A Novel Technique For Measuring Sound Within Turbulent Duct Flows

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INTRODUCTION

When a *conventional* microphone is placed inside a turbulent duct flow, it responds to a pressure signal, p(t), that represents the superposition of essentially three separate signals, viz., the acoustic pressure signal, $p_a(t)$, produced by the air-moving machinery (e.g., a motor/fan assembly) attached to the duct, the turbulence pressure signal inherent to the flow, $p_{ft}(t)$, and a turbulence pressure signal generated by the upstream grid of the microphone housing, $p_{mt}(t)$. Accordingly, measurement of $p_a(t)$ is not possible by means of a *single* conventional microphone located inside the duct. There have been attempts to measure $p_a(t)$ with specially-designed microphones (e.g., [1], [2]). The latter, however, are ineffectual in many applications, being unable to provide a sufficiently high signal-to-noise ratio in terms of the "far-field" sound waves and the "near-field" turbulence pressure fluctuations.

This paper describes a novel technique for the accurate measurement of the *autospectra* of the sound fields embedded in turbulent duct flows. The technique involves the use of *two* conventional microphones and is based on the fact that the acoustic signal [$p_a(t)$] and the two turbulence signals [$p_{ft}(t)$ and $p_{mt}(t)$] detected by any microphone are uncorrelated with each other *and* with the two turbulence signals detected by another microphone.

ANALYTICAL DETAILS

The autocorrelation function of a stationary signal, p(t), is given by:

$$R(\tau) = \overline{p(t)p(t+\tau)},$$

where the over bar denotes time average, t denotes time, and τ denotes a time lag. The corresponding autospectrum of the signal is defined as:

$$S(f) = \int_{-\infty}^{+\infty} R(\tau)e^{-i2\pi f\tau}\,d\tau,$$

where f denotes frequency. The cross-correlation function of two stationary signals, $p_1(t)$ and $p_2(t)$, is given by:

$$R_{12}(\tau) = \overline{p_1(t)p_2(t+\tau)}.$$

The corresponding cross-spectrum is defined as:

$$S_{12}(f) = \int_{-\infty}^{+\infty} R_{12}(\tau)e^{-i2\pi f\tau}\,d\tau.$$

This is a complex function whose magnitude, $|S_{12}(f)|$, is referred to as the cross amplitude spectrum. If the two signals, $p_1(t)$ and $p_2(t)$, are uncorrelated, the cross amplitude spectrum of the signals is zero. On the other hand, if the two signals are correlated with

$$p_2(t) = kp_1(t+\tau_o),$$

where k and $|\tau_o|$ are positive constants, then the cross amplitude spectrum of the two signals is the same as k times the autospectrum of $p_1(t)$, i.e.,

$$|S_{12}(f)| = kS_1(f).$$

Moreover, the autospectrum of $p_2(t)$ is k^2 times the autospectrum of $p_1(t)$, i.e.,

$$S_2(f) = k^2S_1(f).$$

It is interesting to note that, in this case,

$$\log_{10}[|S_{12}(f)|] = \{\log_{10}[S_1(f)] + \log_{10}[S_2(f)]\}/2.$$

EXPERIMENTAL DETAILS

To validate the technique, autospectra and cross-spectra of the pressure signals from two conventional microphones located in a turbulent flow were determined. The flow and sound were generated in an open-circuit wind tunnel with a motor-fan assembly located at its intake end. A loudspeaker was installed inside the tunnel downstream from the fan outlet in order to produce an 'artificial' sinusoidal sound field, with prescribed sound pressure level (SPL) values and frequencies. A Cartesian coordinate system was employed, with the x-axis in the streamwise direction, the y-axis in the vertical direction and the z-axis in the spanwise direction. The origin of the coordinate system was taken to be the centre of the loudspeaker. The x and y positions of the two microphones, which were designated #1 and #2, were the same, with x equal to 10D, where D denotes the microphone diameter, and y equal to zero. The microphones were separated in the z direction by a distance of 15D to ensure that $p_{ft1}(t)$ and $p_{ft2}(t)$ would be uncorrelated.

The analogue signals from the two microphones were digitized simultaneously, and the various spectra were obtained with the aid of the fast Fourier transform algorithm. Each spectrum was converted into an SPL spectrum via the following relationship:

$$SS_p(f) = 10\log_{10}[S_p(f)] + C,$$

where $S_p(f)$ denotes the spectrum of a signal p(t), $SS_p(f)$ denotes the corresponding SPL spectrum in decibels (dB), and C is a constant.

Measurements were taken for the following three cases: (a) no flow and 'artificial' sound in the tunnel, with selected values of the sinusoidal frequency, f_o, (b) flow only, and (c) flow and 'artificial' sound in the tunnel.

RESULTS AND DISCUSSION

The SPL spectra $SS_{p1}(f)$, $SS_{p2}(f)$, and $SS_{p1p2}(f)$, are presented in Figure 1 for case (a) with f_o = 500 Hz. (Similar results were obtained for f_o = 250 Hz and 1000 Hz.) The three spectra are identical, establishing that, in this case, the two microphones sensed the same sound signal, i.e., $p_1(t) = p_2(t) = p_a{*}(t)$, where $p_a{*}(t)$ represents the 'artificial' sound signal [plus the ambient noise].

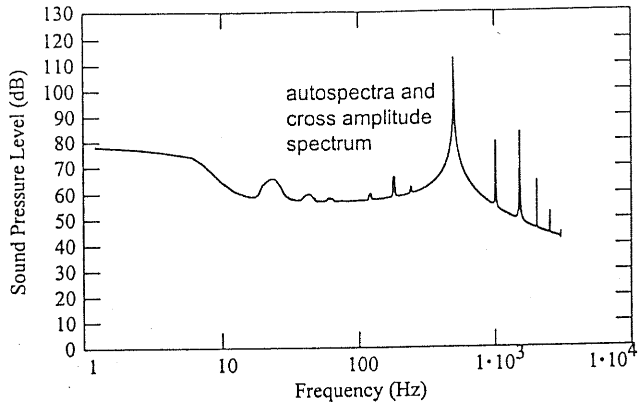

Figure 1. SPL autospectra and cross amplitude spectrum for case (a): no flow and 'artificial' sinusoidal sound with f_o = 500 Hz.

Figure 2 shows $SS_{p1}(f)$, $SS_{p2}(f)$, and $SS_{p1p2}(f)$ for case (b). It can be seen that $SS_{p1p2}(f)$ is about 10 dB below $SS_{p1}(f)$ and $SS_{p2}(f)$ for all frequencies. Moreover, $SS_{p1}(f)$ and $SS_{p2}(f)$ are effectively the same, indicating that the two microphones sensed signals, $p_1(t) = p_{a1}(t) + p_{ft1}(t) + p_{mt1}(t)$ and $p_2(t) = p_{a2}(t) + p_{ft2}(t) + p_{mt2}(t)$, with essentially *the same statistical properties*. Note that $p_1(t)$ and $p_2(t)$ cannot be the same, since $p_{ft1}(t) \neq p_{ft2}(t)$ and $p_{mt1}(t) \neq p_{mt2}(t)$. However, the fact that the microphones used were identical and the flow velocity and turbulence intensity were approximately the same at the two microphone locations signifies that $SS_{mt1}(f) \cong SS_{mt2}(f)$ and $SS_{ft1}(f) \cong SS_{ft2}(f)$. It then follows that $SS_{a1}(f) \cong SS_{a2}(f)$, which is entirely consistent with $p_{a1}(t) = p_{a2}(t + \tau_o)$, where the constant τ_o can be 0. Thus, it can be inferred that $SS_{p1p2}(f)$ represents $SS_{a1}(f)$ or $SS_{a2}(f)$,

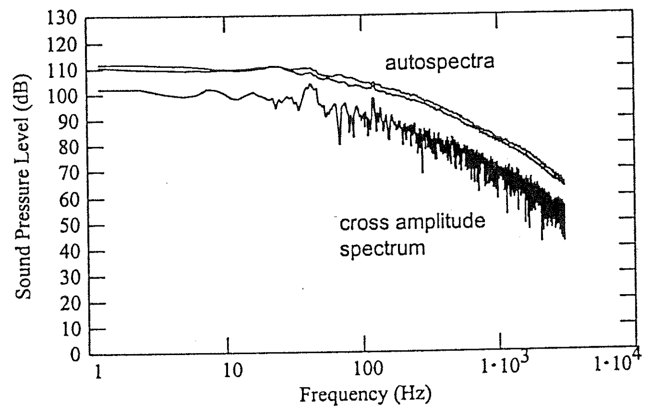

Figure 2. SPL autospectra and cross amplitude spectrum for case (b): flow only.

The spectral results for case (c) with f_o = 500 Hz are presented in Figure 3. Clearly, these results exhibit the same traits as those shown in Figure 2. But, in this case, $p_1(t) = p_{a1}{*}(t) + p_{ft1}(t) + p_{mt1}(t)$ and $p_2(t) = p_{a2}{*}(t) + p_{ft2}(t) + p_{mt2}(t)$, where the acoustic pressure signals, $p_{a1}{*}(t)$ and $p_{a2}{*}(t)$, each consist of two components. One of these components is the artificial sound signal, $p_a{*}(t)$, which is the same at the two microphone locations. The other component is the sound signal produced by the flow-machinery, which is such that $p_{a1}(t) = p_{a2}(t + \tau_o)$. Accordingly, as in case (b), the cross amplitude spectrum of the two microphone signals represents the autospectrum of the acoustic signal produced in the duct at either microphone location.

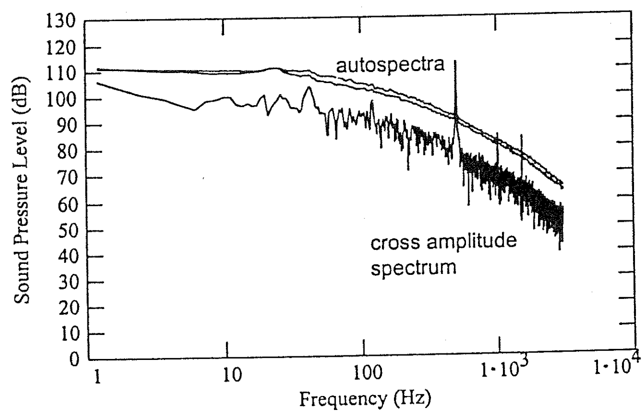

Figure 3. SPL autospectra and cross amplitude spectrum for case (c): flow and 'artificial' sinusoidal sound with f_o = 500 Hz.

On the basis of the foregoing results, it can be concluded that the present technique is an efficacious means of *accurately* measuring the autospectra of acoustic fields embedded within turbulent duct flows.

ACKNOWLEDGEMENT

This research was supported by the Natural Sciences and Engineering Research Council of Canada through grant 203462-98 .

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