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BISTABLE FLOWS OF TWO UNEQUAL SQUARE CYLINDERS IN VARIOUS STAGGERED ARRANGEMENTS

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ABSTRACT

Experimental investigation of the mean static pressure distributions of two square cylinders of dimension ratio 2:1 is presented. The staggered arrangements were $1.12 \leq T/D \leq 2.0$ and $0 \leq L/D \leq 1$. Bistable flow was found at $1.12 \leq T/D \leq 1.75$ and $0.375 \leq L/D \leq 0.5$, where switching of the gap flow between the small and large cylinder, together with the sudden change of back pressure coefficients, was observed. This biased gap flow caused reattachment and separation bubble on either cylinder, thus, inducing a lift force.

INTRODUCTION

Flows over two circular cylinders at different arrangements and of different diameter ratios had been studied extensively by Kim et al.(1988), Baxendale et al.(1985) and Zdravkovich(1977). Flip-flopping of the gap flow at critical spacings is associated with the sudden change of the back pressures C_{pb}. Hayashi et al.(1986) observed bistable nature of the flows over flat plates. Aerodynamic forces on two identical square cylinders in various arrangements were also studied. Okajima et al. established the existence of bistable flow in side-by-side arrangements and a change-over from negative to positive lift, unlike that of circular cylinders, for small transverse spacing. In tandem arrangement, at critical spacings, Luo et al.(1990) found that the separated shear layer from the upstream square cylinder reattaches onto the downstream cylinder, thereby, suppressing the vortex formation of the former. As the flows over unequal square cylinders, however, have not been studied in details, the present investigation was aimed to understand the bistable flows as well as their aerodynamics.

EXPERIMENTAL SET-UP

Experiments were performed on two unequal square cylinders (Fig.1) of face width D of 38.2mm and d of 19.1mm in a wind tunnel of cross-section 560mm x 560mm. The large cylinder was placed upstream. The freestream velocity U_o was 19.7m/s, which corresponded to a Reynolds number, based on D, of 5×10^4. End plates were used to eliminate the boundary layer effect of the wind tunnel.

Nine pressure tappings at the mid-span of both cylinders were used to measure the mean static pressure distributions. The regime of investigation was $0 \leq L/D \leq 1$ and $1.12 \leq T/D \leq 2.0$, where L and T are the streamwise and transverse separations between the centres of the cylinders respectively.

RESULTS AND DISCUSSION

As there are numerous data obtained, the present presentation only concentrates on the bistable flows. For simpler presentation, Mode 1 is defined for the gap flow being biased towards the large cylinder and Mode 2 biased towards the small cylinder(Fig.1). The typical pressure distributions of the two cylinders at the critical spacings, T/D = 1.12 and 1.75, $0.375 \leq L/D \leq 0.5$, are shown in Figs.2 and 3. In addition, pressure distributions at L/D = 0 and 1 are also shown as reference.

In general, the front stagnation point of the small cylinder is shifted by ~0.1d from the centre of the front face(0,1) towards its gap face(Figs.2b and 3b). On the large cylinder, only small or negligible shift is found, suggesting that the accelerated gap flow has significant effect on the small cylinder.

At the critical spacing, T/D = 1.12, L/D = 0.5(Fig.2), bistable phenomenon is indicated by the existence of two C_{pb}. It is found that the C_{pb} = -0.7 on the large cylinder in Mode 2 is nearly the same as that of -0.71 on the small cylinder in Mode 1. These two C_{pb} are associated with the large wake behind the cylinders(Figs.1 and 2). The outer face pressure distributions of the two cylinders are the same as the C_{pb}, suggesting that the outer shear layers separate from the leading edges(0) and (1) of the large and small cylinder respectively. The pressure on

the small cylinder gap face(-1,0) is also the same. Thus, the above pressure distributions indicate that the large wake of both modes extents on two faces of the large cylinder and three faces of the small cylinder. The large cylinder gap face(1,2) in Mode 2 has non-uniform distribution with a pressure peak associated with separation bubble. Similar separation bubble occurs on two equal square cylinders (Okajima et al. 1984).

For the small wake, the large cylinder gap face(1,2) in Mode 1 also shows the pressure peak which pressure is higher than that of the large wake in Mode 2. On the small cylinder, the pressure on the gap face(0,-1) in Mode 2 seems to oscillate and is lower than the C_{pb} of -1.3 on the other two faces. It is the lowest of the two wakes of the bistable flow. However, this pressure on the gap face is higher than that at L/D = 0, suggesting different flow behaviour of unsteady separation and reattachment.

Outside the bistable regime, T/D = 1.12, $0 \leq L/D < 0.5$, the base pressure coefficients C_{pb} of both cylinders are the same as those of Mode 2 of bistable flow (Fig.2). The small cylinder C_{pb} is close to that of single cylinder of -1.3 of the present study. This also agrees with that of single cylinder of -1.38 (Bearman et al. 1972). In this regime, the separation bubble is also found on the gap side of the large cylinder, though shifts slightly upstream. On the gap side of the small cylinder, there seems to be a small separation bubble very near the edge(0), followed by the usual development of the boundary layer.

At T/D = 1.12, $0.5 < L/D \leq 1$ the pressure distribution of the small cylinder is the same as that of Mode 1 of bistable flow. For the large cylinder, the base pressure C_{pb} is higher than that of Mode 1. On the gap face the separation is found to shift downstream and nearly reaches the trailing edge(2).

Bistable flow is also found at T/D = 1.75, L/D = 0.375(Fig.3). For the large wake, the near constant C_{pb} on the three faces, besides the front one, of the large cylinder in Mode 2 suggests the separation of the boundary layers at the leading edges(0 and 1). This characteristic is the same as the large wake of Mode 1 of small cylinder. This means that at this critical spacing the large wake of the bistable flow behaves differently from that at the last critical spacing of T/D = 1.12, L/D = 0.5 and the separation bubble on the large cylinder does not exist. For the small wake, separation bubble is still found on the gap side of the large cylinder in Mode 1, though of lower pressure than that at T/D = 1.12. In Mode 2 of the small cylinder, the gap side has the development of the boundary layer till its separation near the trailing edge(-1). Further, the pressure and the C_{pb} are significantly lower than those of other cases.

These differences in the pressure distributions of the large and small wakes at these two critical spacings indicate that although bistable flow is found in these two cases, their flow characteristics and the development of the boundary layers on the surfaces are significantly different.

Outside the bistable flow regime, T/D = 1.75, $0 \leq L/D < 0.375$, the C_p distributions on the two cylinders basically follow that of Mode 2, except that on the gap face of the small cylinder. For $0.375 < L/D \leq 1$, the C_p distributions basically follow that of Mode 1.

The differences in the flow characteristics of the two bistable flows are also shown by the lift and drag coefficients distributions(Fig.4). Bigger difference in the lift coefficients of the two modes is found for critical spacing of T/D = 1.12 and bigger difference in the drag coefficients for T/D = 1.75. For the large wake in the two modes, the drag coefficients of both cylinders are constant at about 1.6. For the small wake, difference in the drag coefficient is found and the C_d of the small cylinder at T/D = 1.75 is as high as about 2.7, significantly higher than that at T/D = 1.12(Fig.4b).

CONCLUSION

Bistable flows are found at $1.12 \leq T/D \leq 1.75$ and $0.375 \leq L/D \leq 0.5$. Based on the pressure measurements, the flow characteristics of the bistable flows are different at different critical spacings. Generally, for both modes, the flow over the outer side of both cylinders separates at the leading edge. On the gap face, however, the formation of the separation bubble depends on the critical separation of the two cylinders. These differences are also found in the lift and drag coefficients.

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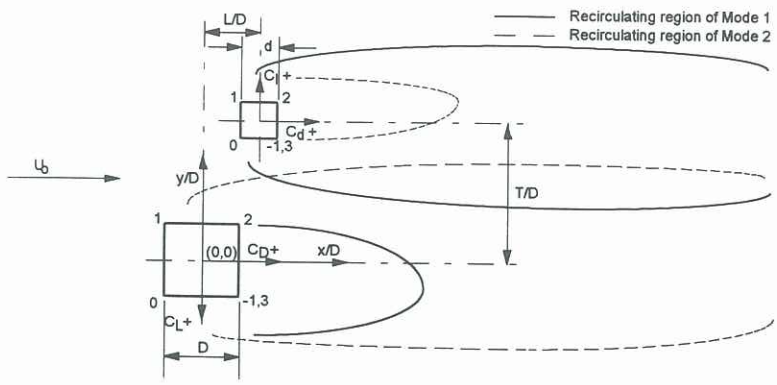
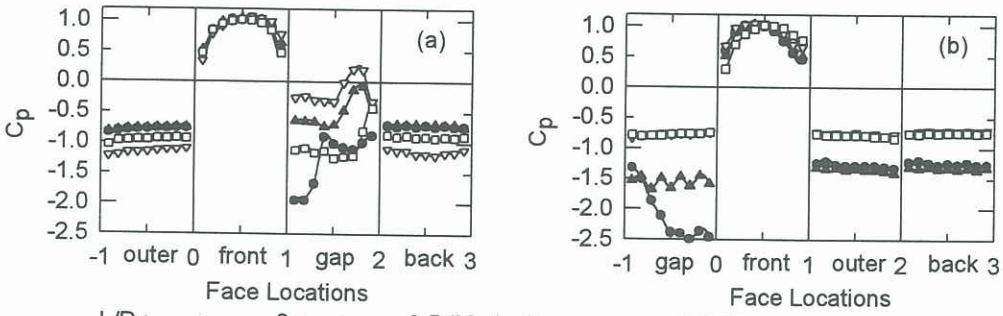
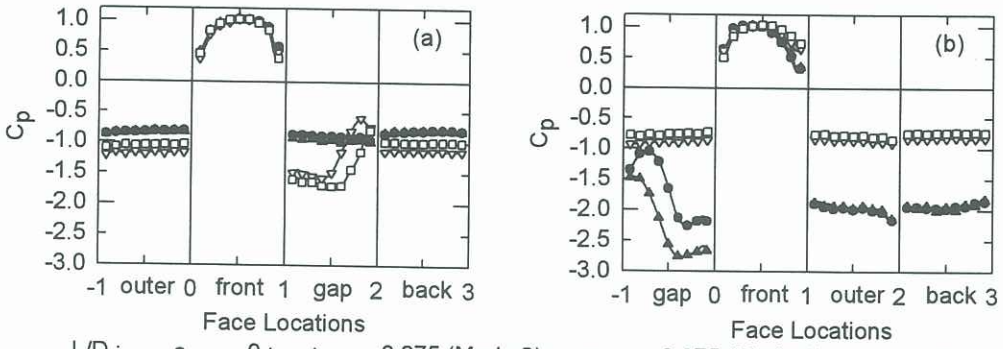


FIG. 1 EXPERIMENTAL SETUP OF CYLINDERS



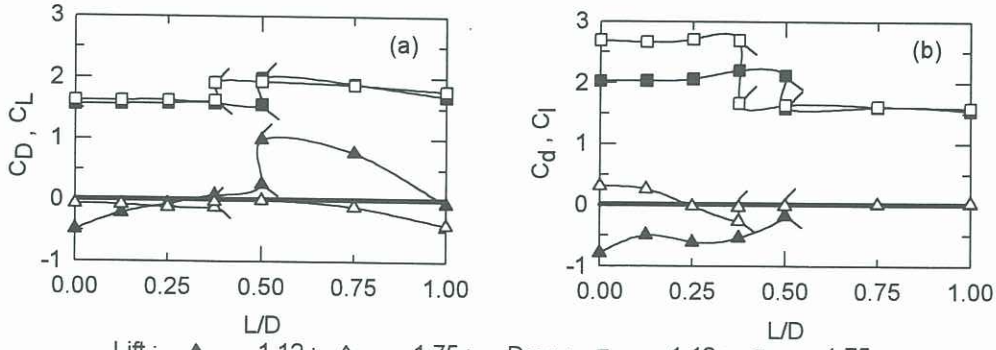
L/D : ● , 0 ; ▲ , 0.5 (Mode 2) ; ▽ , 0.5 (Mode 1) ; □ , 1.0 .

FIG.2 MEAN STATIC PRESSURE DISTRIBUTIONS (a) LARGE AND (b) SMALL CYLINDERS. T/D = 1.12.



L/D : ● , 0 ; ▲ , 0.375 (Mode 2) ; ▽ , 0.375 (Mode 1) ; □ , 1.0 .

FIG.3 MEAN STATIC PRESSURE DISTRIBUTIONS (a) LARGE AND (b) SMALL CYLINDERS. T/D = 1.75.



Lift : ▲ , 1.12 ; △ , 1.75 ; Drag : ■ , 1.12 ; □ , 1.75 .

Flag up : Mode 1 ;Flag down : Mode 2 .

FIG.4 LIFT AND DRAG COEFFICIENTS (a) LARGE AND (b) SMALL CYLINDERS. T/D = 1.12, 1.75.