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Brief Communication

Flow around two side-by-side closely spaced circular cylinders

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Abstract

The flow structure around two side-by-side circular cylinders is investigated at $T/d = 0.1-0.2$ (T is the gap spacing between the cylinders, and d is the cylinder diameter), where the gap flow between the cylinders has a significant influence on the time-averaged lift on the cylinders. Two distinct flow structures are identified at $T/d = 0.1$ and 0.2, based on time-averaged pressure measurement and surface oil-flow patterns. The gap flow forms a separation bubble in the base region of one cylinder at $T/d = 0.1$ but separates from the cylinders without further reattachment at $T/d = 0.2$. At $T/d = 0.13$, this bubble occurs on and off spontaneously and abruptly, causing the corresponding time-averaged lift force on the cylinder to jump among different discrete values.

1. Introduction

Flow interference can cause some drastic changes in fluid forces on multiple structures subjected to a cross-stream. Flow around a pair of circular cylinders could provide an in-depth understanding of vortex dynamics, pressure distribution and fluid forces associated with multiple cylinders. Aerodynamic interference between two cylinders may result in flow separation, reattachment, vortex impingement, recirculation and quasi-periodic vortices, involving most generic flow features associated with multiple cylinders. As such, the flow around two cylindrical bluff bodies has been extensively investigated in the past (Zdravkovich, 1977; Zhou et al., 2001; Alam et al., 2003; Chen et al., 2003).

Three flow regimes have been identified previously based on the behavior of Strouhal number St and the near-wake characteristics of two side-by-side circular cylinders as the cylinder gap spacing ratio T/d is varied (Zdravkovich, 1977; Ishigai et al., 1972). The single bluff body regime occurs at $T/d < 0.2$–0.3, where the two cylinders behave like one bluff body, generating a single vortex street and a single St (Spivack, 1946). The asymmetrical wake regime occurs at $T/d = 0.2-0.3$ to 1.2–1.5, where the biased gap flow results in one wide wake and one narrow wake, which correspond to a lower and higher St, respectively (Bearman and Wadcock, 1973; Zhou et al., 2001; Alam et al., 2003). Xu and Zhou (2003) observed that the flow structure in the asymmetrical regime ($T/d = 0.2-0.6$) changed from one vortex street to two, even at the same T/d given different Reynolds numbers. At $T/d > 1.2-1.5$, two coupled vortex streets of the same St are generated, and they are either in-phased or anti-phased, often referred to as the coupled street regime. At $Re \leqslant 40$, Kang (2003) observed a single-bluff-body-like wake for $T/d < 0.5$ and a steady wake for $T/d \geqslant 0.5$. Ishigai et al. (1972) argued that the biased flow in the gap was due to the Coanda effect, that is, the flow tends to attach itself more to one cylinder surface than the other due to asymmetric separation. Later, this was proved to be incorrect because Bearman

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and Wadcock (1973) observed a biased flow between two flat plates in the side-by-side arrangement. Alam et al. (2005) argued that the side-by-side arrangement is a critical configuration of two slightly staggered cylinders, i.e. $\alpha < 90°$ and $\alpha > 90°$, where α denotes the angle between the free-stream flow and the line through the cylinder centers. The gap flow for $\alpha < 90°$ say $\alpha = 85°$, is biased steadily towards one cylinder and that for $\alpha > 90°$, say $\alpha = 95°$, is biased steadily towards the other. As a result, the gap flow for $\alpha = 90°$ switches intermittently from one side to the other.

Based on the measured time-averaged lift coefficient $\overline{C_L}$ on two side-by-side circular cylinders, Hori (1959) for $T/d > 0.2$ and Bearman and Wadcock (1973) for $T/d > 0.5$ concluded that the two cylinders were always repulsive. A similar observation was made by Zdravkovich and Pridden (1977) for $T/d > 0.3$ and by Zhou et al. (2001) at $T/d = 0.13$, 0.7 and 3.0. However, Alam et al. (2003) measured at $T/d = 0.1$ a $\overline{C_L}$ of -0.12 and 0.65 on cylinders associated with narrow and wide wakes, respectively. At $T/d = 0.1$ the gap flow was observed to sweep around the cylinder surface for a longer peripheral length. The positive and negative lift correspond to outward-directed (repulsive) and inward-directed (attractive) forces, respectively. The corresponding $\overline{C_L}$ was 0.37 and 0.56 at $T/d = 0.2$, respectively [see Fig. 7 in Alam et al. (2003)]. The sign change in $\overline{C_L}$ on the cylinder associated with the narrow wake from $T/d = 0.1$ to 0.2 implies a drastic change in the flow structure, which has not been previously documented.

The present investigation aims to clarify experimentally a possible variation in the flow structure as $\overline{C_L}$ on the two cylinders jumps from $T/d = 0.1$ to 0.2, and understand thoroughly the physics behind this jump. To this end, time-averaged pressure distributions and flow on the surfaces of the cylinders are measured using a pressure transducer and surface oil-flow fvisualization technique.

2. Experimental details

Experiments were conducted under the same conditions (e.g. the wind tunnel, cylinders, and Reynolds number as in Alam et al. (2003)). Briefly, the closed-looped wind tunnel has rectangular test-section 300 mm wide, 1200 mm tall and 2200 mm in length. The cylinders used as the test models were made of brass and were each 49 mm in diameter. The free-stream velocity, U_∞, in the test-section was 17 m/s, giving a Reynolds number Re ($= U_\infty d/v$, where v is the kinematic viscosity of fluid) of 4.7×10^4. The longitudinal turbulence intensity was less than 0.5% in the absence of the cylinders.

A semi-conductor pressure transducer (Toyoda PD104K) located at the mid-section of a cylinder was used to measure the surface pressure. The transducers responded reasonably well to the pressure fluctuations up to 500 Hz with a gain factor of 1 ± 0.06, with a negligible phase lag. This frequency was well above the frequency of vortex shedding from the cylinders. Details of the pressure transducer have been given in Alam et al. (2005). The time-averaged pressure coefficient $\overline{C_P}$ was estimated for narrow and wide wakes, respectively, using a conditional sampling technique. The details of the conditional sampling technique have been given in Alam et al. (2003).

The surface oil-film technique was used to visualize the flow structure on the cylinder surface in order to obtain information on the reattachment and separation of flow. Surface oil-flow visualization was performed at the same Re as the measurements of lift force and surface pressure. The experimental uncertainty in the angular position of shear layer separation or the reattachment position obtained from surface oil-film techniques was estimated to be $\pm 2°$. In order to get surface oil-flow patterns for the narrow and wide wakes separately, intermittent gap flow switching was suppressed by placing the cylinders slightly staggered from the side-by-side arrangement, i.e. $\alpha = 90° \pm 3°$. The measured pressures on the slightly staggered cylinders ($T/d = 0.10$) were almost the same as those on the side-by-side arranged cylinders; hence the surface oil-flow patterns on the slightly staggered cylinders should correspond to those on side-by-side arranged cylinders in terms of the narrow and wide wakes (Zdravkovich and Pridden, 1977). More details of the surface oil-flow visualization technique have been given in Alam et al. (2005).

3. Results and discussion

3.1. Flow structure

The measured surface oil-flow patterns and $\overline{C_P}$ distributions at $T/d = 0.1$ and 0.2 are shown in Figs. 1 and 2, respectively. Surface oil-flow patterns at $T/d = 0.1$ (Fig. 1(a)) indicate the occurrence of stagnation lines at $\theta = 333°$ for the narrow wake and 328° for the wide wake. The laminar outer-shear layer separates at 65° for the narrow wake and 70° for the wide wake. The two inner shear layers (gap flow) between the cylinders behave quite differently. For the convenience of discussion, let the narrow and wide wakes correspond to Cylinders 1 and 2, respectively. The gap flow separates from Cylinder 2 at 260° ($-100°$), but sweeps around Cylinder 1 for a longer peripheral length. A turbulent

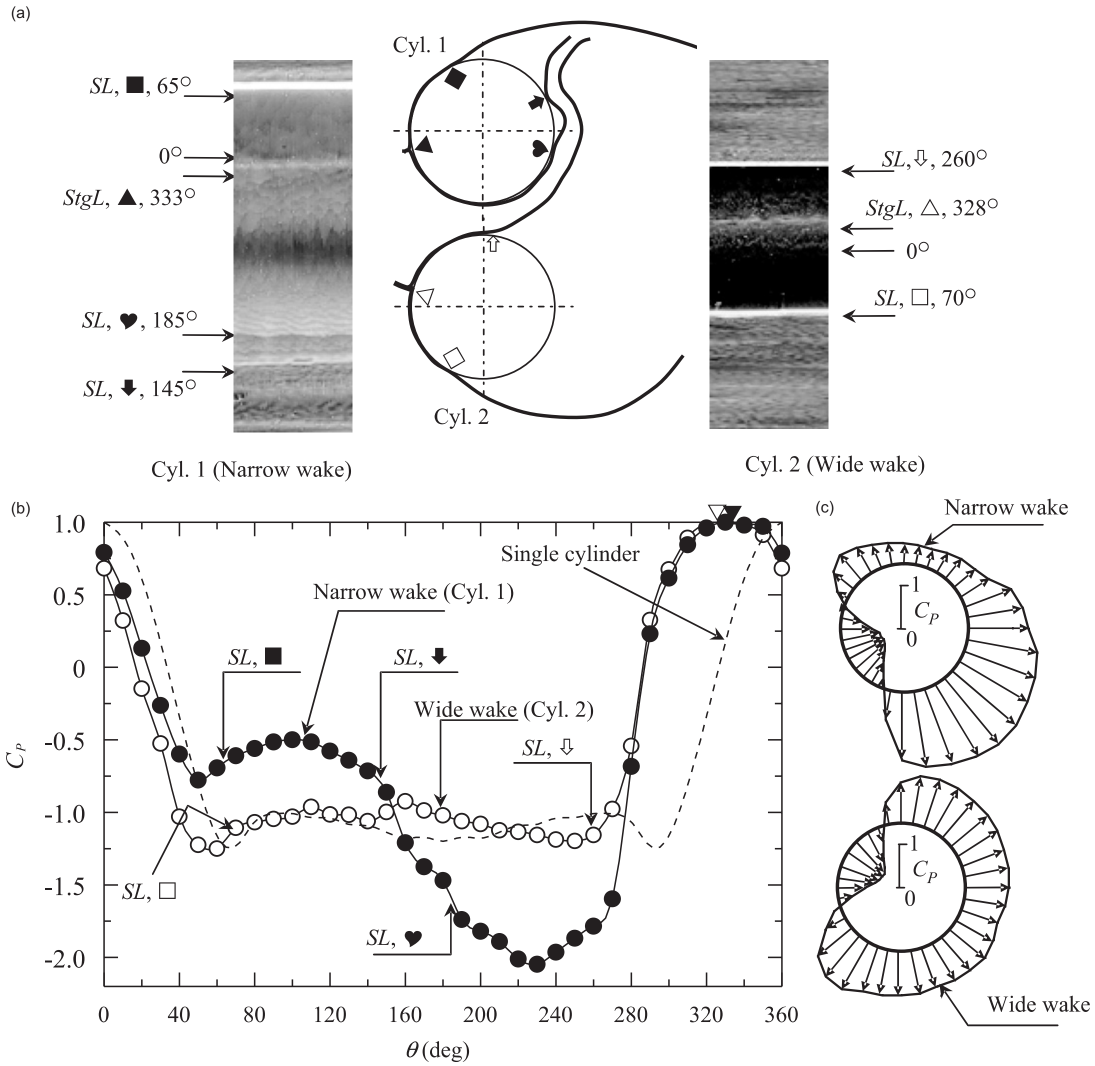

Fig. 1. (a) Surface oil-flow patterns on two cylinders and the corresponding sketch of flow. SL = separation line, RL = reattachment line, $StgL$ = stagnation line. (b) and (c) Time-averaged pressure coefficient, $\overline{C_P}$, on the surface of the cylinders in Cartesian and polar coordinates, respectively (Alam et al., 2003) $T/d = 0.1$.

separation of the gap flow from Cylinder 1 occurs at 185° (−175°) followed by a turbulent reattachment, thus forming a separation bubble. The final separation takes place at 145° (−215°). Thus, the narrow wake consists of a separation bubble formed by the gap flow. Eventually, the separated gap flow merges with the opposite-side shear layer around the cylinder.

$\overline{C_P}$ (Fig. 1(b), (c)) attains a value of unity at around $\theta \approx 330°$ for both cylinders, which coincides well with the stagnation lines observed in the surface oil-flow patterns (Fig. 1(a)). The $\overline{C_P}$ distribution around Cylinder 2 is similar to that for an isolated single cylinder, also given in the figure, except for a shift in the stagnation point. The observation agrees with that from the surface oil-flow pattern (Fig. 1(a)). The stagnation and shear-layer separation positions obtained from the surface oil-flow patterns have been marked on the $\overline{C_P}$ distributions. $\overline{C_P}$ on Cylinder 1 reaches a minimum value of −2.05 at $\theta \approx 230°$ and the pressure recovery region is rather long, implying that the boundary layer around the gap side of the cylinder is highly turbulent (Zdravkovich, 1997; Achenbach, 1968; Farrel and Blessmann, 1983), which is consistent with the turbulent separation in the surface oil-flow pattern (Fig. 1(a)). There is a remarkable change in the pressure gradient at $\theta \approx 140-190°$, indicating that the boundary layer separation is followed by reattachment and another separation, as observed in the surface oil-flow pattern. Interestingly, a highly negative

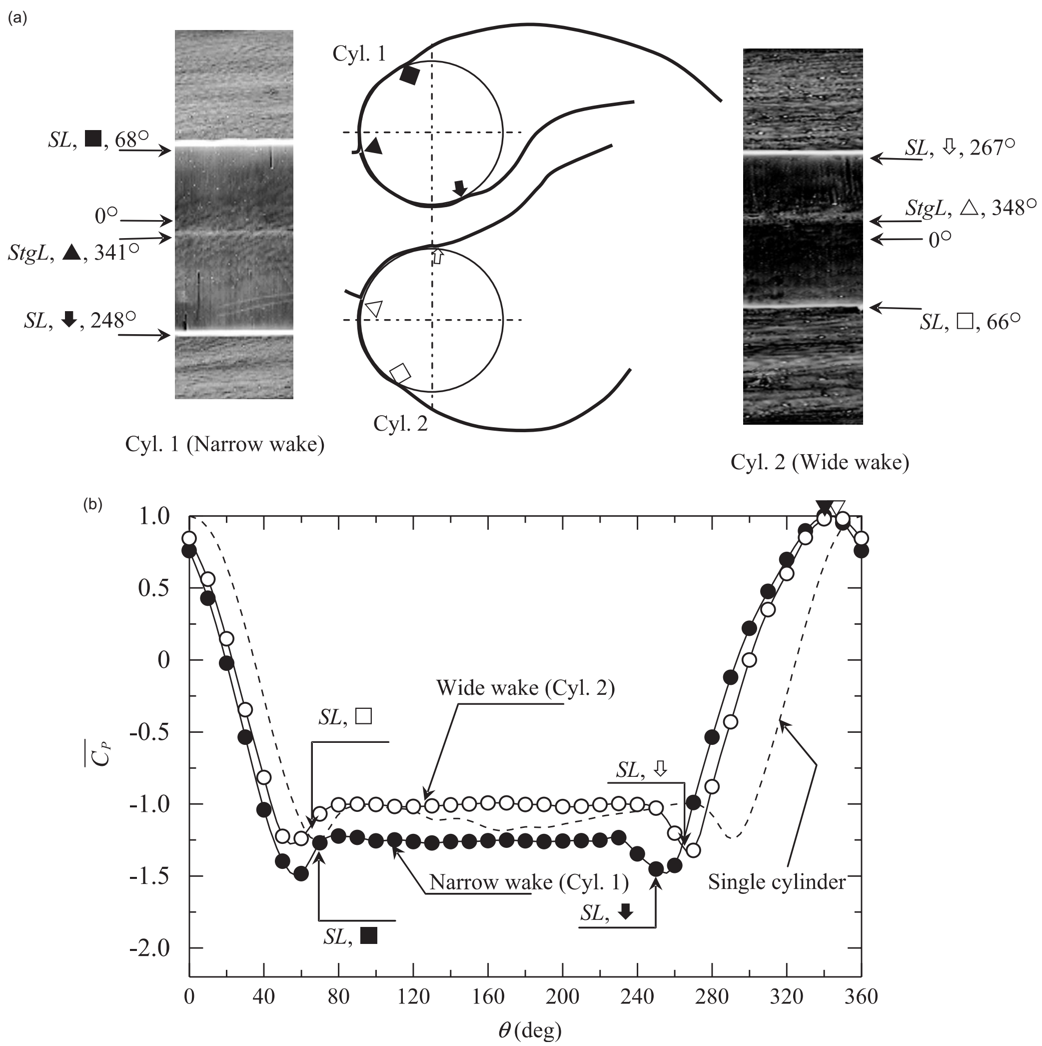

Fig. 2. Surface oil-flow patterns and corresponding sketch of flow. SL = separation line RL = reattachment line, $StgL$ = stagnation line. (b) Time-averaged pressure coefficient, $\overline{C_P}$, on the surface of the cylinders. $T/d = 0.2$.

pressure is generated on Cylinder 1 at $\theta \approx 170-270^\circ$, possibly due to the fact that the small gap between the cylinders results in a jet-like accelerated gap flow. Hence, the gap flow possesses a higher momentum and sustains a longer pressure recovery region prior to separation. Such highly negative pressure generation resembles in a way the highly negative pressure generation by the laminar-separation/turbulent-reattachment bubble formed on one side of an isolated cylinder at a critical Reynolds number (Bearman, 1969; Schewe, 1983; Almosnino and McAlister, 1984), where a significant $\overline{C_L}$ on the isolated cylinder was observed.

Surface oil-flow patterns at $T/d = 0.2$ (Fig. 2(a)) indicate that outer-shear layers separate from Cylinders 1 and 2 at $\theta = 68^\circ$ and 66°, respectively. On the other hand, the gap flow separates from the cylinders at $\theta = 248^\circ$ (-112) and 267° (-93°), respectively. When T/d is reduced to 0.1, the gap flow separation occurs at $\theta = 145^\circ$ (-215°) for Cylinder 1 and 260° (-100°) for Cylinder 2. The difference in the gap flow separation position between $T/d = 0.1$ and 0.2 for Cylinder 2 is only 7° ($= |267^\circ - 260^\circ|$), while that for Cylinder 1 is 103° ($= |248^\circ - 145^\circ|$), which is consistent with the large variation in $\overline{C_L}$ of Cylinder 1 between $T/d = 0.1$ and 0.2 [see Fig. 7 in Alam et al. (2003)]. Note that the difference in the outer-shear-layer separation position between those T/d is very small, 3° ($= |65^\circ - 68^\circ|$) for Cylinder 1 and 4° ($= |70^\circ - 66^\circ|$) for Cylinder 2. Apparently, the outer-shear layer and the gap-flow separation positions of Cylinder 2 are almost unchanged from $T/d = 0.1$ to 0.2; the corresponding variation in $\overline{C_L}$ on this cylinder is small [see Fig. 7 in Alam et al. (2003)].

The surface oil-flow patterns (Fig. 1(a)) agree well with $\overline{C_P}$ distributions presented in Fig. 1(b). Separation positions of the outer-shear layers and the gap flow correspond to the pressure recovery regions. The $\overline{C_P}$ distribution for Cylinder 2 at $T/d = 0.2$ (Fig. 2(b)) is almost the same as that at $T/d = 0.1$ (Fig. 1(b)), reconfirming that the flow around Cylinder 2 at those T/d is almost the same.

The flow structure around Cylinder 1 is quite different at $T/d = 0.20$ (Fig. 2) from that at $T/d = 0.10$ (Fig. 1). Accordingly, there is a rapid rise in $\overline{C_L}$ from $T/d = 0.1$ to 0.2 for Cylinder 1. A separation bubble occurs on Cylinder 1 at $T/d = 0.1$ but not at $T/d = 0.2$. If the separation bubble, which forms for $T/d = 0.1$, bursts, the flow structure for $T/d = 0.1$ will be modified to that at $T/d = 0.2$. Therefore, the change in the flow structure between $T/d = 0.1$ and 0.2 would be discontinuous (Alam et al., 2005). Alam et al. (2005) examined the discontinuous change in the flow structure around two staggered circular cylinders and noted that the change from the flow structure with a separation bubble to that without is always discontinuous. Furthermore, the intermittent formation and burst of the separation bubble caused a bi-stable nature of the flow, giving rise to a great difference in the lift force on the cylinder, which is reconfirmed in the present investigation.

3.2. Flow switching

It is of fundamental interest to understand how the formation and burst of the separation bubble would affect the lift force on cylinders. As discussed earlier, at $T/d = 0.1$ a separation bubble forms on the cylinder, toward which the gap

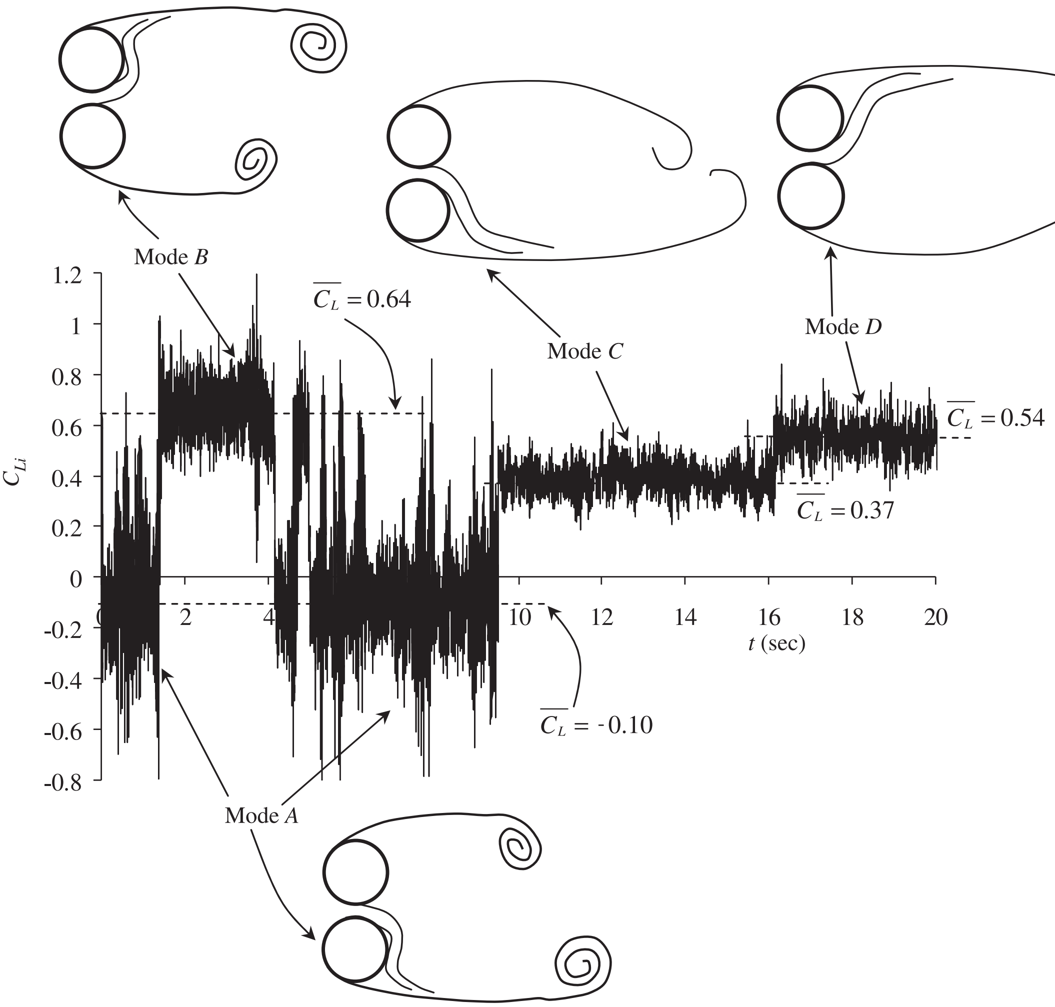

Fig. 3. Time history of instantaneous lift force on the lower cylinder at $T/d = 0.13$ and flow sketches corresponding to the different modes of lift force.

flow is biased. However, the separation bubble is absent at $T/d = 0.2$. Hence, one way to gain information on the formation and burst of the separation bubble is to examine the signal of the lift force of a cylinder at an intermediate T/d between 0.1 and 0.2. Fig. 3 presents the time history of instantaneous lift force on one of the two cylinders at $T/d = 0.13$. Four different modes, i.e. A, B, C and D, may be identified based on the signal, which correspond to $\overline{C_L} = -0.10$, 0.64, 0.37 and 0.54, respectively. $\overline{C_L}$ in Mode A or B is almost identical to its counterpart at $T/d = 0.1$, whilst that in Mode C or D is the same as its counterpart at $T/d = 0.2$ [see Fig. 7 in Alam et al. (2003)]. The occurrence of the two different modes, A and B, results from the gap flow switch from one side to the other, as at $T/d = 0.10$ (Fig. 1(a)). On the other hand, Modes C and D are distinct because of the gap flow switch, similarly to that taking place at $T/d = 0.2$ (Fig. 2(a)). There are two types of discontinuous changes in the flow structure at $T/d = 0.13$ (Fig. 3); one is due to the gap flow switch and other is due to a burst of the separation bubble. Due to the gap flow switch, the signal changes from Mode A to B at time $t = 1.4$ s, B to A at $t = 4.15$ s, A to B at $t = 4.6$ s, B to A at $t = 4.98$ s, and C to D at $t = 16.3$ s. The signal also changes from A to C at $t = 9.8$ s, caused by a burst of the separation bubble. The observation conforms to the Alam et al. (2005) report that the flow structure changed abruptly from the presence to the absence (or *vice versa*) of a separation bubble around one of two staggered cylinders. The geometry $T/d = 0.13$ (between $T/d = 0.1$ and 0.2) was chosen arbitrarily for getting information on intermittent jump in $\overline{C_L}$ due to the formation and burst of the separation bubble, and it is expected that there is a range of T/d for the jump, though the range was not determined exactly.

4. Conclusions

Flow structures around two side-by-side circular cylinders at $T/d = 0.1-0.2$ are investigated based on the time-averaged pressure measurement and surface oil-flow pattern. The investigation leads to following conclusions.

(1) Two distinct flow structures occur at $T/d = 0.1$ and 0.2, respectively, the corresponding $\overline{C_L}$ experiencing a sudden change. The gap flow at $T/d = 0.1$ is highly biased, forming a separation bubble in the base region of one cylinder. At $T/d = 0.2$, the separation bubble is absent.
(2) The change in the flow structure is quite abrupt from $T/d = 0.1$ to 0.2, resulting from the presence and absence, respectively, of a separation bubble in the two configurations. At $T/d = 0.13$, there are two types of discontinuous change in the flow structure: one is due to the gap flow switching from one side to the other, and the other is due to a burst of the separation bubble, resulting in four distinct modes of flow.

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