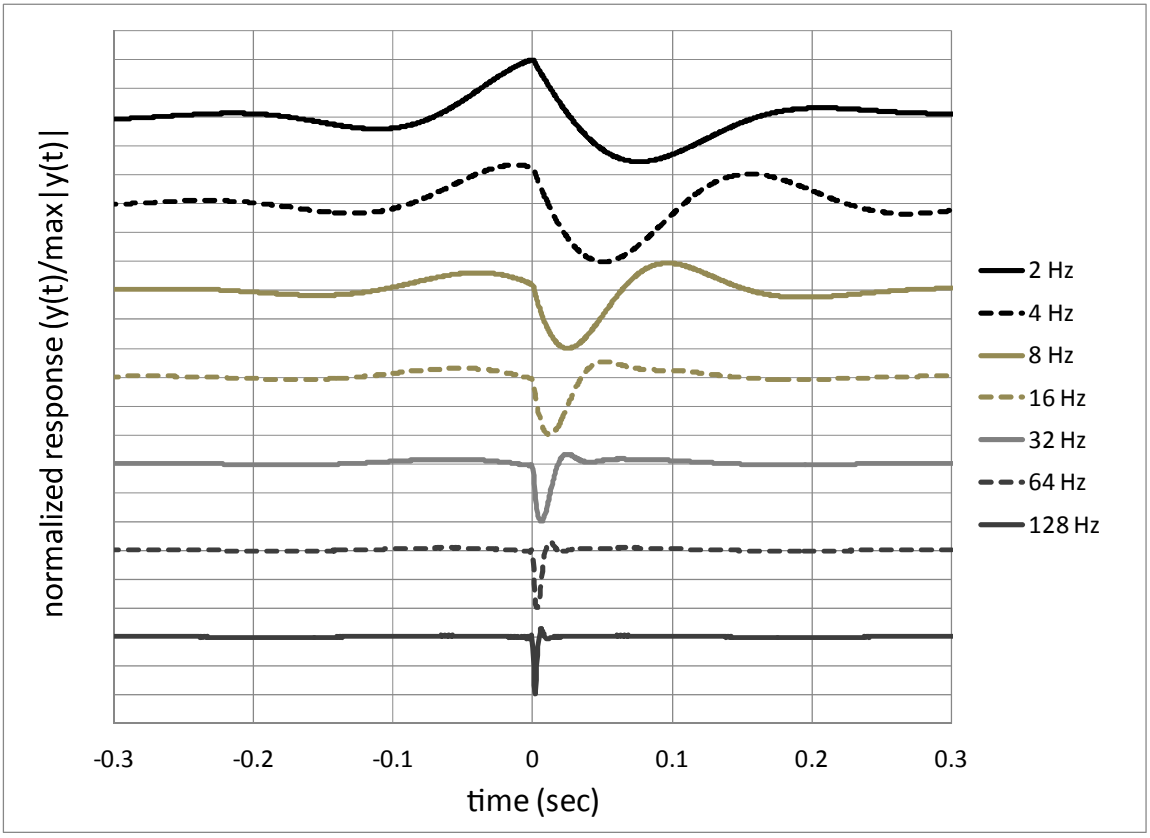

Figure 7. Response to an idealized periodic signal (see Figure 6) as a function of corner frequency. Amplitudes are normalized by the maximum absolute value.

The auditory process is much more complicated than a simple linear filter. Irrespective of the details, lack of low frequency response ought to bias the sensation to favour the higher frequency components. This is modelled by replacing the function of the ear by second order high pass filter that approximates the response of the A weighting network (Figure 8). The high pass filtered signal resembles a short pulse whose time scale is but a fraction of the low frequency pulse (Figure 9). Truncation of the Fourier series at 400 lines (400 Hz) induces 'ringing'. Application of smoothing schemes will reduce the oscillations (5).The signals have been exported as **.wav* files and played back through head phones and high fidelity loudspeakers. They lack the characteristic swoosh of wind turbine sound. It should be noted that random phase mismatch induced by propagation through turbulence generates signals that are swoosh-like (4).

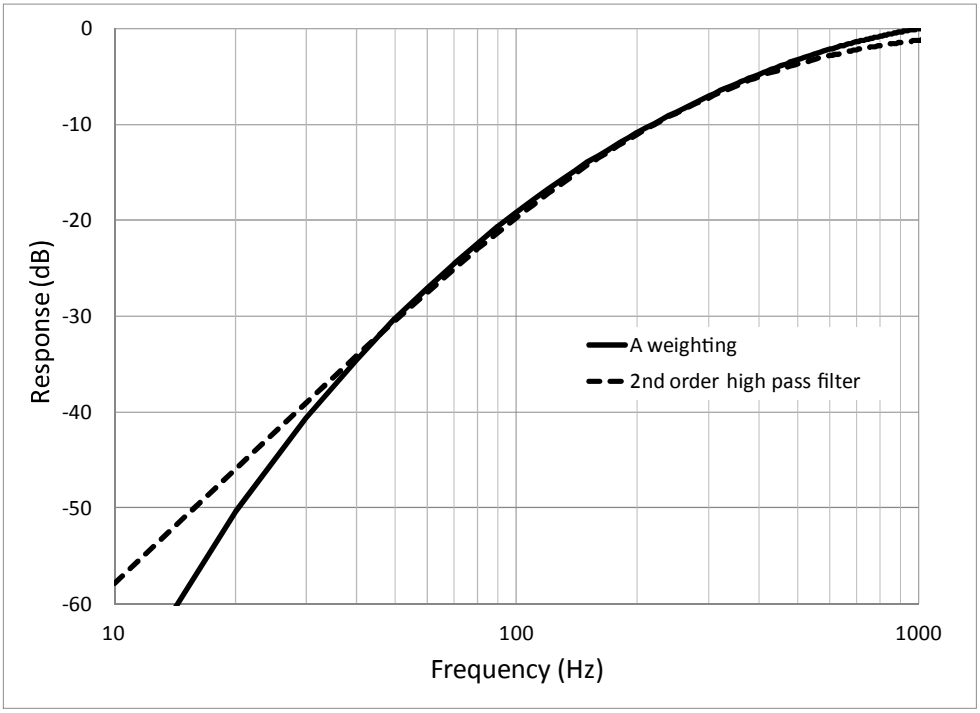

Figure 8. *A* weighting fitted with a second order high pass: $f_0 = 280\ Hz, \alpha = 2.45$

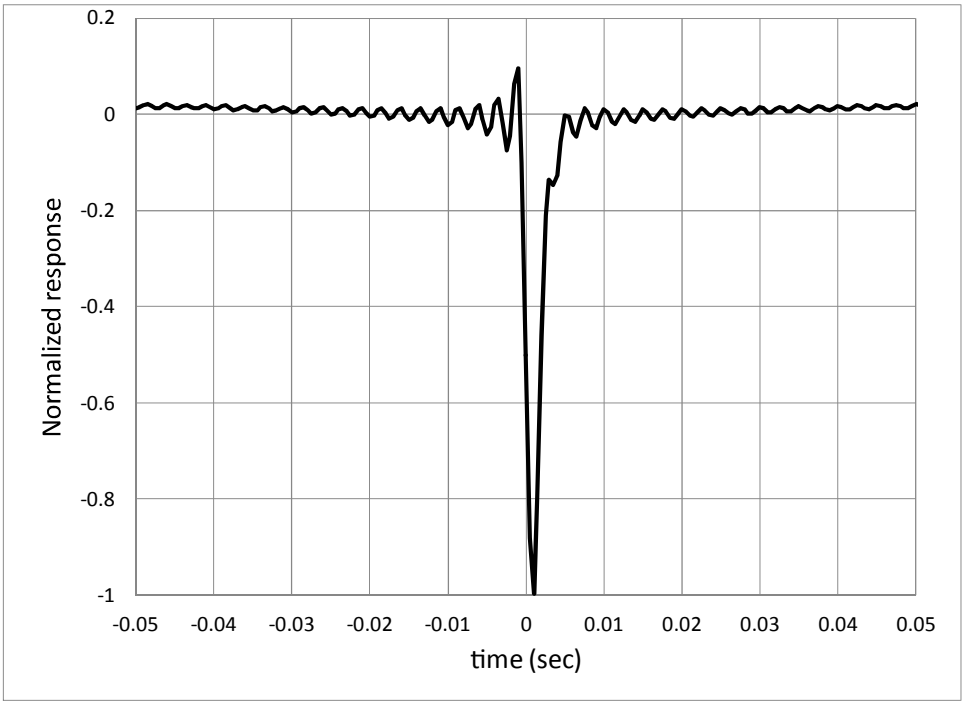

Figure 9. Response of high pass filter in Figure 8 to simulated periodic wind turbine sound.

Multiple Wind Turbines

Under idealized conditions the overall sound pressure from M wind turbines is simply:

[7] $$p_{tot}(t) = \sum_{n=1}^{N}\sum_{m=1}^{M} D_{m,n}\frac{a_n}{R_m}\cos \pi n \frac{t - \frac{R_m}{c} - \Delta t_m}{T_m}$$

$D_{m,n}$ is the source directivity, R_m source-listener distance, $1/2T_m$ the blade passage frequency of the mth wind turbine and Δt_m a time shift accounting for the relative blade orientation of each wind turbine. The dimensions of the Fourier coefficients are *Pa m*. These parameters change slowly over time over time and the results deduced from equation [7] should be considered 'snap-shots' of the type of signals that ca. For this reason long term averaging will not yield realistic results. To date there is no comprehensive model based on the (assumed) distribution of the random variables $D_{m.n}, R_m, T_m, \Delta t_m$. Eventually such a model ought to provide a better understanding of the inherent variability of wind turbine sound.

As more wind turbines contribute to the periodic pulses arrive at different times. For M wind turbines there will be M pulses. Their magnitudes scale as R_m^{-1}. Often wind turbines are arranged in clusters. Consider a cluster of 11 wind turbines turning at identical rates. The cluster has basic regular pattern with inter wind turbine distances of 300m. There are four points of reception that are at least 500m from the closest wind turbine. The respective co-ordinates are tabulated below.

Wind turbine co-ordinates (m)						**Field Points**		
	X	Y		X	Y		X	Y
WT1	-12	-9	WT7	-143	-248	FP1	0	500
WT2	297	11	WT8	-442	-250	FP2	650	360
WT3	-310	2	WT9	292	-527	FP3	775	150
WT4	461	-257	WT10	-2	-514	FP4	950	-260
WT5	139	-272	WT11	-295	-526	FP5	775	150
WT6	-12	-261						

The periodic pattern is now composed of 11 elements. Figures 10 and 11 illustrate full bandwidth patterns and the high pass filtered ones. When a high pass filter is applied, the low frequency waveform is transformed into a series of pulses that appear randomly distributed over the fundamental period of 1 second (note the blade passage frequency used herein is 1Hz). The traces have been normalized by the largest value predicted for each data set.

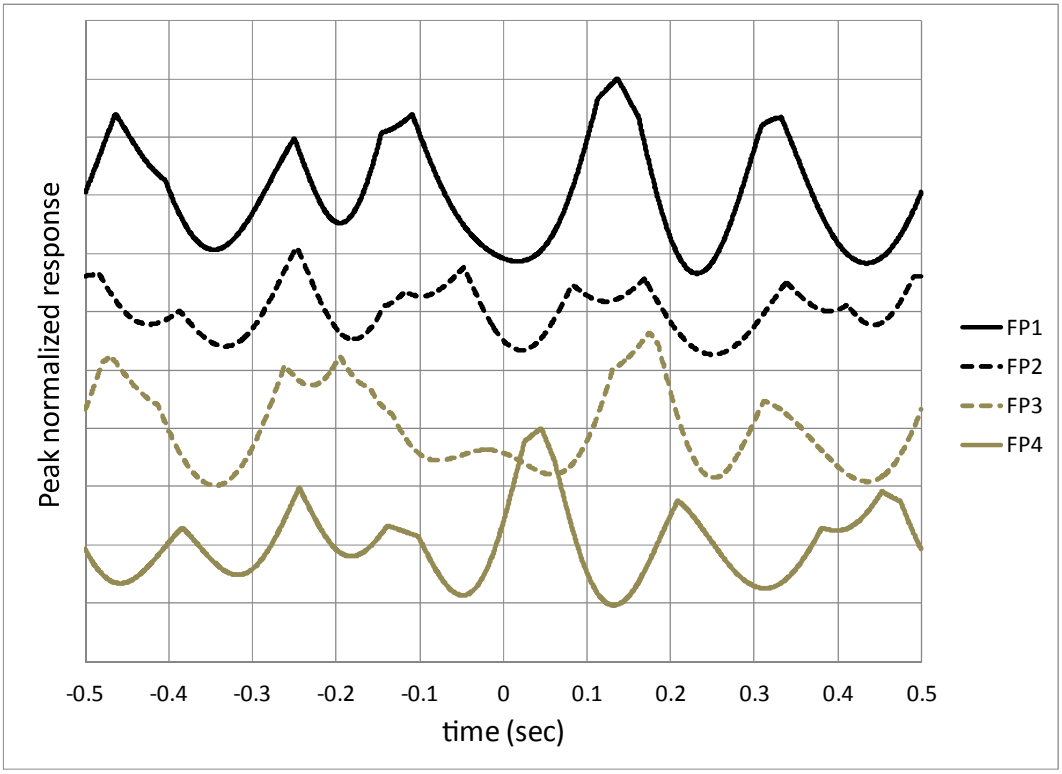

Figure 10. Periodic pulses from 11 wind turbines arrange in a 'cluster'. The traces have been normalized by the largest value in this data set. The spacing between horizontal lines is 0.5. Traces are off-set by 1.0 with respect to each neighbour.

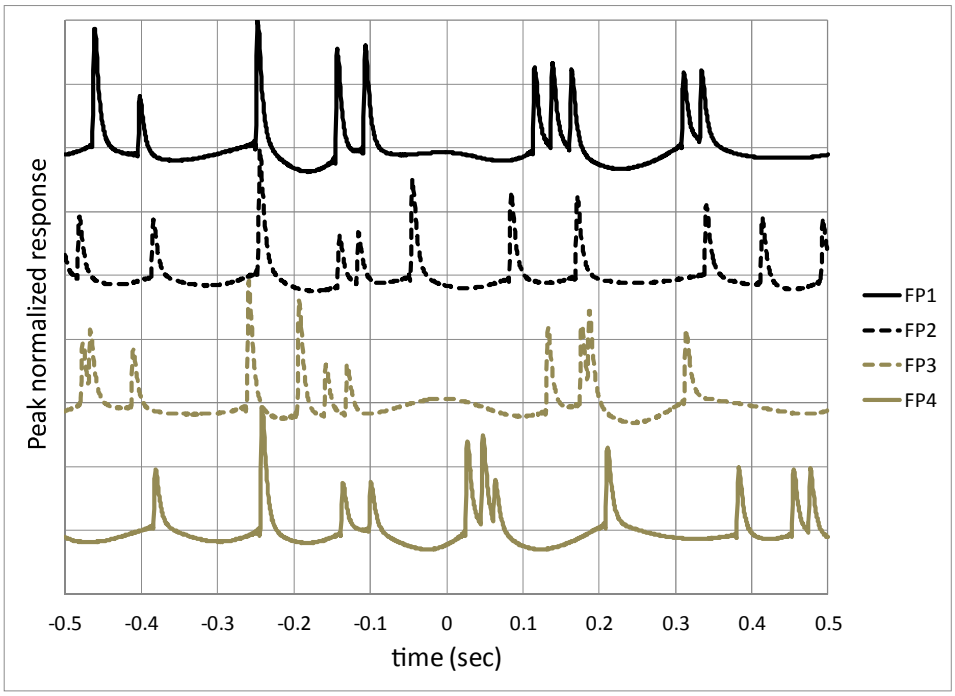

Figure 11. High pass filtered signals from Figure 10. The traces have been normalized by the largest value in this data set. The spacing between horizontal lines is 0.5. Traces are off-set by 1.0 with respect to each neighbour.

In this example all blades are synchronous, that is at a certain instance of time one blade of each wind turbine points vertically up. If this constraint is lifted and the relative positions of the rotors are permitted to slip, the individual peaks with traverse the wind, thereby changing the character of the pulse train.

Summary

The periodic sound associated with the lift forces the thickness of wind turbine blades has been idealized and the influence of relative lack of low frequency response of measurement equipment has been analyzed. It is shown that the periodic pattern that is dominated by low frequency components is transformed into a series of short pulses. For typical wind turbines the energy associated with these pulses is a few dB below that of the boundary layer/trailing edge noise which is responsible for the 'swoosh' sound.

The pattern becomes more intricate when the sound from several turbines is considered. The apparent chaos within the periodic structure may, in part, account for the characteristic wind turbine sound.

References

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