TENTH AUSTRALASIAN FLUID MECHANICS
CONFERENCE - UNIVERSITY OF MELBOURNE
11-15 DECEMBER 1989

10D-3

THE EXCITATION OF ACOUSTIC RESONANCES BY FLOW AROUND TWO CIRCULAR CYLINDERS IN TANDEM IN A DUCT

M.C. WELSH[1], K. HOURIGAN[1], M.C. THOMPSON[1], A.N. STOKES[2] and J. SORIA[1]

[1]CSIRO Division of Building, Construction and Engineering
P.O. Box 56, Highett, Vic. 3190, AUSTRALIA

[2]CSIRO Division of Mathematics and Statistics
Private Bag 10, Clayton, Vic. 3168, AUSTRALIA

ABSTRACT

The excitation of acoustic resonances by the flow around two cylinders located in tandem in a hard walled duct is described. It is hypothesised that the excitation is due to discrete vortices in the shear layers separating from the surface of the upstream cylinder. This hypothesis is supported by flow visualisation studies, numerical simulation of the flows with an acoustic field superimposed and measured high coherence between the resonant acoustic pressure field and the oscillating flow velocity field in the shear layer between the cylinders. It is anticipated that these studies explain one possible mechanism responsible for exciting acoustic resonances in in-line cross-flow tubular heat exchangers.

INTRODUCTION

Over the past 30 years there has been much attention paid to cross-flow induced vibrations in heat exchanger tube arrays (Chen 1968, Paidoussis 1981, Weaver and Adb-Raddo 1985, and many others). A recent detailed review of the literature by Weaver and Fitzpatrick (1988) summarises the current understanding of the subject. It presents design guidelines for overcoming vibration problems and details those areas where more research is required. Although acknowledging that some confusion still exists, Weaver and Fitzpatrick (1988) classify the sources of flow-induced vibration in cross-flow heat exchangers into the categories of (a) turbulent buffeting, (b) Strouhal periodicity, (c) fluid elastic instability and (d) acoustic resonance.

Many researchers have observed and studied acoustic resonance in cross-flow heat exchangers (Fitzpatrick and Donaldson 1980, Fitzpatrick 1985, Hill *et al.* 1986, Blevins and Bressler 1987a, 1987b, and others). These studies approached the resonance problem by correlating when resonance occurred with flow and geometric parameters so that the data could be used to predict the occurrence of resonance in the future. At the same time, Parker and Stoneman (1987) were undertaking similar studies with gas turbines, while the authors of this paper studied acoustic resonance at a more fundamental level seeking to explain the fluid mechanics of how the acoustic resonant field is excited by the flow (Welsh *et al.* 1984, Stokes and Welsh 1986, Stoneman *et al.* 1988 and Welsh *et al.* in press).

Weaver and Fitzpatrick (1988) concluded that there was a need for a more fundamental understanding of the flow-induced acoustic resonance process in cross-flow heat exchangers. The aim of this paper is to describe the fluid mechanics of one of several possible sources of flow-induced acoustic resonance in an in-line tubular cross-flow heat exchanger. It seeks to show that the acoustic resonances can be excited by discrete vortices in the shear layers separating from the leading tubes. The initial experiments, both numerical and experimental, describe the excitation of acoustic resonance by the flow around the simplest configuration of an in-line cross-flow heat exchanger, that is, two circular cylinders located in tandem in a duct.

Experimental Equipment and Procedure

The blow down wind tunnel used to study the excitation of resonant sound by the flow around two cylinders located in tandem in the working section (Fig. 1a) is described in detail in Welsh *et al.* (in press). The cylinders were located with a longitudinal pitch ratio of 1.5 and a transverse pitch ratio of 1.61.

Without the cylinders, the mean velocity profile in the working section was uniform within ±0.5%. The longitudinal turbulence level was 0.3% with the major spectral content (40 dB down) at frequencies less than 300 Hz; there were no sharp spectral peaks in the hot-wire signal.

A probe microphone was used to record the sound level near the cylinders (Fig. 1a). It was located 124.5 mm upstream of the centre of the leading cylinder and 33 mm below the upper wall. A 12.7 mm diameter microphone was calibrated using a standard Bruel and Kjaer piston phone and the transfer function between this microphone and the probe microphone was obtained by locating both microphones close together near a white noise sound source. At flow velocities between 9 and 15 m/s, without the cylinders installed, the background noise level in the wind tunnel was typically 75 dB/Hz.

A hot-wire sensor was located 129 mm downstream of the centre of the leading cylinder and 45 mm below the top wall (Fig. 1a). It could therefore detect perturbations in the shear layer shedding from the leading cylinder.

A ninth-order FFT with 10 averages was used to compute the spectra of the microphone signals, while 100 averages were used to compute the coherence between the probe microphone and the hot-wire signals.

Visualisation of the flow was achieved using hydrogen bubbles in a water tunnel designed specifically for simulating aero-acoustic phenomena. The bubbles were illuminated with a sheet of white light after being introduced into the flow on the surface of the leading cylinder upstream of the point of separation with two 76 μm diameter hydrogen bubble wires. This ensured that the hydrogen bubbles marked fluid with high vorticity. The water tunnel is described in detail in Welsh *et al.* (in press) and has a working section with the same transverse dimensions as the wind tunnel described above. Without the cylinders installed, the mean velocity profile was uniform within ±0.5% between the boundary layers and the turbulence level was 0.1%. There are no sharp spectral peaks in the turbulence spectrum which was measured with a laser doppler anemometer operating in back scatter mode.

The velocity perturbations superimposed on the flow around the cylinders by the acoustic resonant field were simulated in the water tunnel by oscillating the side walls of the working section in a direction transverse to the mean upstream flow velocity. To ensure that the velocity perturbation generated by the oscillating walls had a significant amplitude near where the flow separated from the upstream cylinder, it was necessary to join the cylinders with a thin plate as shown in Fig. 1b. The side walls oscillated at a frequency which produced the same Strouhal number (St) as the resonant acoustic St recorded in the wind tunnel (St = fd/U, where f is the oscillation or acoustic frequency, d is the spacing between the cylinder centres and U is the upstream mean flow velocity calculated from the mean volume flow through the working section). The amplitude of the wall oscillation was adjusted to vary the amplitude of the velocity oscillation superimposed on the flow. It was measured using a hot film anemometer and a laser doppler anemometer just upstream of where the flow separated from the leading cylinder and was adjusted so that the ratio of the perturbation velocity to the upstream mean flow velocity (u'/U) was the same as that estimated from the solution of the wave equation in the air tunnel.

Theory and Mathematical Modelling

In the mathematical models, the duct and cylinder geometries are based on the working section shown in Fig. 1.

Acoustic Field

The acoustic mode to be modelled is a standing wave corresponding to an organ pipe mode of the wind tunnel. In the flows of interest here, the Mach number is low and the acoustic pressure satisfies the wave equation. A detailed description of the method of solution of the wave equation is given in Stoneman *et al.* (1988).

Flow Modelling

A vortex cloud model (Stoneman *et al.* 1988) is used to simulate the flow around the cylinders. It is essentially a two-dimensional inviscid incompressible flow model, irrotational everywhere except at the centres of elemental vortices. The assumption of two dimensionality is acceptable in this case due to the two-dimensional sound field 'feeding back' on to the separating flow. The surfaces of the cylinders are modelled using the surface vorticity method (Stoneman *et al.* 1988) which requires that the surfaces of the cylinders are streamlines and that the tangential velocity on the inside of each vortex sheet representing a cylinder surface is zero. These requirements result in an integral equation (Fredholm) which is discretised by considering each cylinder surface to be a large number of vortex sheet segments. At each time step, the elemental vortices are created having the circulation of each vortex sheet segment on the surface of the cylinders. These vortices are released into the flow to simulate the formation of the boundary layers. Their motion is then determined by monitoring the convection of each vortex under the influence of other vortices and the irrotational flow. The model includes a multi-grid Poisson solver which greatly reduces the processing time. Further details of the flow modelling are described in Stoneman *et al.* (1988).

Sound-Flow Interaction

Howe (1984) showed that when an acoustic oscillation occurs in an inviscid, isentropic but rotational flow, an acoustic power (P) is generated in a volume V and is given by:

$$P \propto \int \omega \times \mathbf{v} \, . \, \mathbf{u} \, dV$$

where $\mathbf{v}$ is the total fluid velocity, ω is the vorticity, and $\mathbf{u}$ is the acoustic particle velocity.

Applying this formula with the mathematical models of both the flow and the sound field, it is possible, as shown with two plates located in tandem in a duct (Stoneman *et al.* 1988), to calculate when a net transfer of energy from the flow to the resonant sound field will occur.

RESULTS

Experimental Results

Spectra of the acoustic pressure fields between 30 and 256 Hz for flow velocities ranging between zero and 14.4 m/s are shown in Fig. 2. Clearly, as the velocity increases the acoustic resonance with frequencies between 89 and 94 Hz become dominant. The variation in the Sound Pressure Level/Hz (SPL/Hz) in this frequency band, for mean flow velocities upstream of the cylinders from 9 to 15 m/s, is shown in Fig. 3. The coherence between the probe microphone signal and the hot-wire anemometer signal at 11.5 m/s and 144 dB SPL/Hz is shown in Fig. 4. Clearly, there is a high coherence between the signals at 91 Hz corresponding to a St of 1.81. The velocity perturbation due to the resonant acoustic particle velocity is estimated, using the solution of the wave equation, to be approximately 2.8 m/s at the point of flow separation from the upstream cylinder. Thus, u'/U is approximately 0.25.

The flow observed around the cylinders in the water tunnel, with and without a velocity perturbation superimposed, is shown in Fig. 5. The upstream mean flow velocity is 95.9 mm/s and the side walls are oscillated at 0.76 Hz with an amplitude of 3 mm, which gives a measured u'/U of 0.25 at a St of 1.81. The vortex structures in the shear layer in the absence of a perturbation are shown with a scale of approximately 10% of a cylinder diameter (Fig. 5a). With the oscillation, the large vortex structure

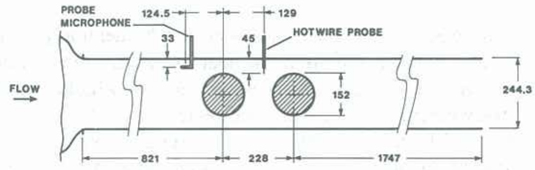

Figure 1a Schematic of working section in wind tunnel.

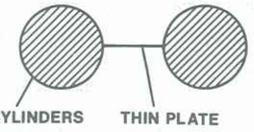

Figure 1b Cylinder geometry used in water tunnel and numerical computations.

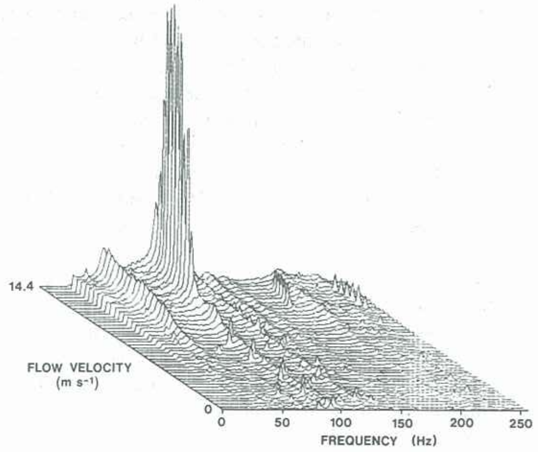

Figure 2 Variation of the probe microphone spectra with flow velocity upstream of the cylinders.

approaching the downstream cylinder is clearly evident. It is shed once per oscillation cycle and demonstrates the effect of an oscillating velocity field synchronising with vortex shedding.

Acoustic Field

The predicted acoustic particle velocities around the cylinders are shown in Fig. 6 for the conditions observed in the wind tunnel at 11.5 m/s and 144 dB/Hz. The acoustic particle velocities oscillate back and forth around the cylinders with a maximum amplitude near where the flow separates from the upstream cylinder. All the particle velocities have a component in the downstream direction for half a cycle and a component in the upstream direction for the remainder of the cycle. This acoustic mode is excited by the flow with a wave length approximately equal to the length of the working section. The frequency of the mode is determined not only by the length of the ducting upstream and downstream of the cylinders but also by the geometry of the cylinders.

Predicted Flow Field

A 'snapshot' of the predicted flow field near the cylinders is shown in Fig. 7 for the same conditions as those recorded in the water tunnel and shown in Fig. 5. The predicted flow with the velocity perturbation superimposed on the flow is qualitatively similar to that observed in the water tunnel with the side walls oscillating (Fig. 5b).

DISCUSSION OF RESULTS

The experimental and numerical data presented here support the hypothesis that the acoustic resonance near 91 Hz is excited by the vortices in the shear layers separating from the upstream

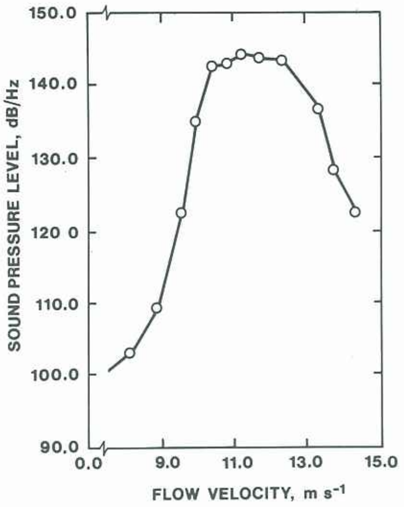

Figure 3 Variation of the peak SPL/Hz between 89 and 94 Hz inclusive with flow velocity.

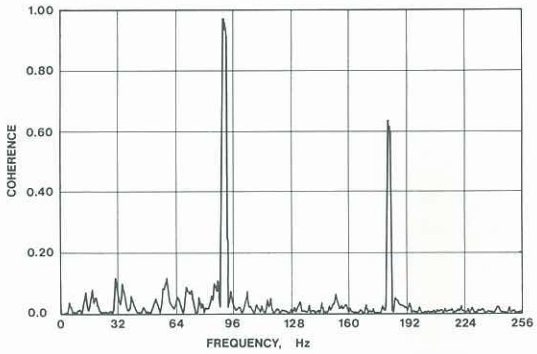

Figure 4 Coherence between the probe microphone and hot-wire signals with a resonant acoustic pressure field of 144 dB/Hz and a flow velocity upstream of the cylinders of 11.5 m/s.

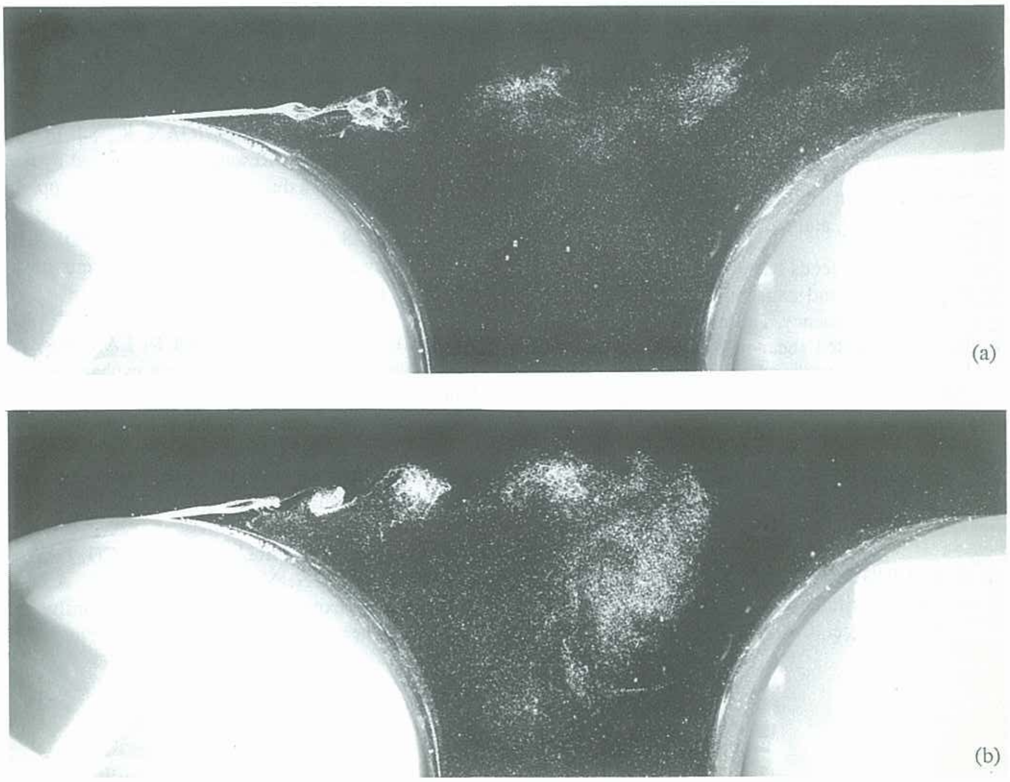

Figure 5 Flow around the cylinders in the water tunnel: (a) without the side walls oscillating; (b) side walls oscillating with an amplitude of 3 mm at 0.76 Hz and an upstream flow velocity of 95.9 mm/s, St = 1.81, u'/U = 0.25.

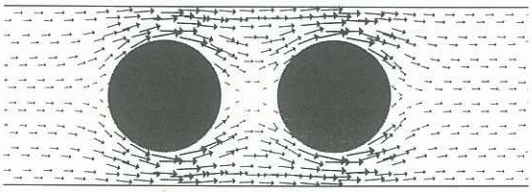

Figure 6 Predicted particle velocities of the acoustic mode excited in the wind tunnel.

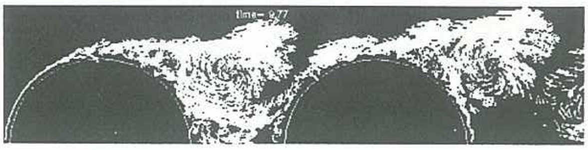

Figure 7 Predicted flow velocities for conditions prevailing in Fig. 5b.

cylinder. High coherence between the probe microphone and the hot-wire signals at 91 Hz is consistent with vortices passing the hot-wire at the sound frequency. Furthermore, flow visualisation in the water tunnel and the vortex cloud model both show a large vortex structure shedding from the upstream cylinder at the frequency of the imposed velocity perturbation. This is a necessary condition for there to be a net transfer of energy from the flow to the resonant acoustic field (Stoneman *et al.* 1988).

Further support for the hypothesis is that a large vortex structure approaching the downstream cylinder once per acoustic cycle, as shown by the vortex cloud model, provides a mechanism for the transfer of net energy from the flow to sustain the resonant acoustic field.

The 'feedback' effect of the oscillating velocity field on to the vortex shedding process at the separation point on the upstream cylinder is demonstrated in both the water tunnel (Fig. 5b) and the corresponding numerically predicted flow (Fig. 7). There are two ways in which the oscillating velocity field changes the shear layer and synchronises the vortex shedding: (a) the oscillating velocity field 'kinks' the shear layer promoting an instability at the oscillation frequency, and (b) the oscillating velocity field modulates the flux of vorticity into the shear layer.

CONCLUSIONS

It is concluded from a study of the excitation of acoustic resonance by the flow around two cylinders located in tandem in a duct that:

(a) resonant longitudinal acoustic plane waves can be excited by the flow through an in-line tubular cross-flow heat exchanger at frequencies related to the geometry of the ducting connected to the tube bank,

(b) the vortices in the shear layers shedding from the leading tubes are responsible for transferring the energy from the flow to the acoustic field, and

(c) the resonant sound field 'feeds back' on to the shear layers at the separation point and causes the vortices to shed regularly at the sound frequency. The 'feedback' causes both a 'kinking' of the separated shear layer and a modulation of the vorticity flux into the shearlayer.

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