# ACOUSTICS OF INFRASOUND FROM WIND TURBINES USING CROSS-SPECTRA

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## 1 Introduction

Measured wind turbine (WT) infrasound near homes often contains mostly wind noise, not the true acoustic signature of the WTs. With appropriately-spaced multiple microphones, the wind noise is essentially random, while the blade pass frequency (BPF) signals are largely coherent, allowing a determination of the total acoustic power (pressure^2) from the WTs, as well as the remaining random wind-induced noise.

Exterior and interior microphone signals will be strongly affected by both wind noise and true WT acoustic signals. Turbulent eddies and random air parcel motion may display spectral maxima around 0.2 Hz, but there is enough energy at frequencies up to 10 Hz or so that it often blankets the true infrasonic WT acoustic signals, which are produced by the fluctuations from the moving blades interacting with the supporting pylon. In what follows we distinguish the pseudo-noise caused by the wind itself, from the true acoustic WT signals that propagate at sound speed.

Earlier we have shown [1] that the total infrasound level can be up to 20 dB above the acoustic pulse level from the nearest WT, and even 10-15 dB higher than a whole wind farm of 100 units. The present paper shows how the acoustic power from the WTs can be separated from the often dominating wind noise, using appropriate microphone arrangements and specific processing. As a byproduct, the acoustic transmissibility from outside to inside a house can also be determined.

## 2 Experiments and analysis

An important experiment for this work was the measurement of infrasound for a typical 2-storey home with a microphone on the porch at the front door, well covered with fiberfill and a blanket, and another about 15m away at the back deck, similarly screened from the wind. It was a moderately windy day and there were no WTs within at least 30 km from the home. GRAS 40AZ microphones with CC preamplifiers had a response down to 0.3 Hz, as measured in a sealed calibration box. The two signals were measured over a 1-hour period, sampled at 800 Hz to encompass all infrasound components and some LF audio as well. Figure 1 shows the spectra of the two signals. The microphone responses fall off below 0.3 Hz, but the true spectra actually rise even more at lower frequencies. A similar experiment with two separated microphones was carried out over flat terrain.

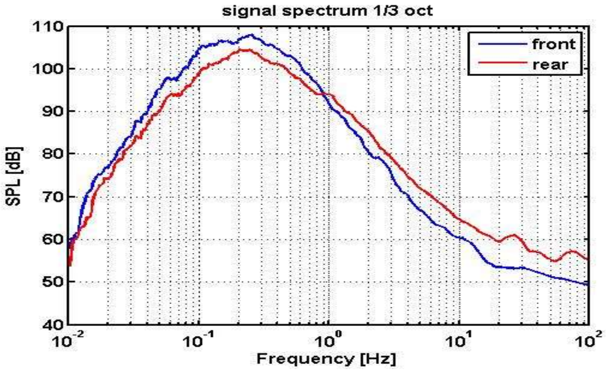

**Figure 1**: Spectra of the microphone signals at the front and back doors of a home far from any wind turbines.

When the two 2.88 million microphone data samples are analyzed in overlapping windowed blocks, the coherence between them is shown in Figure 2. Notice that there is little coherence between these wind-induced signals above about 0.2 Hz, which is where BPFs from WTs reside.

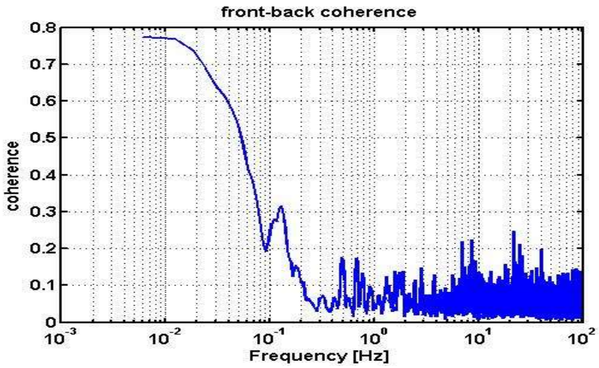

**Figure 2**: Coherence between the microphone signals at the front and back of a residence, with no nearby WTs.

Turbulent wind eddies that are larger than the 15m microphone separation would show coherence between them, but with random air velocities of say 5 m/s, these would not have spectral components above about 5/15 or 0.3 Hz, consistent with the plot in Figure 2. Higher frequencies such as 0.5-10 Hz would be associated with eddies smaller than 15m, so the wind noise would show no coherence in the BPF regime.

True acoustic waves from the WT blade-pylon interaction travel at 340 m/s, and at the very low BPF of WTs, signals will be almost coincident and coherent in microphones spaced only 15m apart. Thus the coherence between outside microphones at infrasonic frequencies above 0.5 Hz will be predominantly due to the true net acoustic signals from the WTs. This fortunate separation is due to the nature

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of wind eddies, and the large difference between typical random air velocities of 2-5m/s and the speed of sound, 340m/s. The wind induced noise may be significant at BPFs, but it will not be coherent, and appropriate processing can control it.

## 3 Signal processing and discussion

The signals $x$ and $y$ at the outside microphones consist of differing random wind-induced components $rx$ and $ry$, together with fluctuating WT true acoustic signals, $a$, which are nearly the same. We thus can model this as:

$$x = rx + a, \qquad y = ry + a. \tag{1}$$

Our major goal is to determine the power of the acoustic component, $a$. Cross-spectral density function terms [2] between $rx$, $ry$, and $a$ will be essentially zero (except perhaps at extremely low frequencies), but the common WT acoustic $a$ signal in both $x$ and $y$ results in a nonzero component. It is easily shown that the cross-spectral density from two properly-spaced microphones will give an unbiased estimate of the acoustic spectral power $Pa(f)$ of the WT farm in either microphone:

$$Gxy(f) \approx Gaa(f) = Pa(f). \tag{2}$$

If there is also a microphone inside the residence, the acoustic amplitude transfer function $T$ from outside to inside can also be obtained as a secondary goal. We can also describe $T$ by its impulse response, $t$.

Let's continue the assumption that the two acoustic WT outside signals $a$ are equal, that no noise is generated inside the house, and that the outside random wind signals all around the house leak in to produce an interior random signal, $ri$, that is also uncorrelated with $rx$ and $ry$. Thus the inside microphone gets a signal $z$,

$$z = ri + t{**}a, \tag{3}$$

where the ** operation is a time convolution. The averaged cross-spectrum, between the exterior and interior signals $x$ and $z$, becomes

$$Gxz(f) \approx T\,Gaa(f) => |T|\,Pa(f). \tag{4}$$

Thus the ratio $|Gxz(f)/Gxx(f)|$ gives $|T|$, the frequency-dependent transmissibility. Figure 3 shows the transmissibility of a home adjacent to a wind farm of about 100 WTs. The cross-spectra displayed strong BPF lines and we implemented Eq. 4 by selecting cross-spectral data near each harmonic, joining the points between the harmonic frequencies with straight lines. Measurements were taken during the spring, so a window may have been open. The data point that exceeds unity transmissibility may indicate a resonance condition, but could also be due to some residual noise.

The total spectral power of the cross-correlation is some 9dB lower than the spectral power of either outside microphone, substantially removing the random wind noise, but not affecting the spectrum of the BPF components.

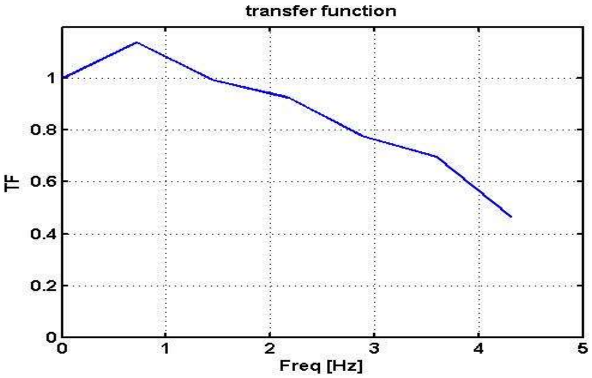

**Figure 3**: Transmissibility of the subject house determined from the amplitude ratios of the BPF cross-spectra.

A high-pass filter could also have been used to reduce the wind noise power, but the cross-spectral method also removes such noise in the BPF region. The random wind noise is not produced by the WTs, so the major conclusion is that infrasound from WTs may be much less than that deduced from single microphone measurements.

## 4 Summary

By making appropriate measurements with two exterior and one interior microphones, we can determine the total WT acoustic infrasound level, and also get a reasonable estimate of the acoustic inside/outside transmissibility. Measurements of a few wind farms show that the wind-induced infrasound is often considerably larger than the acoustic signal. If we wish to impute health effects to infrasound level, we should use these lower acoustic levels, since the wind-induced noise occurs anyway, even away from the wind farm.

## Acknowledgements

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## References

[1] J. Vanderkooy and R. Mann, “Measuring Wind Turbine Coherent Infrasound”, 6th International Conference on Wind Turbine Noise (WTN2015), Glasgow 20-23 April 2015.

[2] J. S. Bendat and A. G. Piersol, “Engineering Applications of Correlation and Spectral Analysis”, Wiley, 2nd edition, 1993.