Twelfth Australasian Fluid Mechanics Conference
The University of Sydney, Australia 1995

THE MECHANISM CONTROLLING VORTEX SHEDDING FROM RECTANGULAR BLUFF BODIES

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ABSTRACT

Results of an experimental study of the vortex shedding and base drag coefficient for flow around rectangular plates are reported. The flow was perturbed by a transverse acoustic perturbation of variable frequency. For each plate chord-to-thickness ratio, the base drag coefficient was found to attain maxima at applied acoustic Strouhal numbers close to the Strouhal numbers for peak duct acoustic resonance found by Stokes and Welsh (1986) and the natural Strouhal numbers measured by Nakamura *et al.* (1991). It is concluded however that the mechanism responsible for the vortex shedding in general is not a shear layer impingement instability, as proposed by Nakamura *et al.*. For long rectangular plates, the shear layer separating from the leading edge reattaches and sheds discrete vortices at around 5 plate thicknesses, well short of the trailing edge. Rather than shear layer impingement at the trailing edge, a more general vorticity interaction occurs that can generate sound completing the feedback loop back to the receptive shear layers separating at the leading edge. The application of a higher level of sound can over-ride this feedback loop; nevertheless, the system responds optimally at the same frequency.

INTRODUCTION

The active control of globally-unstable separated flows has been recently reviewed by Rockwell (1990). In the presence of controlled forcing, such as oscillating flaps or sound waves, bluff-body wakes are found to have the following response close to the synchronisation frequency: a resonant amplitude peak at the forcing frequency; attenuation of the amplitude at the inherent frequency of the system; and a large phase shift between the loading on the body and its displacement. In the absence of forcing, separated shear layers can become unstable in the presence of sharp trailing edge corners. This was found to lead to a feedback to the receptive separating shear layers and stepwise changing in the Strouhal number against distance of shear layers to the sharp trailing edge corner.

One such globally-unstable flow is the separated flow around rectangular plates, which has been investigated by Parker and Welsh (1983), Stokes and Welsh (1986), Ojikama *et al.* (1983), and recently by Nakamura *et al.* (1991). For moderately low Reynolds number (based on plate thickness) flows ($Re \leq 2000$), Nakamura *et al.* (1991) claim that the vortex shedding from rectangular plates with chord to thickness ratios c/t between 3 and 15 can be characterised by the impinging shear layer instability, as discussed by Rockwell and Naudascher (1979). This type of instability arises from the feedback of pressure waves generated when shear layers shed from the leading edge interact with the trailing edge of the plate. It was found that the Strouhal number, based on plate chord, increased in a stepwise manner, with peak values approximately equal to integer multiples of 0.6. No evidence for this synchronisation was found for Reynolds number greater than 2000; the vortex shedding from the leading edge then exhibits a broad spectral peak around a Strouhal number based on chord of approximately 1.4. Consistent results were found in the numerical study by Ohya *et al.* 1992.

On the other hand, the earlier results of Stokes and Welsh (1986) and Okajima et al. (1983) indicated there were four possible vortex shedding regimes depending on the chord to thickness ratio c/t. However, for natural shedding at these higher Reynolds numbers, there was not the same stepping in Strouhal number observed by Nakamura *et al.*. The results of Stokes and Welsh were obtained at Reynolds numbers of (1.5-3.1)$\times 10^4$ as opposed to 1×10^3 for Nakamura *et al.*. It was suggested by Nakamura *et al.* that although the impinging shear layer instability at high Reynolds number may be masked by inherent turbulent fluctuations and may not be easy to detect, it does not vanish and can be excited by external forcings. They point to the stepping in Strouhal number observed by Stokes and Welsh in the case where the duct resonance is excited.

In the experiments of Nakamura *et al.* in the lower Reynolds number range, the selection of the global instability frequency occurred naturally; no information was provided on the mechanism of frequency selection, other than comparing it with, indeed terming it, a shear layer impingement instability mechanism. However, it is not clear that this description is appropriate; for long bluff plates, the shear layer separating from the leading edge clearly reattaches well upstream of the trailing edge. Vortices are shed from the leading edge separation bubble defined by this reattachment and feedback sound waves are generated by the interaction of the shed vortices with the trailing edge. It would be more appropriate to describe the instability that results as a vorticity impingement instability. This more general description includes vorticity impinging both in the form of shear layers and discrete shed entities.

Visualisation of flow in the higher Reynolds number range by Stokes and Welsh (1986) showed that the leading edge vortex shedding could be locked to the forcing frequency over a range of flow velocities; the frequency of the sound being determined by the duct resonance frequency. For each plate chord-to-thickness ratio considered, a peak in the duct acoustic resonance amplitude occurred near the middle of the velocity range. Their results therefore provide information on the preferred frequency of the global instability.

In this paper, we investigate the vortex shedding from long bluff cylinders under acoustic forcing. This allows a generalisation of the experiments of Stokes and Welsh (1986); both applied frequency and flow velocity can be varied independently. Here, the results of frequency variation on the vortex shedding will be reported. In particular, we address the question of whether the global instability, albeit clearly not an impinging shear layer type, can be excited at higher Reynolds numbers?

EXPERIMENTAL EQUIPMENT

A small blow down open-jet wind tunnel (Fig 1) was used to investigate the flows around elongated rectangular plates. Air was supplied by a centrifugal fan powered by a variable speed AC motor, and directed through a wide angle difuser into a settling chamber containing four nylon screens and a honeycomb for minimising turbulence levels. The air then passed through an eight-to-one contraction to form an open jet with an outlet, which was 244 mm square.

The operating range of the tunnel was 0 to 15 m.s^{-1}. The mean velocity profile at the jet outlet was found to be uniform to within $\pm$0.5%. With a mean jet velocity of 10 m.s^{-1}, the longitudinal turbulence intensity at the outlet was 0.26% after filtering to remove low frequency variations ($<$ 1.0 Hz). Due to the natural instabilities in the free shear layers originating at the jet exit, the minimum turbulence level obtainable at the exit of an open jet wind tunnel was 0.15%, according to Michel and Froebel (1988).

All the test plates were made from brass, had a nominal thickness of 13 mm, and a span of 135 mm. Three of these rectangular plates had pressure tappings located in them to measure surface pressures around the plates, while a series of spacer plates (with no pressure tappings) were constructed with c/t ratios between 2 and 8 to allow the overall plate length to be varied over the range $6 < c/t < 16$ in integer steps.

The pressure tappings on the plates were connected to a Setra pressure transducer (with a working range of -130 Pa to +90 Pa) via a 48-channel Scanivalve. Atmospheric pressure was used as the static reference pressure. The output of the pressure transducer was connected to a Boston technologies A/D board mounted to a 486 PC, which ran software to automatically scan the pressure stations of the Scanivalve, and record the time-mean pressure at each location. The pressures measured by the PC were found to be accurate to within $\pm$0.5 Pa when compared to a Betz manometer connected in parallel with the Setra pressure transducer.

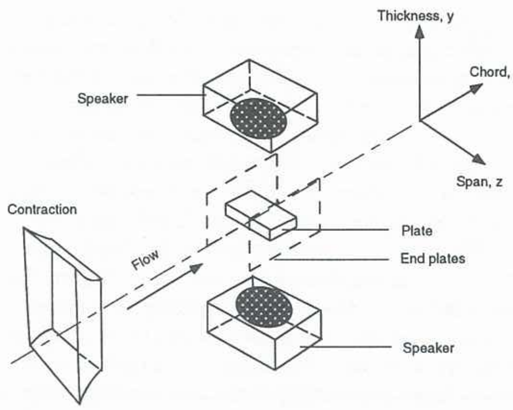

Fig. 1 Schematic of the experimental rig.

An asymmetric velocity field was imposed on the flow by a pair of speakers located above and below the plate (Fig. 1). The speakers were positioned just outside the jet, 370 mm apart, and were connected in anti-phase to a two-channel power amplifier driven by a Wavetek function generator. End plates constructed from 10 mm thick perspex were fitted to the plates to ensure that the forcing field around the plate was two-dimensional (Parker and Welsh, 1983). Acoustic particle velocities, which oscillated in phase around the leading and trailing edges of the plate, were superimposed on the mean flow at the applied forcing frequency. The acoustic particle velocity amplitude was a maximum at the leading and trailing edges and was zero on the plate surface midway along the chord. The symmetry of the acoustic field was checked by traversing a probe microphone about the working section of the tunnel. Laser Doppler Velocimetery was used to measure the amplitude of the applied velocity perturbation. At the leading edge corners of the plates, the amplitude of the velocity perturbation was 4.5% of the freestream velocity for all cases reported.

Flow visualization was performed using a smoke wire technique (e.g. Corke *et al.*, 1977). A sheet of smoke streaklines was produced by vaporising oil droplets from a 0.1mm diameter NiChrome wire placed vertically across the working section of the wind tunnel. The smoke was illuminated using a 10 Ws strobe with a 20ms flash duration

RESULTS AND DISCUSSION

Consistent with the results of Stokes and Welsh (1986), the vortex shedding from the leading edge separation bubble locked in frequency to the applied acoustic frequency over a range of frequencies. Figure 2 shows visualisation using smoke streaklines for a plate of chord-to-thickness ratio of 10. The two images were taken at 180 degrees apart in the applied sound cycle; the vortex shedding is also seen to be locked to the sound frequency. Stokes and Welsh found that during each acoustic cycle, a vortex was shed from the separation bubbles at the leading edge of the plate. In line with their finding, we see that the vortices are shed alternately from the two separation bubbles.

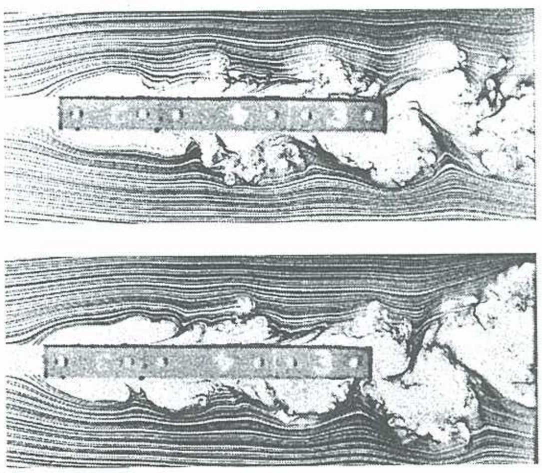

Fig. 2 Photographs (reverse image) of observed smoke streaklines for chord-to-thickness ratio 10 and taken 180 degrees apart in the applied sound cycle.

In the study of Stokes and Welsh, the quantity associated with the locking of the vortex shedding was the duct acoustic resonance level of constant frequency. For each chord-to-thickness ratio, a Strouhal number was found for which a peak in the duct acoustic level occurred. In the present study, the acoustic field was a controlled input of constant amplitude but variable frequency. The quantity chosen to be associated with the response of the system was the base drag coefficient. The variation of the the base drag coefficient with applied Strouhal number for different plate lengths is shown in Figure 3. It is clear that there are discrete bands in the space of plate length and applied Strouhal number within which the base drag coefficient attains a local maximum. Generally, for each plate chord-to-thickness ratio, there exists at least one well-defined peak in the base drag coefficient.

In Figure 4, the Strouhal number correponding to the local maxima of the base drag coefficient in Figure 4 are plotted against plate length. For comparison, the acoustic Strouhal numbers corresponding to peak duct acoustic resonance amplitude from the results of Stokes and Welsh (1986) are shown. Also shown are the Strouhal numbers of the natural vortex shedding for lower Reynolds number, as measured by Nakamura *et al.* (1991). It is seen that there is close agreement between the three sets of results, with all showing stepwise variation with chord-to-thickness.

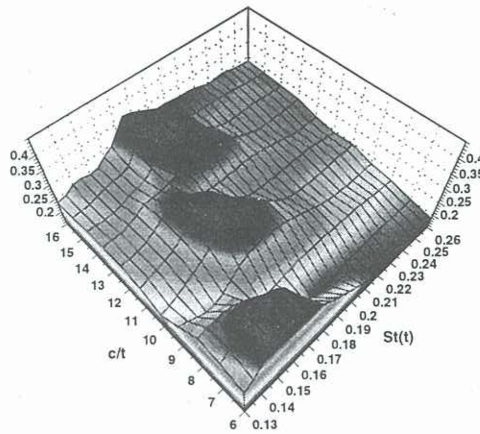

Fig. 3 Plot of base pressure coefficient against acoustic Strouhal number and chord-to-thickness ratio.

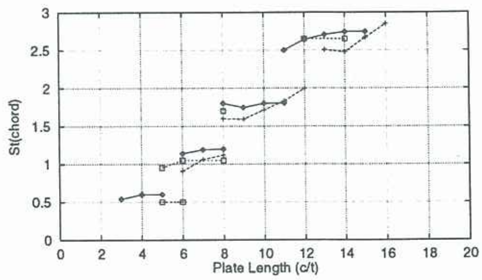

Fig. 4 Plot of acoustic Strouhal numbers (+) the present study at which the base pressure drag coefficient is locally a maximum versus chord-to-thickness ratio. Also shown are the acoustic Strouhal numbers (□) corresponding to peak duct acoustic resonance amplitude from the results of Stokes and Welsh (1986), and the natural Strouhal numbers (◇) from the experiments of Nakamura *et al.* (1991).

The visualisation here and that of Stokes and Welsh show clearly that for long plates, the reattachment of the shear layers separating from the leading edge always occurs well short of the trailing edge; one can therefore rule out the impinging shear layer instability hypothesised by Nakamura *et al.*, although this may occur for short plates in the absence of applied forcing. One may speculate on the coincidence of the results of the three studies. It would appear that forcing of the flow, whether by loud speakers or excited duct resonance, can overide the presumably far lower amplitude pressure waves generated by each vortex interacting with the trailing edge. It is hypothesised that the leading edge separation bubbles respond optimally to the same frequency of perturbation, independent of its source. This would help explain why different effects of vortex shedding, such as excited duct acoustic resonance and base drag coefficient, are maximum at the most receptive frequencies manifest in the natural case. Future studies will investigate more closely this link.

CONCLUSIONS

A number of previously seemingly disparate lines of research into the shedding of vortices from long bluff bodies have been drawn together in this paper: first, the higher Reynolds number study of Stokes and Welsh (1986) in which duct acoustic resonance was excited and fed back onto the leading edge separating shear layers; second, the lower Reynolds number studies of Nakamura *et al.* (1991) and Ohya *at al.* (1992) where a natural global instability emerged; third, the current study where sound was applied through loud speakers. A number of different chord-to-thickness ratios were considered. The naturally occuring Strouhal numbers found by Nakamura *et al.* were found by Stokes and Welsh to be coincident with the Strouhal Numbers at which the acoustic resonances were loudest, and for which the base drag coefficient was maximum in the present study. The Strouhal numbers displayed a stepwise increase with plate chord-to-thickness ratio. At least for the longer plates, no direct impingement of the leading edge shear layers occurs with the trailing edge so the Impinging Shear Layer Instability is not relevant. However, vortices shed from the leading edge separation bubbles are hypothesised to serve a similar function when interacting with the trailing edge; pressure pulses feed back upstream to the receptive leading edge shear layers, locking the vortex shedding and completing the feedback loop. This picture is consistent with the more general concept of global instability.

ACKNOWLEDGEMENT

This work was supported by an Australian Research Council Large Grant. R. Mills acknowledges the support of an Australian Postgraduate Research Award and the support of the Advanced Fluid Dynamics Laboratory of the CSIRO. The authors wish to thank Dr M. Thompson for many helpful discussions.

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