MEASUREMENT OF PRESSURE FLUCTUATIONS IN TURBULENT FLOW

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Introduction

The measurement of pressure fluctuations is fundamental to the science of acoustics. With growing interest in aeroelastic phenomena the need has emerged to measure pressure fluctuations in turbulent flow where it is usually assumed that fluctuations are associated with local turbulence and not sound. However, both types of fluctuation will be present to some extent in all practical flows.

Apart from the importance of this point to the simulation and scaling of aero eleastic systems, it is crucial in the field of aeroacoustics where one is usually attempting to measure the acoustic fluctuations [1]. In the application of active sound attenuation to flow ducts, the confounding effect of turbulent pressure fluctuations can be critical [2]. How can one determine the source(s) of the pressure fluctuations and obtain their respective characteristics?

2. EXPERIMENTAL METHODS

2.1 Correlation with two microphones

Taking the general case where both turbulence and acoustic pressure fluctuations are random wide-band variables, they are distinguishable only by their space-time correlation patterns. The acoustic component comprises one or more waves which propagate in a fixed pattern at the speed of sound, while the component due to local turbulence is characterized by an eddy pattern which is continually altering as it propagates downstream with the flow.

Consider the simple case, shown in Fig.1, of a turbulent flow in a duct which is also carrying a unidirectional plane wave and has two microphones in the duct at spacing s. Let the microphone pressures 1 and 2 comprise acoustic and turbulent components so that the Cross Spectral Density (CSD) of the two signals is given by [3]

$$S_{12}(j\omega) = [A_1(j\omega) + F_1(j\omega)]^*[A_2(j\omega) + F_2(j\omega)] \qquad 1.$$

where $S_{12}(j\omega)$ = the CSD of microphone signals,

$A_1(j\omega)$, $A_2(j\omega)$ are the Fourier Transformed acoustic components,

$F_1(j\omega)$, $F_2(j\omega)$ are the turbulent components and

ω = angular frequency.

Provided S is large enough, the turbulent components correlate neither with each other nor with the acoustic components. Thus

$$S_{12}(j\omega) = S_{A1A2}(j\omega) = S_{A1}e^{-j\omega S/c} \qquad 2.$$

and $S_{A1(j\omega)} = |S_{12}(j\omega)|$ 3.

since

$$A_2(j\omega) = A_1(j\omega)e^{-j\omega S/c} .$$

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Since the turbulent and acoustic components of pressure fluctuation do not correlate, the turbulent spectrum can be obtained by subtraction, thus

$$S_{FF}(j\omega) = S_{11}(j\omega) - |S_{12}(j\omega)| \qquad 4.$$

Coherence $\gamma^2(j\omega)$ is defined as [3]

$$\gamma^2(j\omega) = |S_{12}(j\omega)|^2/(S_{11}(j\omega)S_{22}(j\omega)) \qquad 5.$$

If one microphone, say 1, is positioned out of the flow but in a position where it still senses the acoustic content radiated from the duct, the coherence indicates the proportion of in duct mean square fluctuations associated (in a linear system sense) with the sound outside the duct. Thus lack of coherence is a measure of the turbulent contribution to mean square fluctuations in the duct.

It should be noted that although the above analysis provides an estimate of the spectra, it does not allow reconstruction of either turbulent or acoustic signals as a functions of time.

2.2 Preferential couplers

Taking the same flow-acoustic situation, it is possible to devise microphone combinations which are either insensitive to acoustic fluctuations or less sensitive to turbulence.

The strong self coherence which is inherent in the acoustic component can be utilized as shown in Fig.1 (lower part) to eliminate it, leaving a combination of the turbulent signals. With the potentiometer gain g = 1, the acoustic component of the pressure signal is eliminated and the mean square voltage fluctuations $\overline{e^2(t)}$ given by

$$\overline{e^2(t)} = \overline{f_1{}^2(t)} + \overline{f_2{}^2(t)}$$

where $f_1(t)$, $f_2(t)$ are the turbulent component at 1 and 2 and are assumed to be uncorrelated.

If the turbulent levels at 1 and 2 can be related, say

$$\overline{f_2{}^2(t)} = \alpha^2\overline{f_1{}^2(t)}$$

where α is a decay factor,

$$\overline{f_1{}^2(t)} = \overline{e^2(t)}/(1+\alpha^2) \qquad 6.$$

Figure 2 illustrates a method of enhancing the acoustic content of the signal by utilizing N microphones. If the time delay $\tau = s/c$ and s is greater than the turbulent correlation length, the acoustic component of pressures will constructively reinforce at each summing junction, while the turbulent component will add as uncorrelated noise. The turbulence rejection relative to the sound is given by

$$R = 10 \log N \text{ (dB)} .$$

The principle of the microphone turbulence screen, depicted in Fig.3, is similar. The screen consists of a long tube (about 0.5m) with a microphone at the end furthest from the source. The microphone couples to the pressure field in the duct via a narrow axial slit which is covered with a material of suitable flow resistance. An acoustic plane wave is generated inside the tube and as it propagates towards the microphone, acoustic waves outside the tube, reinforce it constructively while turbulent fluctuations do not. Such devices have about 10 dB turbulence rejection at 100 Hz rising to about 25 dB rejection at 1000 Hz.

2.3 Experimental equipment

The methods described in Section 2 were used on the test situation depicted in Figure 1. Air was drawn at up to 30 m/s through asquare rigid walled duct by a silenced fan. The air inlet was a sharp edged flange (to generate turbulence) and the opposite end was an acoustically anechoic termination. Microphones could be mounted either flush on the duct walls or held in the flow. A survey of the working section of duct with cross hot-wires and a total pressure probe showed that the mean velocity was 92% of the maximum and the stream wise and transverse levels of turbulence were 7% to 10% and 5% to 6% respectively.

Loudspeakers mounted flush with the walls near the air inlet, provided a sound source for setting the delay and summing potentiometer in Fig. 1 (lower) to eliminate acoustic contributions from the output. During the actual tests, the loudspeakers were not operated.

3. RESULTS AND DISCUSSION

The pressure spectrum recorded with a microphone turbulence screen is shown in Fig.4, which also shows the spectrum when the acoustic component is subtracted by the method depicted in Fig.1 and described in Section 2.2. Clearly, the acoustic contribution to pressure fluctuations generated by the separated flow at the inlet, is of the same order as the turbulent fluctuations.

Figure 5 shows spectra of microphone measurements made inside and outside the exhaust diffuser of a large ventilating fan which was generating troublesome noise. The inside microphone was fitted with a B & K turbulence screen (UA0436). Coherence of the two signals, as shown in Fig.5, indicates that except for two discrete frequencies, the signals are not related in the linear system sense. Since it can be assumed that the acoustic components of the signals will so relate, the lack of coherence indicates that the fluctuations are dominated by local turbulence, except at 108 Hz and 216 Hz where about 0.62 and 0.8 respectively of the mean square fluctuations is attributable to acoustic sources.

4. CONCLUSIONS

Two types of pressure fluctuations, namely acoustic and those associated with local turbulence, can be expected in turbulent flows. The two types are indistinguishable from observations at a single point but their individual spectra can be estimated from multiple point measurement.

Several experimental techniques are described and two case studies are presented, which show significant content of both types of source.

References

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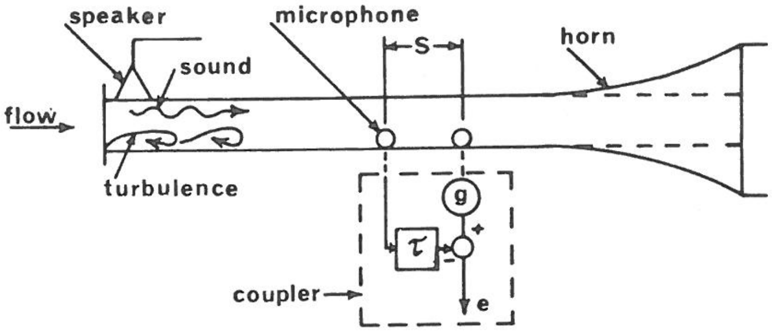

Figure 1 Aero-acoustic duct

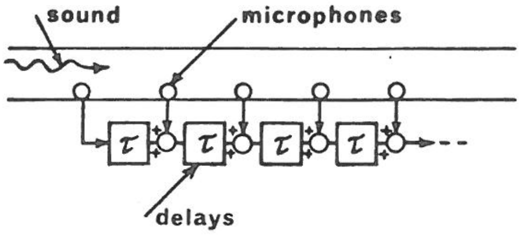

Figure 2 Directional coupler

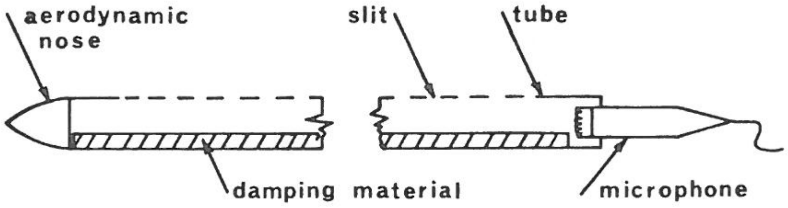

Figure 3 Microphone turbulence screen

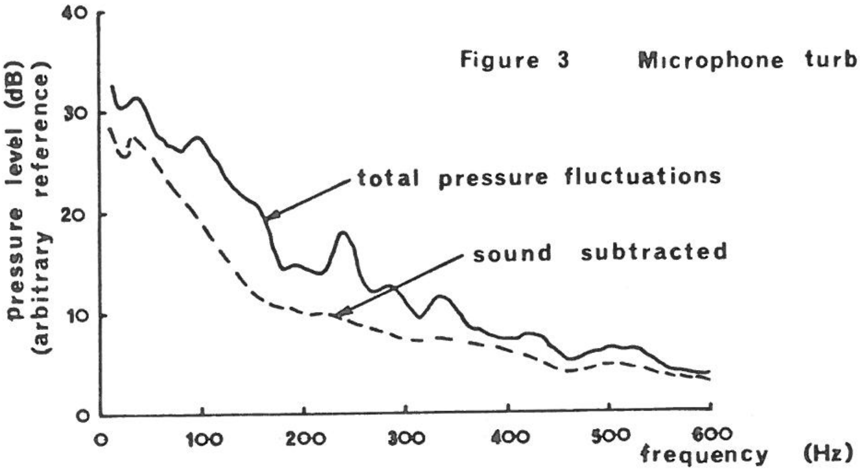

Figure 4 Total and turbulent spectra

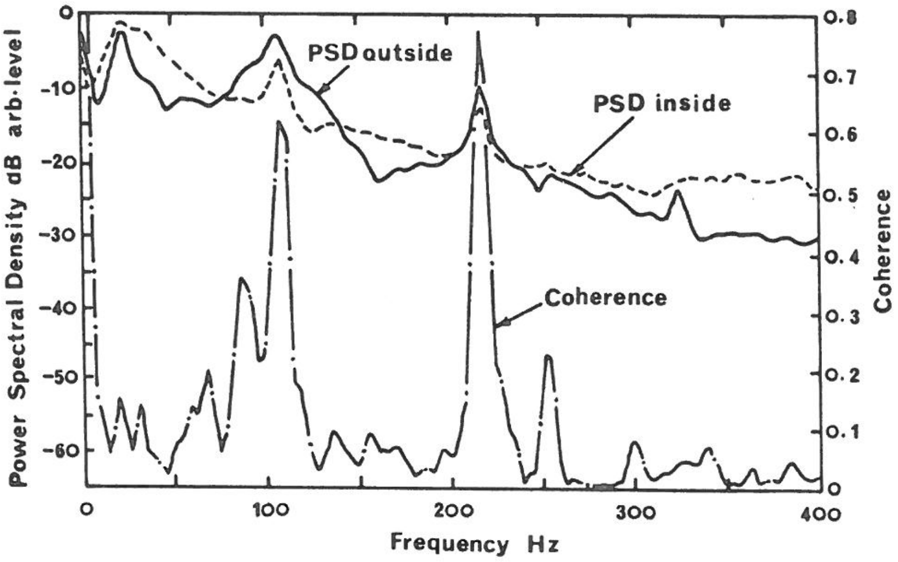

Figure 5 Power Spectral Density inside & outside diffuser