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A Low Wind-Noise Microphone for Wind Turbine Noise

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Summary

A persistent challenge in characterizing wind turbine noise is that turbulent noise on the microphones is dominant in the same spectral area as the turbine noise. While baffles certainly help, they generally also modify the reception of signals of interest.

In response to this problem we describe a new approach where a closely-spaced array of microphones is mounted flush into a small-diameter surface. When wind is incident on this surface, a turbulent boundary layer forms, whose thickness and spectral properties depend on wind speed and distance downwind from the leading edge. The distance from individual microphones to the upstream leading edge of the surface varies depending on wind direction and microphone location. The result is that a number of independent measurements are made of the local wind noise, allowing for correction.

We present the theory for this new method and first results with our small microphone arrays under controlled conditions.

1. Introduction

Microphones respond to pressure fluctuations due to turbulence created in a boundary layer above the surface of the microphone (Bradley et al., 2003; Beranek and Vér, 2006). These wind-dependent fluctuations can degrade the estimation of external sound. The aeroacoustic noise peaks at low audio frequencies and, in many applications, can be removed via spectral filtering. However, in applications such as recording the noise from wind turbines, the external signal of interest and the locally generated wind noise on the microphone have overlapping spectral peaks of comparable strength (Heckl and Petersson, 2005). Directionality of microphones does not necessarily help. The usual approach is to use wind shields, but it may be necessary to have multiple, and physically large, shields. Alternative approaches, such as recording the external audio only during low-wind periods at the microphone, risk biasing data (von Hünerbein et al., 2017).

For the case of small microphones, dipole noise is the dominant turbulent noise, and Ffowcs-Williams and Hall (1970) showed that the mean-square sound pressure varies as

$$\overline{p^2} \propto U^5 l \frac{\overline{u^2}}{U^2} \tag{1}$$

due to turbulence of intensity $\overline{u^2}/U^2$ of correlation length l, where U is the speed in the undisturbed flow. The turbulent scales are limited by the boundary layer thickness, which increases approximately as the square root of the distance d downstream of the leading edge. Putting these factors together, the mean-square voltage output from a microphone (which is proportional to the mean-square sound pressure) can be approximated by

$$\overline{v^2} = \overline{v_n^2} + \overline{v_{ext}^2} \tag{2}$$

where

$$\overline{v_n^2} = \frac{aRe^2}{1+bSt^5}. \tag{3}$$

and $\overline{v_{ext}^2}$ is due to the external sound source of interest. The term $\overline{v_n v_{ext}}$ doesn't appear because v_n and v_{ext} are uncorrelated, and circuit noise and microphone self-noise are generally negligible by design. The dimensionless parameters involved are the Strouhal number $St = fd/U$ and the Reynolds number $e = Ud/\nu$, where ν is the kinematic viscosity, and f the frequency. In general a and b are functions of d.

The wind-noise spectrum described by (3) depends on the distance of a microphone from the leading edge of the microphone mounting, unlike the spectrum from an external sound source such as a wind turbine. This potentially provides a method for separating the local turbulence-generated spectrum from the external sound source spectrum.

2. Design of a composite microphone

A number of circular composite microphones were designed, of the general form shown in Figure 1.

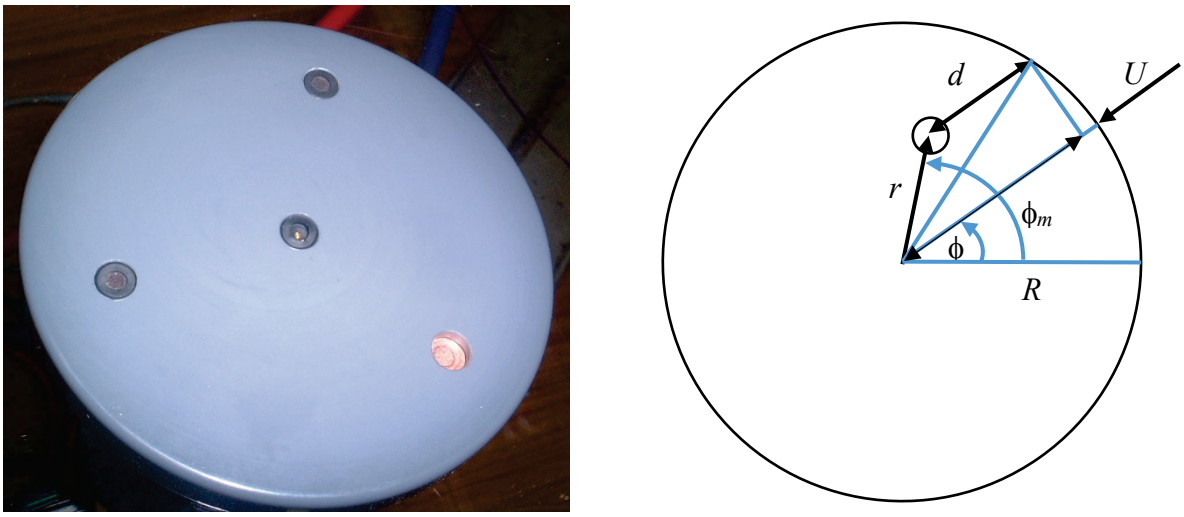

Figure 1. A circular composite microphone (left - one microphone is not mounted) and the geometry for computing d (right).

This gives

$$d = \sqrt{R^2 - r^2 \sin^2(\phi - \phi_m)} - r\cos(\phi - \phi_m). \tag{4}$$

The design shown has four microphones and, for any given wind direction, there will be four distances d and four equations (2) in the two unknowns U and ϕ.

3. Proof of concept

The first step is to check the validity of (3) and to determine the dependence of a and b on d. To do this, a small, quiet, wind tunnel was used (Figure 2). Measurements of normalised spectra at fixed wind speed and at fixed wind direction are shown in Figure 3. The f^{-5} dependence at higher frequencies is evident. Also shown is the background noise spectrum from a microphone not exposed to the air flow, showing that the external sound pressure is negligible.

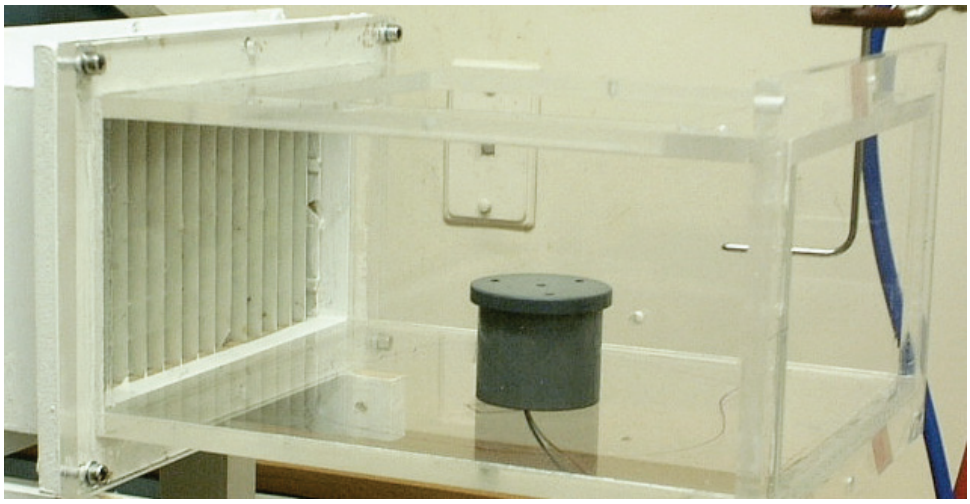

Figure 2. The composite microphone under test.

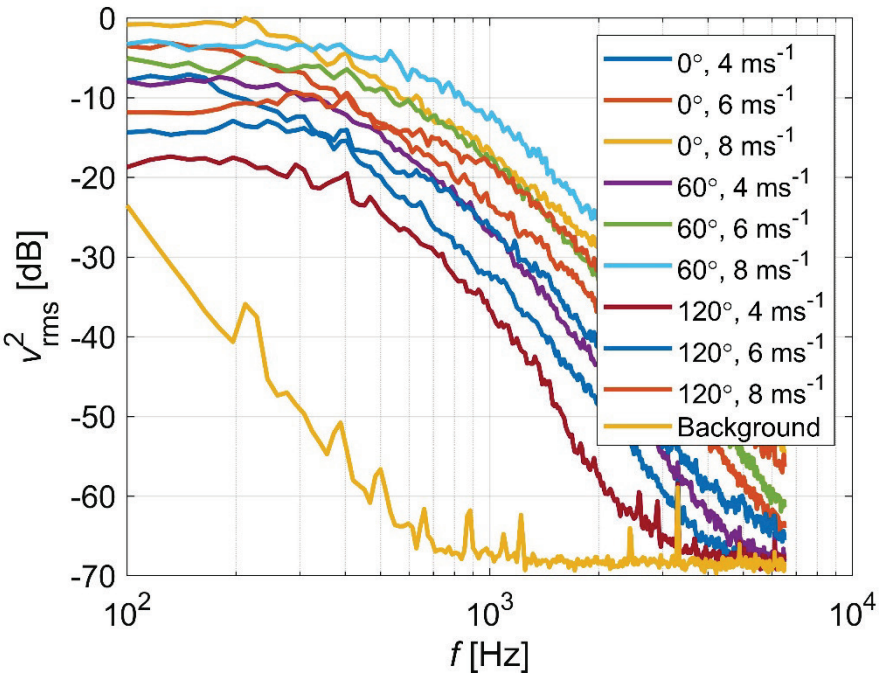

Figure 3. Spectra at U = 4, 6, and 8 m s^{-1} and three microphone angles 0°, 60°, and 120°.

Next, the simple scaling with a and b constant is tested. Figure 4 shows that the -3 dB frequency and the low-frequency intensity are both dependent on d. Figure 5 shows scaled spectra with $a \propto d^{-4}$ and $b \propto d^{-5/4}$ which captures the main dependence on wind speed and direction.

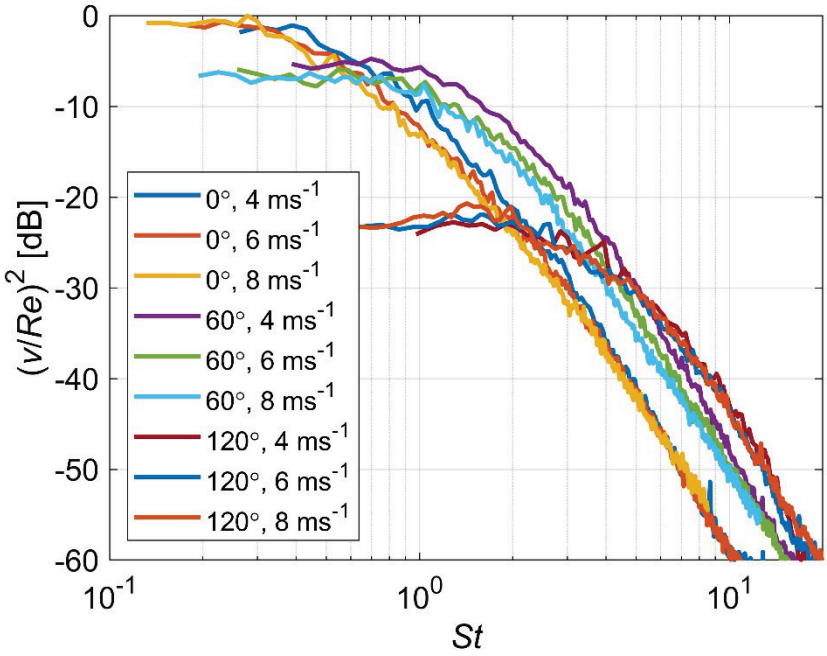

Figure 4. Scaled spectra versus Strouhal number.

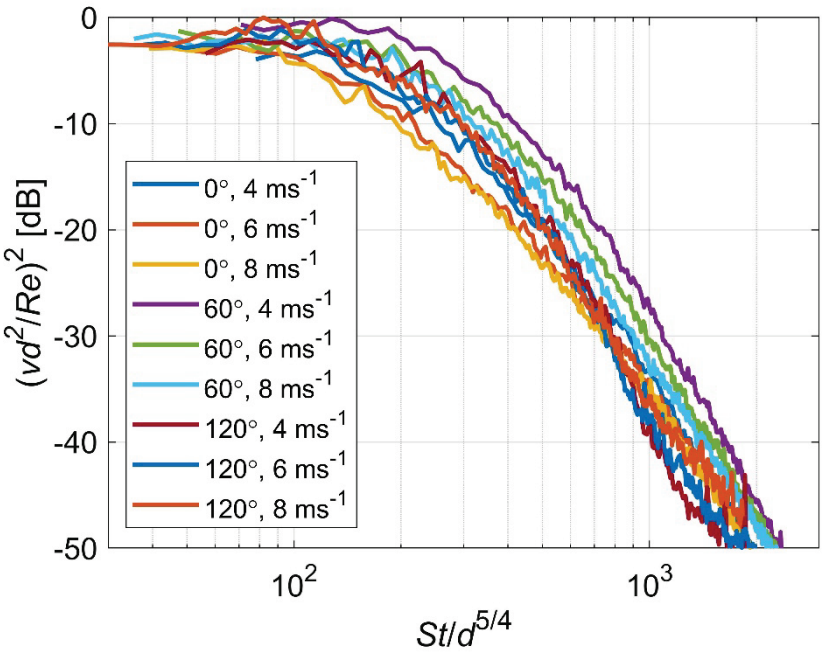

Figure 5. Spectra with a and b dependent on d.

4. Estimating wind noise

The spectra shown above did not include the central microphone for which $d = R$. However, an indication of the estimation of U and ϕ can be given from 3 microphones. Highest accuracy may be expected with the full fit over the frequency range, but a first estimate can be obtained with the simpler low-frequency plateau part of the spectrum, since the fit is then of the form

$$\overline{v^2} = A\left(\frac{U}{d}\right)^2 + \overline{v_{ext}^2} \tag{5}$$

where A is known from the above wind tunnel calibrations. For example, for U = 6 m s^{-1}, and using the measured spectra for the cases of 0°, 120°, and also using the 120° spectrum for -120°, a simple fit by searching parameter space gives the result in Figure 6. The estimated wind speed is 5.76 m s^{-1}, and the estimated value of ϕ is 0°. The rms error in this simple fit is 2% of the mean low-frequency $\overline{v_n^2}$

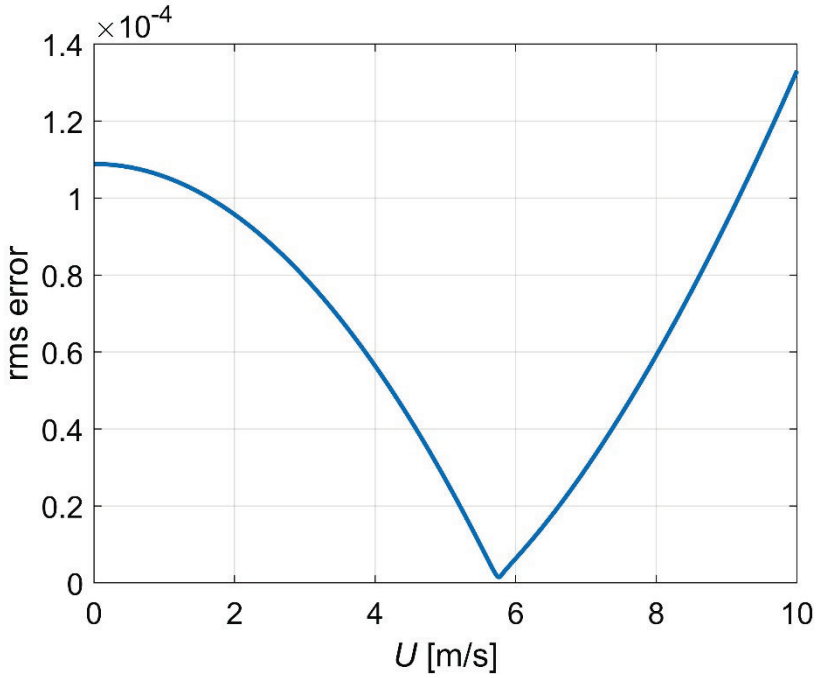

Figure 6. The rms error for fitting versus trial U values.

5. Conclusions

We have described a method by which locally-generated wind noise on microphones can be distinguished from sound from an external source. An simple example of estimation of wind speed and direction based on wind tunnel data has an estimation error of $0.02\,\overline{v_n^2}$, where $\overline{v_n^2}$ is the noise spectrum. If the method gives 2% error in estimated wind noise, and the intensity of the wind noise is comparable to the intensity of the external sound, then the error in estimation of the required external sound intensity is also 2%. Thus if the masking wind noise spectrum is of comparable magnitude to the external sound source spectrum, high quality spectral 'cleaning' should be possible.

References

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