RESONANT STRUCTURAL AND ACOUSTIC VIBRATIONS INDUCED BY VORTEX SHEDDING

M.C. Welsh*

Introduction

Sarpkaya [1], and more recently Bearman [2], reviewed the literature on vortex induced oscillations. These reviews indicate a considerable effort has been devoted to studying resonant structural vibrations of bluff bodies shedding vortices. A smaller effort has been devoted to studying resonant acoustic vibrations induced by vortex shedding from rigid bluff bodies immersed in duct flows.

Parker [3] and Parker and Llewelyn [4] examined the flow around a thick flat plate when both structural and acoustic vibrations occur simultaneously. Although it is natural to assume that when resonant acoustic and structural frequencies coincide disastrous vibration would occur, Parker showed this assumption is often unfounded. The acoustic vibration can either suppress structural vibration or induce structural vibration when it would not normally occur.

The aim of this paper is to present an explanation of the interaction between structural and acoustic resonances when their frequencies are coincident.

Details of Acoustic Resonance Excited by Vortex Shedding

Recently Welsh, Stokes and Parker [5] examined the fluid mechanics of resonant acoustic processes when a rigid thick plate sheds vortices in a hard walled duct. Although many acoustic modes are possible, here the simplest acoustic mode will be assumed (Parker β-mode). In this mode the acoustic particle velocities oscillate in phase around the leading and trailing edges. When the plate is held rigid and the flow velocity is increased from zero, the vortex shedding frequency increases linearly with flow velocity towards the acoustic resonant frequency. Near the resonant frequency the vortex shedding process suddenly locks to the resonant acoustic frequency which is slightly less than the measured resonant value without flow (Figure 1) [5]. As the velocity is increased further the sound and the vortex shedding frequencies remain locked together increasing gradually until they are slightly greater than the resonant frequency without flow. With a further increase in flow velocity the vortex shedding frequency suddenly jumps to the Strouhal value and the resonance ceases. The point in the acoustic cycle when a vortex commences growing during the locked regime (resonance) virtually does not change. Welsh et. al.[5] showed that during resonance a vortex commences growing from the trailing edge corners as the acoustic particle velocity increases the flow velocity past the corners.

Details of Structural Resonance Excited by Vortex Shedding

When Toebes and Eagleston [7] mounted a similar plate on a torsional spring system in a water tunnel, again vortices were initially shed at a frequency proportional to the flow velocity. As the flow velocity increased from zero the vortex shedding frequency approached the transverse resonant frequency of the plate and spring mounting system. With a further increase in flow velocity the

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* CSIRO Division of Energy Technology, Melbourne, Australia.

plate began to vibrate and the vortex shedding frequency locked to the vibration frequency in a similar manner to the acoustic case described above (Figure 1).

Zdravkovich [8] showed in the early stages of "lock-on" a vortex was shed from one side of the body when the body was near maximum displacement towards the opposite side. With increasing flow velocity while the plate was still vibrating, the phase difference between the displacement of the body and the vortex shedding process changed suddenly; a vortex was shed when the body was near maximum displacement towards the same side.

Figure 2 shows polar diagrams illustrating the phase relationships for zero damping, between the driving force (F_v) due to the vortex shedding, the transverse plate velocity (v_p) and the plate displacement (y_p). Two cases are shown in Figure 2 where the body is vibrating slightly below, (A), and above, (B), its structural resonant frequency. For condition (A) the driving force and the displacement are in phase and trail the plate velocity by 90°. The vortex street is illustrated for the plate at maximum positive displacement with a vortex just shedding from the lower surface. For condition (B) the driving force leads the displacement by 180° and the plate velocity by 90°. The vortex street is illustrated for the plate at maximum negative displacement with a vortex just shedding from the lower surface.

The Superposition of Structural and Acoustic Resonance

At the onset of separate structural or acoustic resonances the vortex shedding becomes coherent across the span of the plate; there is a threshold level of transverse velocity relative to the plate below which the vortex shedding is not coherent. Correlated vortex shedding is a necessary condition for sustained resonance (Zdravkovich [8]).

If a plate is located on flexible mounts in a duct without flow so that the structural resonant frequency is equal to the acoustic resonant frequency (Figure 1), then the vibration due to the two resonances can be deduced as follows. Welsh et al. [5] showed that during acoustic resonance at the instant illustrated in Figure 2, the acoustic velocity is about to become positive (up the page). At the same time, for case (A) the plate velocity is about to become negative (down the page). The resulting transverse fluid velocity relative to the plate is increased by the presence of the acoustic field. Therefore, the vortex shedding becomes correlated at lower structural velocities (and amplitudes), and structural resonance can occur prematurely. Alternatively, for case (B) the acoustic particle velocity and the plate velocity are in phase and the presence of the acoustic field reduces the transverse velocity of the fluid relative to the plate. If the transverse velocity reduces below the threshold necessary to correlate the vortex shedding, then sustained resonant vibrations do not occur.

Recommendations and Conclusions

When flows around bluff bodies are being examined in closed wind tunnel working sections the acoustics of the space surrounding the test body should be examined. A microphone should be traversed near the tunnel walls just outside the boundary layers. The presence of an acoustic resonance will be obvious in a spectrum even though it may not be audible. Furthermore, it is important to have the test body installed during the examination since it not only generates a source of acoustic energy but also changes the resonant frequency corresponding to a particular acoustic mode.

References

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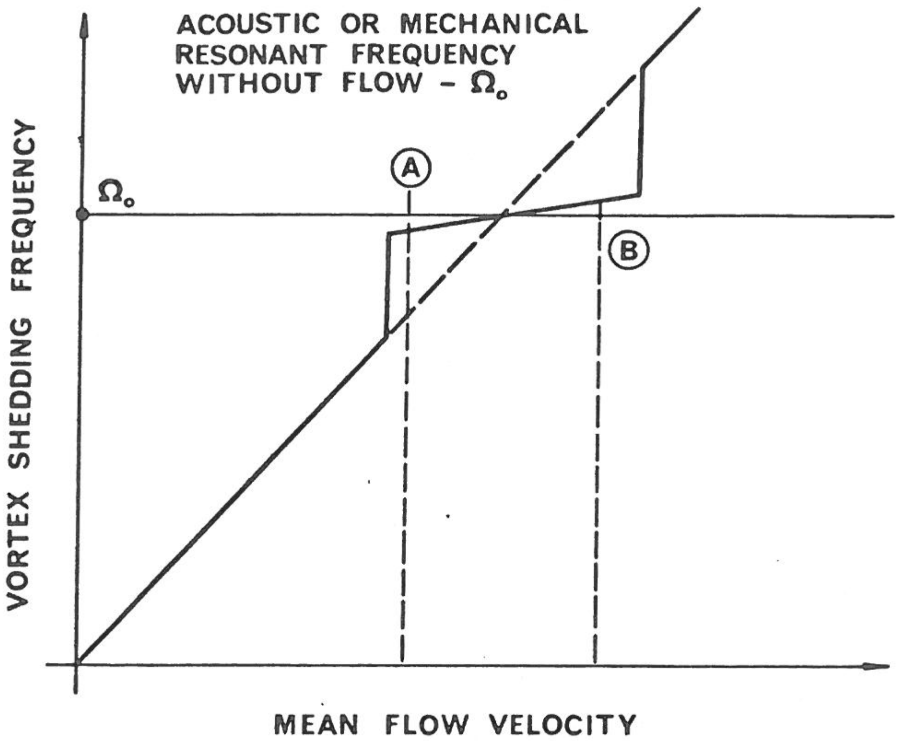

Figure 1: A typical plot of flow velocity versus vortex shedding frequency during resonance.

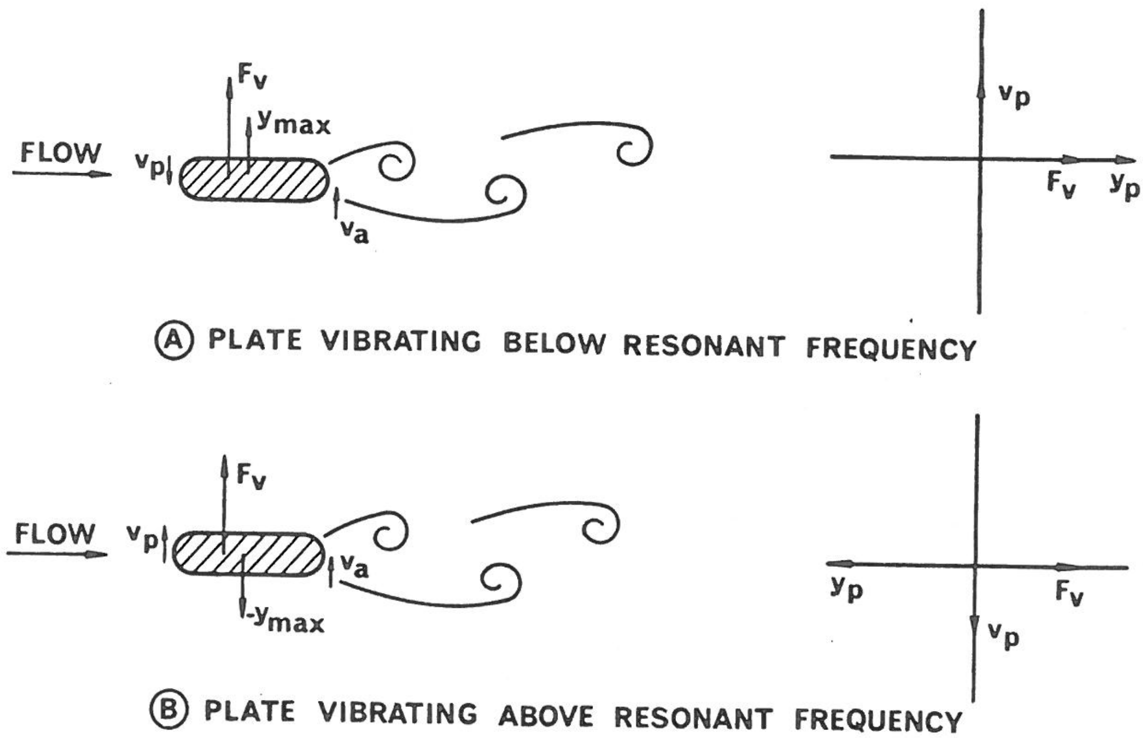

Figure 2: Relationship between vortex street and vibrating plate surrounded by a β-mode acoustic field; F_v, force exerted on plate due to vortex street; y_{MAX}, maximum vertical displacement of plate; y_P, vertical displacement of plate; v_P, transverse plate velocity; v_a, acoustic particle velocity.