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FLOW REGIMES AND BASE PRESSURES ON TANDEM ARRAYS OF PLATES OF RECTANGULAR CROSS-SECTION

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ABSTRACT

Velocity-fluctuation, base-pressure and separation-bubble-length measurements were made for different configurations of rectangular-cross-section plates in a uniform flow. Five flow regimes can be identified for the configuration of two plates in tandem with a range of plate separations. In Regime 1A, for the configuration with a short upstream plate and a very small gap between the plates, a separation bubble bridging the gap is formed with a flow pattern characteristic of single plates of similar overall chord. In Regime 1B, for slightly bigger gaps, the separation bubble continues to bridge the gap between plates, as in Regime 1A, but periodic vortex formation in the reattaching shear layers occurs. In Regime 2, for the gap further increased, the shear layers separating from the leading edge of the upstream plate form a vortex wake in the gap between the plates.

For the plate configurations with the upstream plate of longer chord, a separation bubble is formed on the leading plate itself. Two flow regimes can be then identified: Regime 3, where for small gaps a trapped vortex flow is formed in the gap, and Regime 4, where for bigger gaps a vortex street is formed in the gap.

INTRODUCTION

The results which are presented were obtained as a part of an investigation of the mechanisms responsible for noise radiation from linear arrays of plates of rectangular cross-section in a uniform flow. The primary concern of this paper is the fluid mechanics of the process.

In previous papers (Bull, Pickles, Blazewicz and Bies, 1992; Blazewicz, Pickles and Bull, 1993) it was shown that for a two plate array, two distinct flow regimes can be identified according to the value of $(C_1 + G)$ where $C_1 = c_1/t$ and $G = g/t$ are respectively the ratios of the chord c_1 of the leading plate and the gap g between the plates to the plate thickness t. In Regime 1, for which $(C_1 + G) \leq 4.5$, flow separation occurs at the square leading edge of the upstream plate, followed by reattachment on the streamwise surface of the downstream plate; a separation bubble is formed bridging the gap between the plates. In Regime 2, corresponding to $(C_1 + G) \geq 3$ (there is some overlap between the two regimes), the shear layers separated from the leading edge of the upstream plate form a vortex wake in the gap between the plates, which interacts with the leading edge of the downstream plate. The transition from one regime to the other is accompanied by a discontinuous change in the Strouhal number of vortex shedding from the trailing edge of the downstream plate (Blazewicz et al., 1993).

In this paper it is shown that Regime 1 can be further divided into two sub-regimes. In Regime 1A, for very small gaps (typically $(C_1 + G) \leq 2$), the flow pattern around the plates is similar, in terms of characteristic vortex shedding, to the flow around a single rectangular plate of the same overall chord length. In Regime 1B, for $2 \leq (C_1 + G) \leq 4.5$, a new flow pattern characterised by regular vortex shedding from the separation bubble occurs.

Also, two additional flow regimes can be identified for plate configurations with a longer-chord upstream plate: Regime 3, for which $C_1 \geq 4.5$ and $G \leq 2$, and Regime 4 for which $C_1 \geq 4.5$ and $G \geq 3$. In these cases, flow separation from the leading edge and flow reattachment take place on the leading plate. Flow visualisation and base pressure measurements indicate that flow patterns for these conditions are similar to those observed on two-plate arrays in which the leading plate has a faired leading edge (Bull, Pickles, Martin

and Welsh, 1989; Bull and Pickles, 1992): for $G \lesssim 2$ trapped vortex flow occurs in the gap between the plates, and for $G \gtrsim 3$ a vortex street is formed in the gap.

EXPERIMENTAL ARRANGEMENT

A family of single plates of different chord-to-thickness ratios ($C = c/t$, where c is the chord of the plate) and a two-plate array with a range of plate separations were tested in a rectangular jet, 340mm x 690 mm, issuing from the contraction of a low speed wind tunnel. The single plates covered a range of C values from 6.6 to 26.4. The plates in tandem were of equal thickness; and various configurations of two upstream plates having $C_1 = 1.0$ and 12.68, and the three downstream plates having $C_2 = c_2/t = 6.1$, 6.63 and 15.78 (c_2 is the chord of the downstream plate) were used. Two plate thicknesses were used, t = 17.9 mm and 39.4 mm. The plates were confined between large side walls 690 mm apart. The gap between the plates was varied between G = 0 and G = 25.

Measurements were made over a range of mean flow velocity U, measured at the exit plane of the wind-tunnel contraction of $6.5 \leq U \leq 19.5$ m/s, giving a range of Reynolds numbers $Re_t = Ut/\nu$ of $8.1\text{x}10^3 \leq Re_t \leq 5.3\text{x}10^4$.

Fluctuations in flow velocity were detected by a hot-wire anemometer probe located at various positions between the leading edge of the upstream plate and a location downstream of the trailing edge of the downstream plate, as indicated in figures 1a, b and c.

The measurements of the mean base-pressure coefficient $Cp_b = (p_b - p_\infty)/\frac{1}{2}\rho U^2$ (where p_b is the base pressure and p_∞ is the free-stream static pressure and ρ the fluid density) were made with a static-pressure tapping located in the centre of downstream face of the downstream plate.

The mean length of separation bubble x_R was determined from measurements made with a differential-pressure surface-fence probe at a number of streamwise positions near flow reattachment.

RESULTS AND DISCUSSION

The characteristic regimes identified on the basis of velocity-fluctuation, base-pressure and separation-bubble-length measurements are indicated schematically in figure 1. Figures 2, 3 and 4 show respectively the variation of Strouhal number $St = ft/U$ (where f is a vortex-shedding frequency), Cp_b and $X_R = x_R/t$ with C (an overall chord-to-thickness ratio which for plates in tandem is given by $C = (C_1 + G + C_2)$). Results for single plates are included for comparison with those for plates in tandem with similar overall values of C. The data presented are for one particular Reynolds number ($Re_t = 20\text{x}10^3$), but the general form of the variations is similar for the whole range of Reynolds numbers investigated.

From the variation of St, Cp_b and X_R with C, three characteristic flow regimes can be identified for the tandem plate configurations of $C_1 = 1.0$ with $C_2 = 6.1$ and 6.6: Regime 1A, which can exist for very small gaps $0 \leq G \lesssim 1.0$, Regime 1B; for $1 \lesssim G \lesssim 3.5$; and Regime 2 for $G \gtrsim 2.5$. There is an overlap region

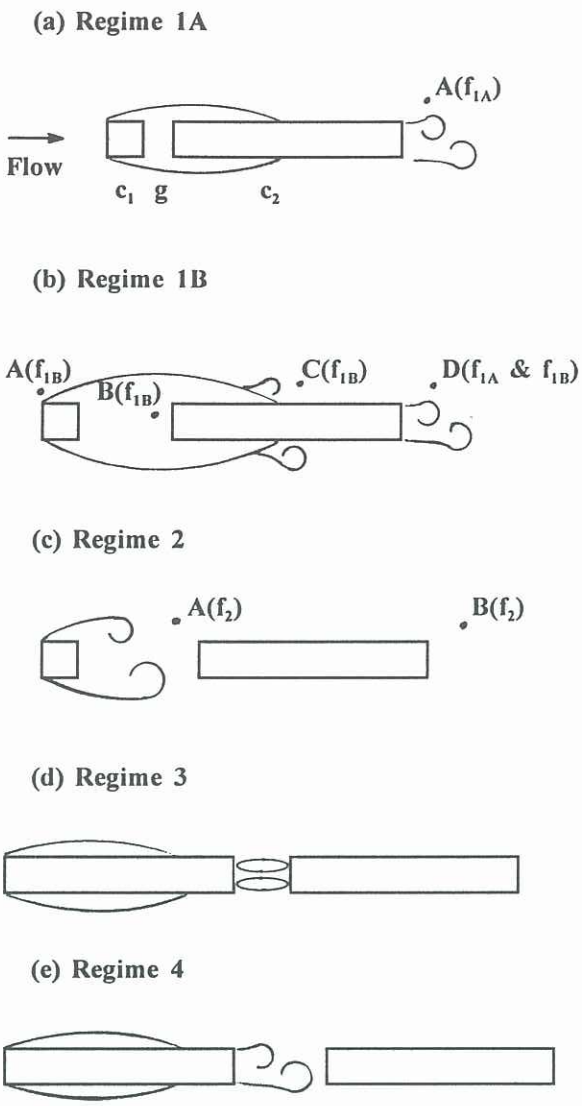

Figure 1. Characteristic flow patterns for linear arrays of two plates of rectagular cross-section.

where either Regime 1B or Regime 2 can exist. As found in previous studies (Bull et al., 1992), at small G (Regimes 1A and 1B - figures 1a and 1b respectively) the separated shear layers from the upstream plate reattach on the downstream plate, while at larger G (Regime 2, figure 1c) the separated shear layers roll up to form a vortex street between the plates.

Regime 1A

As for single plates of the same overall chord, the hot wire measurements in this regime indicate only one characteristic frequency f_{1A} (and Strouhal number St_{1A}, figure 2), detectable immediately downstream of the trailing edge of the downstream plate (near A in figure 1a) and indicating trailing-edge vortex-shedding. As the gap increases from zero, Cp_b decreases below the

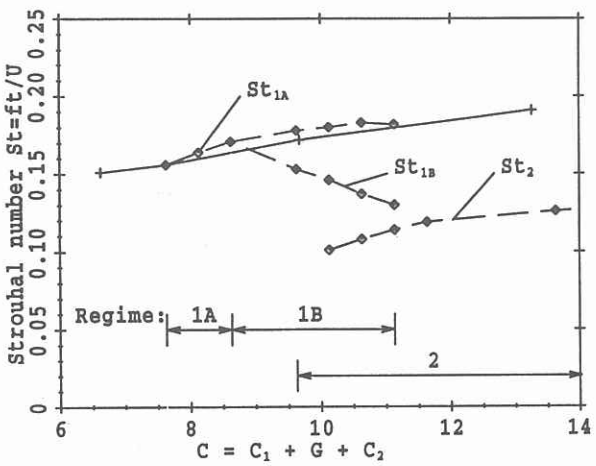

Figure 2. Strouhal number as a function of C for different flow regimes. +, single plates; ◇, C_1 = 1.0, C_2 = 6.63.

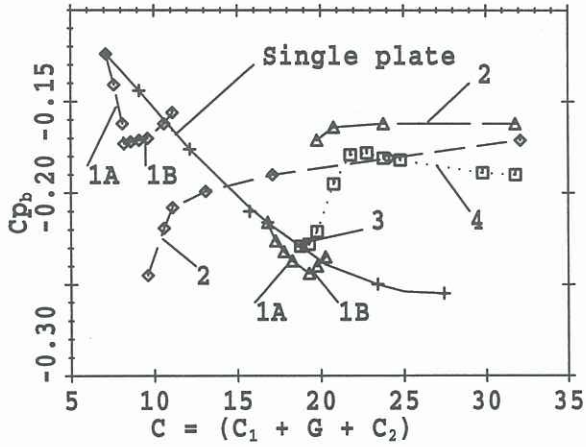

Figure 3. Variation of base presure Cp_b with C for different flow regimes. +, single plates; ◇, C_1 = 1.0, C_2 = 6.1; △, C_1 = 1.0, C_2 = 15.78; □, C_1 = 12.38, C_2 = 6.1.

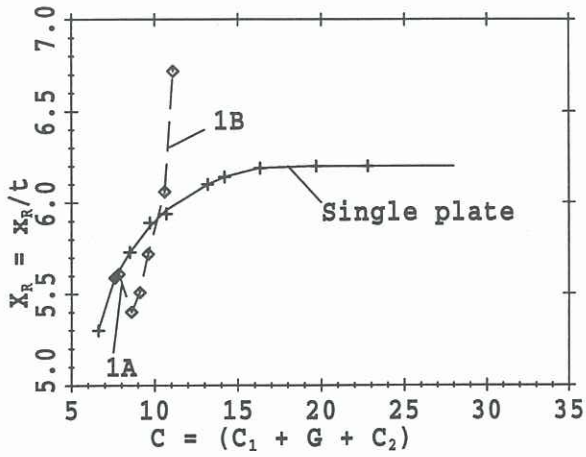

Figure 4. Variation of mean separation-bubble length X_R with C for different flow regimes. +, single plates; ◇, C_1 = 1.0, C_2 = 6.63.

value obtained for the corresponding single plates and reaches a minimum at G = 1.0 (curve 1A in figure 3). A generally similar character of Cp_b variation with G occurs for the plate combination of C_1 = 1.0 and C_2 = 15.78 (figure 3). The mean separation-bubble length (figure 4) initially increases with gap in a manner similar to that of the single plate until G = 0.25. Above this gap it decreases, reaching a minimum at G = 1.0.

Thus, somewhat surprisingly, the communication between the flow above and the flow below the plates afforded by the gap produces no change in the Strouhal number of trailing-edge vortex-shedding as compared with that for a single plate (figure 2), but produces a quite dramatic change in both base-pressure coefficient (figure 3), and length of separation bubble (figure 4).

Regime 1B

In the velocity-fluctuation measurements, in addition to the frequency f_{1A} associated with trailing edge vortex shedding, a second characteristic frequency f_{1B} is detectable for all the probe positions (A, B, C and D) indicated in figure 1b. The variation of the corresponding Strouhal number St_{1B} is shown in figure 2. At the minimum gap at which Regime 1B can first be detected (G = 1), f_{1B} coincides with f_{1A}. As the gap is increased f_{1B} decreases and f_{1A} increases towards a constant value. As indicated in Blazewicz et al., 1993 the frequency f_{1B} is associated with vortex formation in the reattaching shear layer; the authors also observed that the noise generated by the pressure fluctuations on the plate surface (associated with that vortex formation) dominates the radiated sound field, overwhelming any contribution from the trailing-edge vortex-shedding.

Previous investigations of the leading-edge separation on a single plate indicate irregular or pseudo-periodic vortex-shedding from the separation bubble with a frequency of about $0.65U/x_R$ (or $ft/U \approx 0.14$), associated with a broad peak in the spectrum of surface pressure fluctuations (Kiya, 1989). In contrast, for the present two-plate configurations, vortex shedding from the reattachment region is strongly periodic, as indicated by a sharp peak in the spectrum of the velocity fluctuations.

The velocity-fluctuation spectra show a peak at f_{1B} even with the probe located near the leading edge of the upstream plate (figure 1b, position A) which would suggest that the separated shear layer fluctuates at the shedding frequency rather than the much lower frequency given by $fx_R/U \approx 0.1$ or $ft/U \approx 0.02$ observed for single plates (Kiya, 1989). The frequency f_{1B} was also detected in the gap near the leading edge of the downstream plate (figure 1b, position B) indicating the possibility of cross-flow through the gap associated with the vortex formation.

Both Cp_b (curve 1B, figure 3) and X_R (figure 4) increase from the minimum at G = 1.0 as the gap is increased, to values that lie above the values obtained for corresponding single plates. In the case of the base pressure a similar trend occurs for the configuration with C_1 = 1.0 and C_2 = 15.78.

Regime 2

In the velocity-fluctuation measurements only one characteristic frequency f_2 was observed at all probe locations (figure 1c and St_2 in figure 2) indicating that the vortex-shedding from the trailing edge of the downstream plate is synchronised with shedding from the upstream plate (Blazewicz et al. 1993). It was also concluded that the interaction between the vortex wake formed by the separated shear layers and the downstream plate is a dominant factor in acoustic noise radiation for this configuration (Bull et al.1992 and Blazewicz et al. 1993).

The transition from Regime 1B to Regime 2 is also characterised by a sudden change of Cp_b (curves 1B and 2, figure 3). In Regime 2, after initially increasing with G, Cp_b seems gradually to approach the value for a single plate of chord C_2 as G is further increased. There is an overlap of regions 1B and 2. The base pressure measurements further confirm that the transition from Regime 1B to Regime 2 can occur over a range of gaps $2.5 \lesssim G \lesssim 3.5$, as observed by Blazewicz et al. 1993 on the basis of velocity-fluctuation measurements.

Regimes 3 and 4

In Regime 3, for $C_1 = 9.68$, $C_2 = 6.1$ and $G \lesssim 2$, increasing G from the single plate value $G = 0$ causes Cp_b initially to rise slowly above the single plate value (curve 3 in figure 3, figure 1d), and then to increase rapidly as G passes through a transition region in the range $2 \lesssim G \lesssim 3$. Finally, in Regime 4, Cp_b decreases with further increase in G (curve 4 in figure 3, figure 1e). As G is increased even further the rate of decrease of Cp_b becomes smaller, suggesting slow approach to the value for a single plate of chord C_2 for very large gaps. In both Regime 3 and Regime 4 flow separation occurs at the leading edge of the upstream plate and reattachment take place on the upstream plate itself; the separation bubble is then located entirely on the upstream plate, and the gap between the plates is located downstream of the reattachment position. Flow visualisation shows flow patterns for these conditions similar to those observed on two-plate arrays in which the leading plate has a faired leading edge (Bull et al., 1989; Bull and Pickles, 1992): for $G \lesssim 2$, the gap contains a trapped vortex flow consisting of a pair of stationary counter-rotating vortices (figure 1d); for $G \gtrsim 3$ vortex-street flow occurs in the gap (figure 1e).

SUMMARY AND CONCLUSIONS

1. The velocity-fluctuation, base-pressure and separation-bubble-length measurements for plate configurations consisting of two plates in tandem with a short-chord upstream plate, consistently indicate the existence of three flow regimes:

(i) In Regime 1A, for which $(C_1 + G) \lesssim 2$, flow separation occurs at the square leading edge of the upstream plate followed by reattachment on the streamwise surface of the downstream plate, forming a separation bubble bridging the gap between the plates. Only one characteristic frequency, associated with trailing-edge vortex-shedding, is detectable. Such a flow pattern is characteristic of single plates of similar overall chord. The gap between the plates has a strong influence on the base pressure on the downstream plate and the separation bubble length, but not on the Strouhal number of trailing-edge vortex-shedding.

(ii) In Regime 1B, for which $2 \lesssim (C_1 + G) \lesssim 4.5$, the separation bubble continues to bridge the gap between plates, as in Regime 1A, but an additional characteristic frequency, associated with periodic vortex formation in the reattaching shear layers, is detected.

The velocity-fluctuation measurements also suggest the possibility of separation-bubble fluctuations at the vortex-shedding frequency, and indicate the possibility that vortex formation involves cross-flow in the gap.

(iii) In Regime 2, corresponding to $(C_1 + G) \gtrsim 3$ (and overlapping Regime 1B), the shear layers separating from the leading edge of the upstream plate form a vortex wake in the gap between the plates. The single characteristic frequency that is observed indicates that the vortex-shedding from the trailing edge of the downstream plate is synchronised with shedding from the upstream plate.

2. Transition from Regime 1B to Regime 2 is accompanied by a discontinuous change in both the Strouhal number of vortex-shedding from the trailing edge of the downstream plate and the base pressure on the downstream plate.

3. For the plate configurations with the upstream plate of longer chord, two flow regimes can be identified: Regime 3, for which $C_1 \gtrsim 4.5$ and $G \lesssim 2$, and Regime 4 for which $C_1 \gtrsim 4.5$ and $G \gtrsim 3$. In these cases flow separation from the leading edge of the upstream plate and shear-layer reattachment take place on the leading plate itself, forming a separation bubble. The gap between the plates is located downstream of the reattachment position. Flow patterns for these configurations are similar to those of two-plate arrays in which shear layers separate from a trailing edge of the leading plate, i.e. for $G \lesssim 2$ a trapped vortex flow in the gap, and for $G \gtrsim 3$ a vortex street flow in the gap.

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