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Low-level flow-induced acoustic resonances in ducts

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Abstract. Acoustic resonances are generated by air moving past a plate with a semi-circular leading edge located in a duct. The sound stimulates the small separation bubble near the leading edge to shed vortices into the boundary layer at the sound frequency. The acoustic energy required to sustain the resonances is generated as these vortices pass the trailing edge of the plate.

1. Introduction

Strouhal (1878) showed that sound is produced when air flows around a body. Although he thought the sound was generated by friction, we now know it is associated with periodic shedding of vortices. Howe's theory (1975) quantified the association.

In a confined space, such as a duct, the sound generated is reflected back and can become very loud. The loud sound influences the vortex shedding process, and may induce "locking", where the shedding and sound are synchronised. This is a "feedback" process, and the sound pressure level (SPL) produced by the flow around a plate with a semi-circular leading edge (Welsh et al. 1984) can reach 160 dB (re 20μPa). In this case, the resonance occurs over a range of flow velocity where the natural Strouhal shedding frequency is close to the frequency of the appropriate acoustic mode in the space.

The possible acoustic modes and their frequencies are many, but the simplest for a plate in a duct, and the one with lowest frequency, is the Parker β-mode (Parker 1967). It is the only one arising in the experiments described here. When the velocity of air flowing past a plate with a semi-circular leading edge in a duct is increasing, the vortex shedding frequency from the trailing edge is proportional to flow velocity (constant Strouhal number) until it approaches the β-mode acoustic frequency. This abstract describes recent observations at low flow velocities when the trailing edge vortex shedding frequency is much less than the β-mode acoustic frequency. At certain velocities, these flows produce sound with marked peaks in the SPL at the β-mode frequency. Acoustic sources associated with these resonances will be described.

2. Instrumentation and procedure

The experiments were performed in a low velocity wind tunnel. A schematic of the working section and instrumentation is shown in fig. 1. The plate had a semi-circular leading edge and a square trailing edge with a chord length in the flow direction of 130.5 mm and a thickness of 12.3 mm. The duct cross section was 244 mm square.

Measurements were made with a probe microphone and two single hot wire sensors. The probe microphone and one hot wire sensor were located 85.5 mm and 10.2 mm, respectively,

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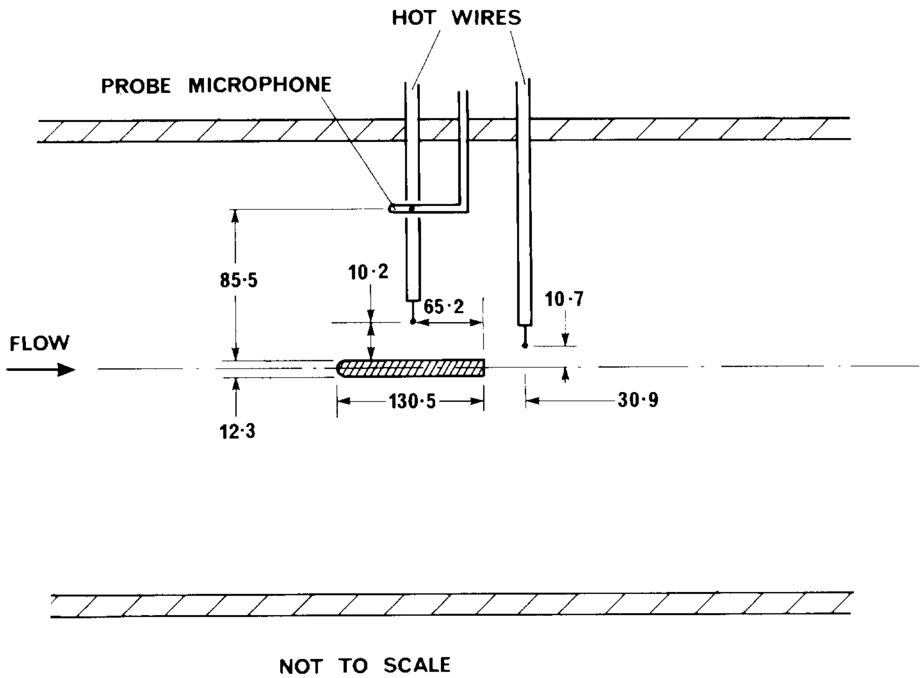

Fig. 1. Schematic of wind tunnel working section.

above the mid-chord position of the plate (fig. 1). These locations ensured that the microphone was located near the position of maximum acoustic pressure for the β-mode, and that the hot wire was positioned where the β-mode acoustic particle velocity in the mean flow direction is zero. A second hot wire was located 10.7 mm above the centreline of the duct and 30.9 mm downstream of the trailing edge of the plate. It detected the vortex shedding frequency from the trailing edge of the plate.

All the signals from the measuring sensors were band pass filtered between 10 Hz and 800 Hz and digitized at 1600 Hz. Their respective spectra were calculated using a ninth order Fast Fourier Transform (FFT) with 10 averages. These results were used to determine the sound pressure level (SPL) at the acoustic resonant frequencies (606 Hz to 619 Hz) and the vortex shedding frequencies. The probe microphone and the signal from the hot wire located above the mid-chord of the plate were processed in a similar manner to determine their coherence.

3. Results and discussion

Fig. 2 shows the variation of the vortex shedding frequency and the SPL, at the frequency of the resonant acoustic β-mode, with flow velocity. The major peak in SPL is due to locked shedding from the trailing edge, and has been described by Welsh et al. (1986). Between 6 m/s and 15 m/s there are seven peaks in the SPL. The sound frequency at each peak is that of the β-mode (606 to 619 Hz) which is much higher than the corresponding vortex shedding frequency shown in fig. 2. The disparity in frequency means that the vortex street is unlikely to be the source of sound. Stokes and Welsh (1986) showed that for a plate with a square leading edge, β-mode resonances were generated over several ranges of flow velocity. The source of the sound was the stream of vortices shed from the leading edge separation bubble. These vortices moved along the plate and past the trailing edge where they exchanged energy with the sound

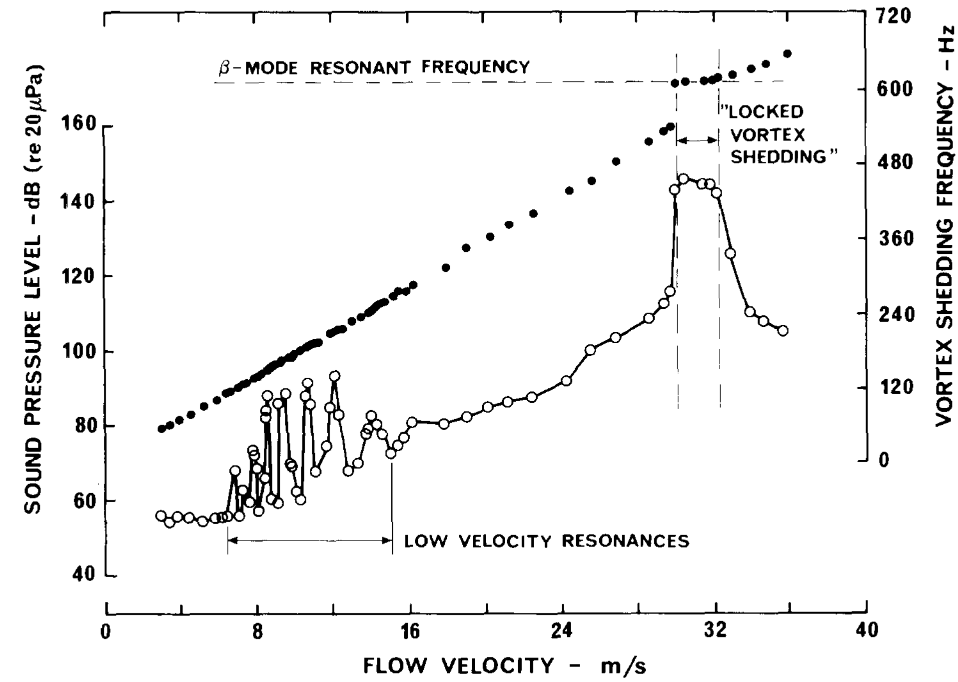

Fig. 2. Variation of vortex shedding frequency and SPL at the β-mode frequency with flow velocity; ●, vortex shedding frequency; ○, SPL at β-mode frequency.

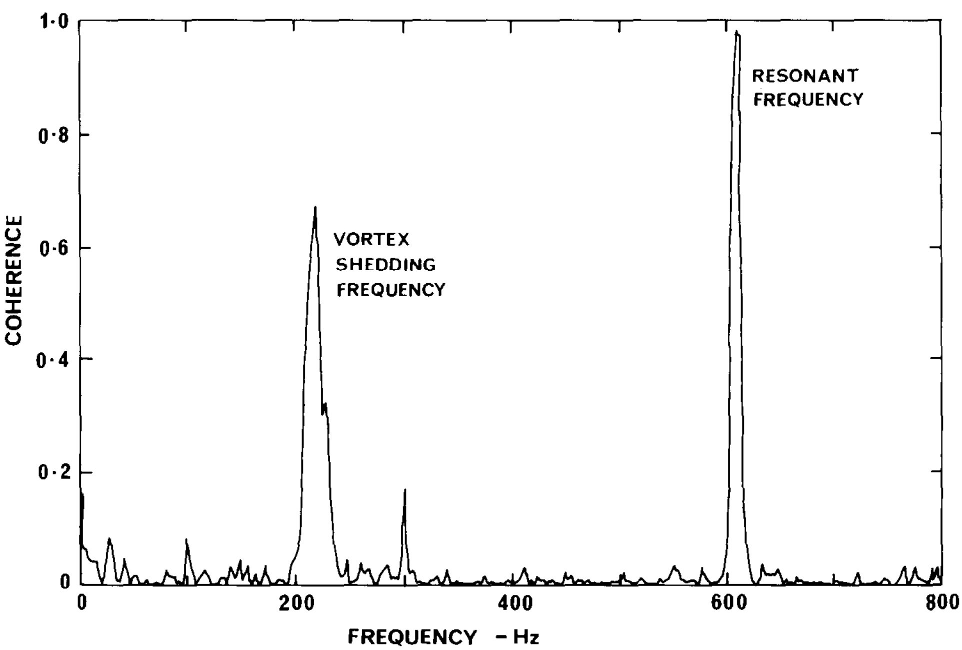

Fig. 3. Coherence of signals from the hot wire and the probe microphone located above the mid-chord position of the plate; flow velocity = 12 m/s; SPL = 93 dB.

field. The direction of the exchange depends on the phase of the acoustic cycle at which each vortex arrives at the trailing edge. This is primarily determined by the time taken for the vortices to traverse the length of the plate, and this in turn depends on the flow velocity. There are many possible time intervals, differing by a discrete number of sound cycles, and each corresponds to a different flow velocity range in which resonance is possible.

Water droplets placed near the semi-circular leading edge of the plate used in the experiments described here show the existence of a small leading edge separation bubble. It is hypothesised that the sound field causes small vortices to shed from this bubble at the sound frequency, just as it does from larger bubbles on plates with square leading edges (Stokes and Welsh 1986). These vortices would then enter the boundary layer and move along the plate, past the trailing edge where they act as a sound source, before merging into the larger vortices observed in the vortex street.

Evidence for this hypothesis is given in fig. 3. At the β-mode frequency, there is high coherence (0.98) between the probe microphone signal and the signal from the hot wire located above the mid-chord position of the plate. This means that the hot wire signal is associated in both frequency and phase with the sound field. However, the acoustic particle velocity at the position of the hot wire is close to zero, and in fact the velocity perturbation measured is much greater than the acoustic velocities anywhere in the region. Therefore, the coherence of the hot wire signal and the microphone response is attributed to the velocity fluctuations induced by passing vortices, whose release has been triggered by the sound field.

4. Conclusion

When a plate with a semi-circular leading edge in a duct excites a loud resonance with locked vortex shedding from the trailing edge, the site of shedding is the sound source, and there is just one range of flow velocity in which it occurs.

At much lower flow velocities, resonant sound is recorded at frequencies unrelated to the frequency of the vortex shedding from the trailing edge. The sound source is attributed to vortices shed near the leading edge and generating sound as they pass the trailing edge. This explains the occurrence of a β-mode resonance over several discrete ranges of flow velocity.

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