International colloquium on Jets, Wakes and Shear Layers
Melbourne, Australia, 18-20 April 1994

EFFECT OF TRANSVERSE PERTURBATIONS ON BASE DRAG FOR FLOWS AROUND RECTANGULAR PLATES

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ABSTRACT

The influence of vortex shedding from the leading edge of rectangular plates of different lengths with the base pressure coefficient is investigated. The vortex shedding is controlled by transverse forcing. In the absence of forcing as also in the absence of leading edge shedding (aerofoil leading edge), the base pressure coefficient is largely independent of plate chord. Forcing the flow can lead to substantial changes in the base pressure coefficient, particularly at certain forcing Strouhal numbers. The Strouhal number at which peak changes occur displays a grouping as a function of chord. It is hypothesised that two aspects of the flow may contribute to this behaviour: first, the phase of the forcing cycle at which the leading edge vortices arrive at the trailing edge; second, the stimulation of a trailing edge instability by the forcing at a critical Strouhal number.

NOMENCLATURE

c	plate chord (mm)
c'	$= c - 2t$ effective plate length (distance that vortices travel on plate surface)
Cp	$= p_s/(^1/_2\ \rho\ U_\infty{}^2)$, time mean local surface pressure coefficient
Cp_b	time-mean base pressure coefficient at mid span
$\mathrm{Cp}_{\mathrm{b(no\ sound)}}$	time-mean base pressure coefficient at mid span, with no transverse forcing applied.
Eu	$= P/(\rho\ U_\infty{}^2)$, Euler number
f	forcing frequency (Hz)
L	$= c/t$ chord to thickness ratio (non-dimensional plate length)
L_{eff}	$= c'/t = L$-2 non dimensional distance that vortices travel on plate surface
p_s	surface pressure (Pa)
P	acoustic pressure (Pa)
St	$= f\,t/U_\infty$, forcing Strouhal number (based on plate thickness)
St'	$= L_{eff}\,St/\alpha$, modified Strouhal number
t	plate thickness (mm)
u'	acoustic particle velocity amplitude (m s^{-1})
U_∞	free stream velocity (m s^{-1})
U_{vortex}	vortex velocity along plate surface (m s^{-1})
α	$= U_{vortex}/U_\infty$
ρ	fluid density (kg m^{-3})

INTRODUCTION

One motivation for the present research is to understand how to increase the heat transfer performance of a long heating element in a cross flow. Initially, the flow was made to separate at the leading edge by making the plate rectangular, leading to turbulent boundary layers along the sides of the plate. Improved heat transfer rate resulted but was accompanied by a drag penalty. It was also observed that the leading edge separation bubble was a region of relatively low heat transfer rate. When a transverse velocity perturbation was applied, the separation bubble length decreased, and the heat transfer rate showed increases of up to 40% overall, and up to 100% at the reattachment point (Cooper *et al.* 1986). Unfortunately, a further drag penalty was sometimes apparent, although the relationship between the drag variation and the frequency of the forcing was not clear.

More recently, it has been observed that, under a transverse forcing field, a dramatic drop in the base pressure coefficient sometimes occurs (depending on plate length) at a critical forcing Strouhal number (Hourigan *et al.* 1990). In this previous study, only three different length-to-thickness ratios were investigated; in the present study, a more detailed investigation has allowed a clearer understanding of the variation in base pressure coefficient.

The interpretation relies to some extent on the following observations of other studies:

(1) over a wide range of frequencies, the vortex shedding from the leading edge of a bluff plate can be locked to the forcing frequency (Welsh and Gibson 1979, Stokes and Welsh 1986 and Hourigan *et al.* 1990).

(2) at least for shorter bluff bodies, it is well-known that the form drag increases as the wake formation length decreases (Roshko 1955, Bearman 1965, 1967).

For bluff bodies with large c/t ratios, a complicated interaction between the vortex shedding from the leading edge and the trailing wake can occur. To partly decouple this effect, studies were undertaken using plates with either aerofoil or rectangular leading edges with zero or finite transverse forcing.

EQUIPMENT

The flows around long plates with rectangular leading and trailing edges were investigated in a small blow-down open-jet wind tunnel (Fig. 1) previously described by Parker and Welsh (1983) and Welsh *et al.* (1990). Air is supplied by a centrifugal fan powered by a variable speed A.C. motor and directed through a wide angle diffuser to a settling chamber containing four nylon screens and a honeycomb for minimising turbulence levels. The air then passes through an eight-to-one contraction to form an open jet with an outlet, which is 244 mm square.

The operating range of the tunnel was 0 to 15 ms^{-1}. The mean velocity at the jet outlet has been found to be uniform to within ±0.5%, while 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 is 0.15% according to Michel and Froebel (1988).

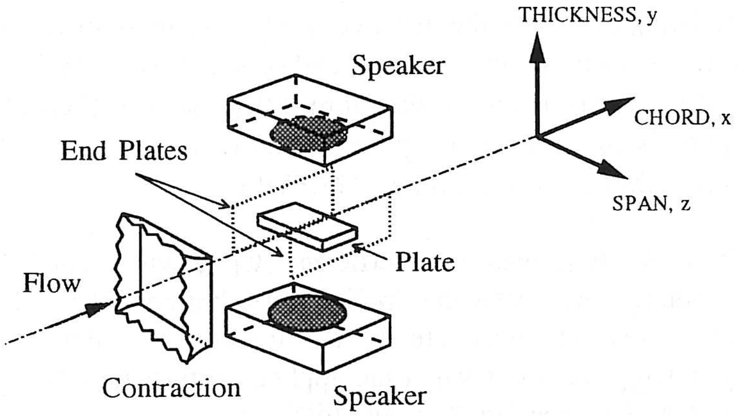

Figure 1. Working section of the open jet wind tunnel showing location of brass models and loudspeakers.

All the test plates were made from brass, using the N.C. milling machine in the C.S.I.R.O. engineering workshop, and have a nominal thickness of 13mm. Three of these rectangular plates have pressure tappings placed at regular intervals along one streamwise surface, one pressure tapping placed in the lid to aid with aligning the plates with the airstream, and tappings on the rear face to enable time mean surface pressure coefficients to be measured. Of these three plates, two were identical having chord-to-thickness ratios c/t=3, while one had c/t=6. A series of spacer plates (with no pressure tappings) were constructed with c/t ratios of 2,3,4,6 and 8 to allow the overall plate length to be varied from $6< c/t <16$ in integer steps. Two leading edge extensions were also constructed; one with a semicircular profile and the other with a C4 aerofoil profile (Wallis 1977).

The plates were oriented parallel to the upstream flow by realigning them in order to equalise mean pressures on the upper and lower faces at two pairs of tappings, one near the plate leading edge, the other near the trailing edge.

A sound 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 generate a transverse velocity perturbation across the flow. End plates constructed from 10mm thick perspex were fitted to the plates to ensure that the forcing field around the plate was two-dimensional. 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. Near the plate this forcing field was equivalent to a resonant Parker β-mode as described by Parker and Welsh (1983).

A 12.5mm Brüel & Kjær microphone was used to measure the sound pressure level due to the transverse forcing field at a reference point near the speakers, and ensure that the level of forcing was consistent for all tests.

THEORETICAL MODEL

Consider a rectangular plate in a flow, where the leading edge vortex shedding is locked to the frequency f of a transverse forcing field. The time taken for a vortex to traverse the length of the plate = c'/U_{vortex}, where $U_{vortex}=\alpha U_\infty$ is the mean convection velocity of the vortex, c' is the distance that the vortex travels over the plate surface, and α is approx. 0.75. The acoustic forcing period is $T_s=1/f$. The traversal time is therefore $c'/U_{vortex} = (c'/t)t/(\alpha U_\infty)$. For a vortex to take n forcing periods to traverse the plate, we have $f = n\alpha U_\infty/(t(c'/t))$. The acoustic Strouhal number is $\mathrm{St} = ft/U_\infty$. Therefore, $n = \mathrm{St}(c'/t)/\alpha$.

The hypothesis is that peaks in the base pressure coefficient $|Cp_b|$ will occur if the leading edge vortices arrive at the trailing edge when the applied perturbation field is directing the vortex, which is a region of low pressure, towards the base of the plate (see Fig. 2 (a) and (b)). Conversely, a minimal drop in Cp_b will occur when the applied perturbation field directs the vortex away from the base of the plate (see Fig. 2 (c) and (d)).

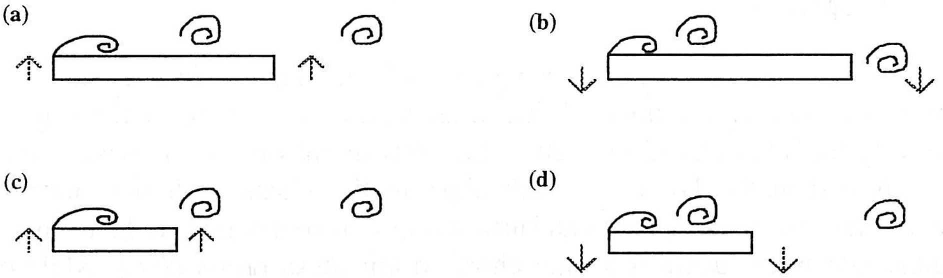

Figure 2. illustration of vortex shedding from two different length rectangular plates with transverse forcing applied.

According to the model, maximums in $|Cp_b|$ will occur only at integer values of n (corresponding to leading edge vortices being directed towards the base of the plate as they pass the trailing edge) for any value of plate length (c/t), .

RESULTS AND DISCUSSION

As outlined in the section dealing with equipment, experiments have been undertaken for rectangular plates with chord-to-thickness ratios (c/t) varying in unit steps between 6 and 16. Corresponding results were obtained when the rectangular leading edge was replaced by an aerofoil leading edge in order to suppress leading edge shedding. For all the measurements, the upstream flow velocity was 10.0 m s^{-1}, the sound was applied at 110 dB (as measured by the reference microphone).

The variation in the mean base pressure coefficient as the acoustic Strouhal number was varied for different plate chords is shown in Fig. 3. Peaks in $|Cp_b|$ are found to appear in a grouped manner as the plate chord is increased. This may be seen more clearly in Fig. 4 where the number of acoustic periods for a vortex to traverse the plate (n) corresponding to the maximum $|Cp_b|$ is shown as a function of plate chord.

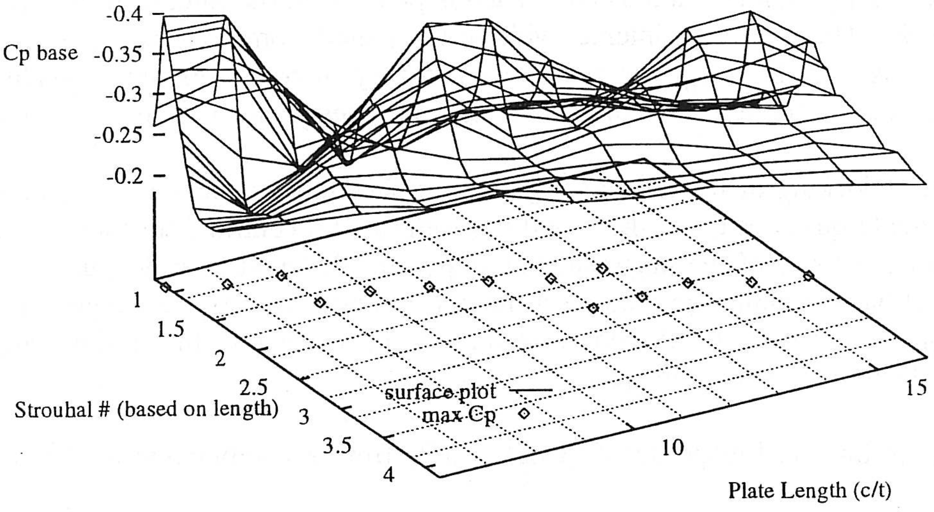

Figure 3. **Contour plot of $|Cp_b|$ vs Strouhal number (based on plate length) vs Plate length (c/t) for rectangular plates.**

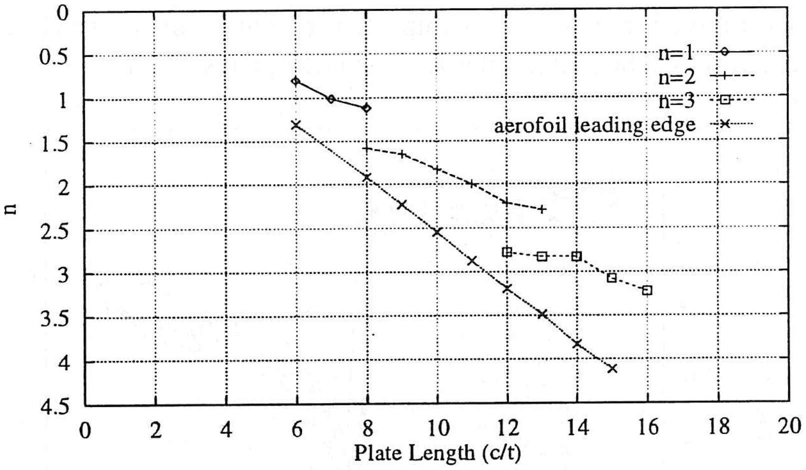

Figure 4. **The variation of the number of forcing periods (*n*) for a vortex to traverse the plate (at which maximum $|Cp_b|$ occurs) vs plate length-to-thickness ratio (*c*/*t*) for the rectangular leading edge case.**

The peaks are in three groups, occurring near integral values of *n*, showing a periodicity based on the spacing of vortices along the plate surface. The occurrence of the largest peaks in $|Cp_b|$ (for plates with c/t ratios of 6,7,10,11,14 and 15) near the same forcing Strouhal number (based on plate thickness) of 0.17, suggests a periodicity of the peaks of approximately 4 plate thicknesses. Assuming the vortex velocity along the plate surface is $0.75U_\infty$, then the spacing between vortices for a forcing Strouhal number of 0.17 is approximately 4.4 plate thicknesses. This is consistent with both the observed spacing between the largest peaks in $|Cp_b|$, and the theoretical model which predicts that maximums in $|Cp_b|$ will occur in groups at integer values of *n*, with regular spacing between groups (in terms of plate length c/t).

At present it is unclear what caused the observed changes of $|Cp_b|$ in response to changes in forcing frequency and plate length for the rectangular leading edge plates. Two possible mechanisms are:

1. Vortices from the trailing edge are stimulated to shed in phase with the forcing at or near a "critical" frequency. These vortices interact with vortices shed from the leading edge to either produce a maximum in $|Cp_b|$, or result in a recovery of base pressure depending upon the timing in the forcing cycle of the arrival of leading edge vortices at the trailing edge.
2. The enhancement or locking of the leading edge vortex shedding to the forcing is more pronounced at some frequencies than others, and is strongest at a central frequency. This can explain the different size of the maximums in $|Cp_b|$ for different plate lengths. As outlined in the section describing the theoretical model, the occurrence of a maximum or minimum in $|Cp_b|$ will depend on the phase in the forcing cycle that the leading edge vortices arrive at the trailing edge of the plate.

It is most likely that the observed response of $|Cp_b|$ results from a combination of the two mechanisms.

Corresponding experiments were carried out with plates having aerofoil-shaped leading edges, in order to de-couple the effects of leading and trailing edge shedding upon base pressure. As a means of comparing results, the forcing Strouhal number at which the peaks in $|Cp_b|$ occur for the aerofoil leading edge plates are shown in Fig. 4, after conversion to be equal to the number of forcing cycles (n) that leading edge vortices would take to traverse an equivalent length rectangular leading edge plate. It is important to note that no grouping is evident for these peaks, as is the case for the rectangular leading edge plates

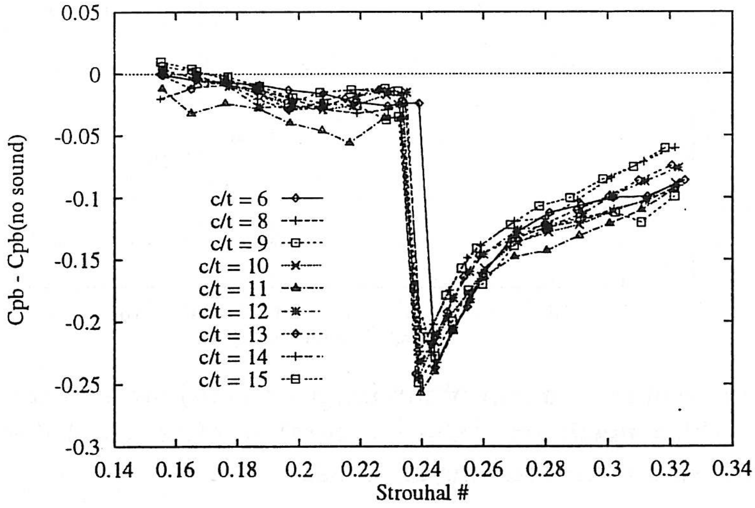

Figure 5. Plot of $\{Cp_b - Cp_{b(\text{no sound})}\}$ vs sound Strouhal number (St) for plates with aerofoil leading edges.

Figure 5 shows the relationship between forcing Strouhal number and $(Cp_b - Cp_{b(\text{no sound})})$ for different length plates. The sudden drop in base pressure at a Strouhal number of about 0.24 indicates that the vortex shedding at the trailing edge is locked to the applied forcing field at this Strouhal number. It is clear that for aerofoil leading edge plates without leading edge shedding, and with a transverse forcing field applied to lock the vortex shedding from the trailing edge, that the occurrence of peaks in $(Cp_b - Cp_{b(\text{no sound})})$ is independent of plate length.

CONCLUSION

Evidence has been obtained experimentally that the mean base pressure coefficient can be modified substantially when transverse forcing is applied to the flow around rectangular plates. A substantial decrease in the base pressure coefficient occurs for an acoustic Strouhal number corresponding to leading edge vortices arriving at the trailing edge at a particular phase of the acoustic cycle. Plates with chord to thickness ratios of 6,7,10,11,14 and 15 show the largest change in base pressure coefficient, all at a forcing Strouhal number of about 0.17. This value could be related to the vortex shedding at the trailing edge locking to the forcing field, as observed for plates with aerofoil leading edges. At present it is unclear how the vortices shed from the leading edge are interacting with the forcing field at the trailing edge. Ways of de-coupling the leading and trailing edge shedding (eg. aerofoil leading edge plate) are being investigated, in order to clarify this.

ACKNOWLEDGMENTS

This work is continuing with the support of a grant from the Australian Research Council. The first author acknowledges the support of a Australian Postgraduate Award.

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