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TANDEM CYLINDERS IN IMPULSIVELY STARTED FLOW

D. SUMNER,[1] S. J. PRICE AND M. P. PAÏDOUSSIS
Department of Mechanical Engineering, McGill University, Montréal, Québec, Canada

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The impulsively started flow field for circular cylinders of equal diameter arranged in tandem was investigated using flow visualization and particle image velocimetry (PIV), over a longitudinal pitch ratio range of $L/D = 1{\cdot}0{-}3{\cdot}0$, and for Reynolds numbers from Re = 1200–3800. The PIV technique was used to obtain a time history of the instantaneous in-plane vorticity field from the moment of impulsive start, from which the spatial and temporal development of the flow was studied. Measurements of vortex strength and vortex position relative to the cylinders were obtained from these data. Three types of fluid behaviour were identified based on L/D: single bluff-body behaviour when the cylinders are in contact, constrained streamwise growth and lateral expansion of the gap recirculation zones at small and intermediate L/D, and independent formation of recirculation zones similar to a single impulsively started circular cylinder at larger L/D. © 1999 Academic Press

1. INTRODUCTION

THE TIME EVOLUTION of the flow field for a circular cylinder of diameter D impulsively set into motion at cross-flow velocity U is characterized by the formation of a symmetrical recirculation zone in the cylinder near wake, containing a pair of stationary eddies of equal strength and opposite rotation (Bouard & Coutanceau 1980; Nagata *et al.* 1989; Chu & Liao 1992). Eventually, these eddies are shed from the cylinder, and the familiar steady flow pattern of periodic vortex shedding is initiated, provided the Reynolds number is sufficiently high. The impulsively started flow field of the circular cylinder is also marked by the formation of small regions of secondary vorticity, located downstream of the point of boundary layer separation; these regions are not observed for a circular cylinder under steady cross-flow conditions.

Small groups of circular cylinders in close proximity, however, have not been investigated extensively under unsteady conditions, although the side-by-side configuration has recently been examined (Sumner *et al.* 1997a, b). Their study in impulsively started flow may provide insight into the development of the flow patterns seen under steady mean flow conditions.

In these experiments, the main interest is in the basic features of the starting flow dynamics for circular cylinders arranged in a tandem configuration, and the effects of varying the centre-to-centre longitudinal pitch ratio L/D separating the cylinders (see Figure 1). Only under steady-flow conditions has their behaviour been well-studied (Igarashi 1981; Ljungkrona & Sundén 1993).

2. EXPERIMENTAL APPROACH

Flow visualization and particle image velocimetry (PIV) were adopted as the methods of investigation. Two- and three-cylinder arrangements of $L/D = 1{\cdot}0{-}3{\cdot}0$ were tested in

[1] Currently with the Department of Mechanical Engineering, University of Saskatchewan, Saskatoon, Saskatchewan S7N 5A9, Canada.

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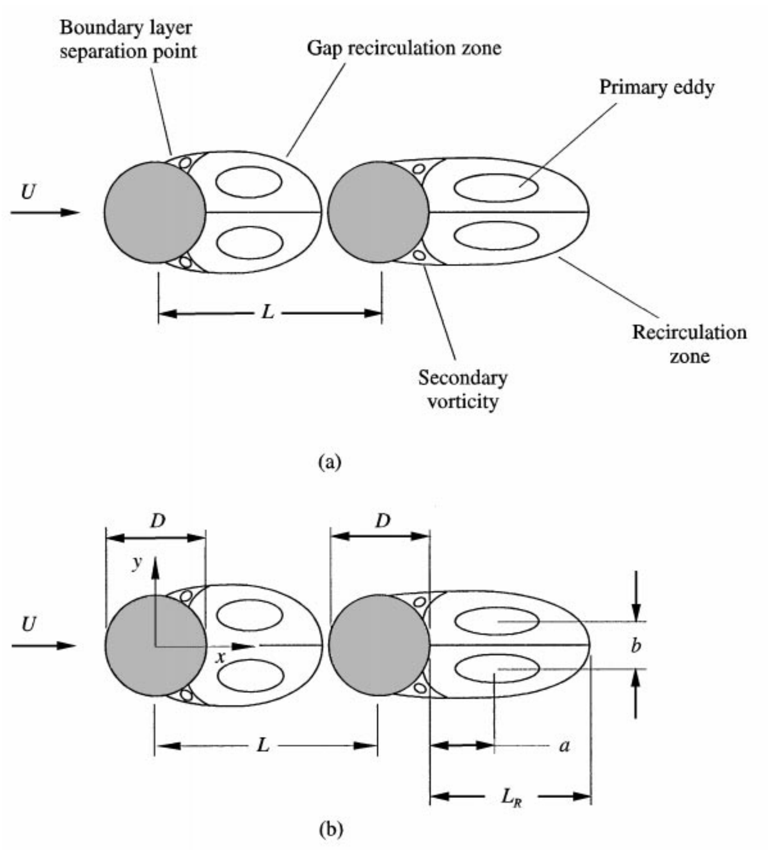

Figure 1. Tandem circular cylinders impulsively set into motion: (a) features of the flow field; (b) quantitative description.

a small vertical water towing tank of dimensions 305 mm × 610 mm × 1200 mm (see Figure 2). Plexiglas cylinder models of $D = 25{\cdot}4$ mm, with an aspect ratio of 9·0 and a solid blockage ratio of 4·2%, were mounted in a cantilevered fashion from a flat plate, and were pulled upwards through stationary fluid at velocities of $U = 50$–150 mm/s after a nearly impulsive start, yielding Reynolds numbers of Re = 1200–3800. This Reynolds number range was chosen to coincide with previously reported experiments on circular cylinders impulsively set into motion [e.g., Bouard & Coutanceau (1980), Nagata *et al.* (1989), Chu & Liao (1992), and other references cited in Sumner *et al.* (1997b)]. The gap between the free ends of the cylinders and the tank wall remained less than $0{\cdot}2D$. For most of the tests, the nondimensional acceleration parameter A_p [$= DU^{-2}(\mathrm{d}u/\mathrm{d}t)$, for streamwise acceleration $\mathrm{d}u/\mathrm{d}t$, and actual cylinder velocity $u \leq U$] ranged from 0·2 to 0·8, indicating that nearly impulsively started conditions were usually achieved (Sarpkaya 1991). The velocity of the cylinders was determined from the digital flow visualization images and the PIV data, as discussed below, with an estimated measurement uncertainty of 3%. In this limited range of Re, no apparent Reynolds number dependence was found, and similar flow structures were identified at the same nondimensional times, t^* ($= tU/D$, where t corresponds to the elapsed time); the measurement uncertainty in t^* was estimated at 5%.

For the flow visualization and PIV experiments, the water in the towing tank was seeded with irregularly shaped, nearly neutrally buoyant particles (specific gravity of 1·03), of

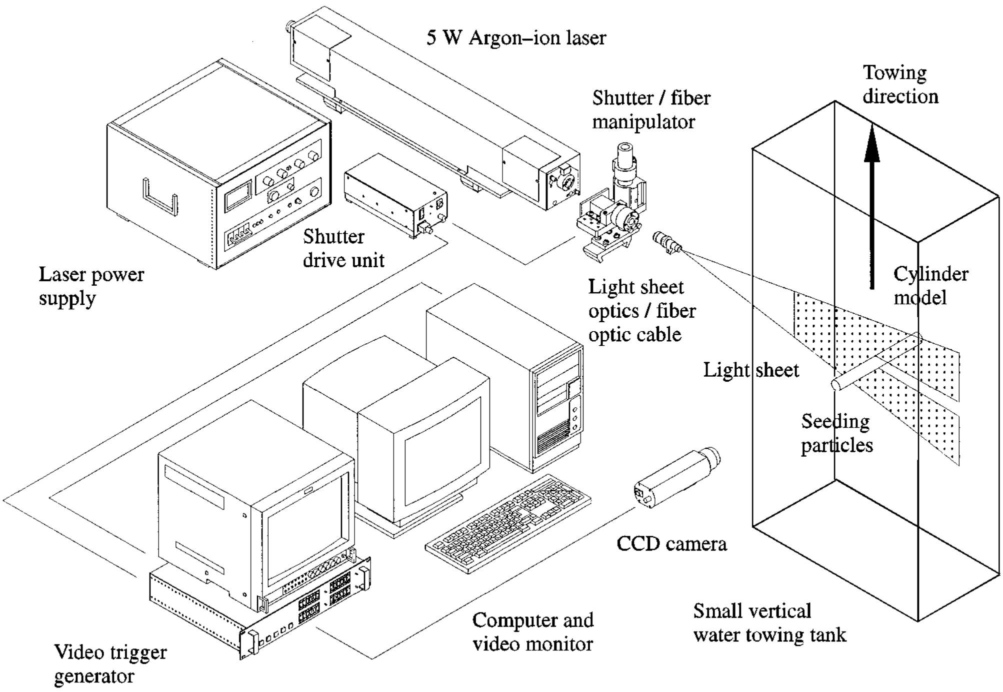

Figure 2. Schematic of the experimental setup and instrumentation, for flow visualization and PIV.

100–300 μm in size. A section of the flow was illuminated with a pulsed light sheet generated by a 5 W argon-ion laser and a mechanical shutter, and successive pairs of single-exposed digital particle images (each of 512 × 480 pixels) were acquired with a Dantec Double Image 700 CCD camera and frame grabber (see Figure 2). In each case, the camera was mounted in a fixed position in front of the towing tank, and the light sheet originated from the side of the towing tank and was aimed at the centre-span of the cylinder.

2.1. Flow Visualization

In the flow visualization experiments, some of the heavier seeding particles were allowed to settle on the upper surfaces of the cylinder models, before the cylinders were impulsively set into motion. The particle motions were then recorded using the laser light sheet and the digital camera described above, using a 14 ms pulse duration, such that the moving particles appeared as short, bright streaks. Images were captured at 0·2 s intervals from the moment of the impulsive start.

2.2. Particle Image Velocimetry (PIV)

The PIV technique was used to obtain the time history of the nondimensional instantaneous in-plane vorticity field, $\omega_z D/U$, as the flow developed over a range of nondimensional elapsed time t^*. The horizontal image magnification was of the order of 0·3 mm/pixel, and each image covered an area of approximately 150 × 150 mm (6 × 6 cylinder diameters) within the flow field. The image exposure time was typically 6 ms, and the time between single-exposed images constituting a pair was typically 4 ms.

Dantec FlowGrabber digital PIV software employing the cross-correlation algorithm of Willert & Gharib (1991) was used to compute the raw displacement vector field from the

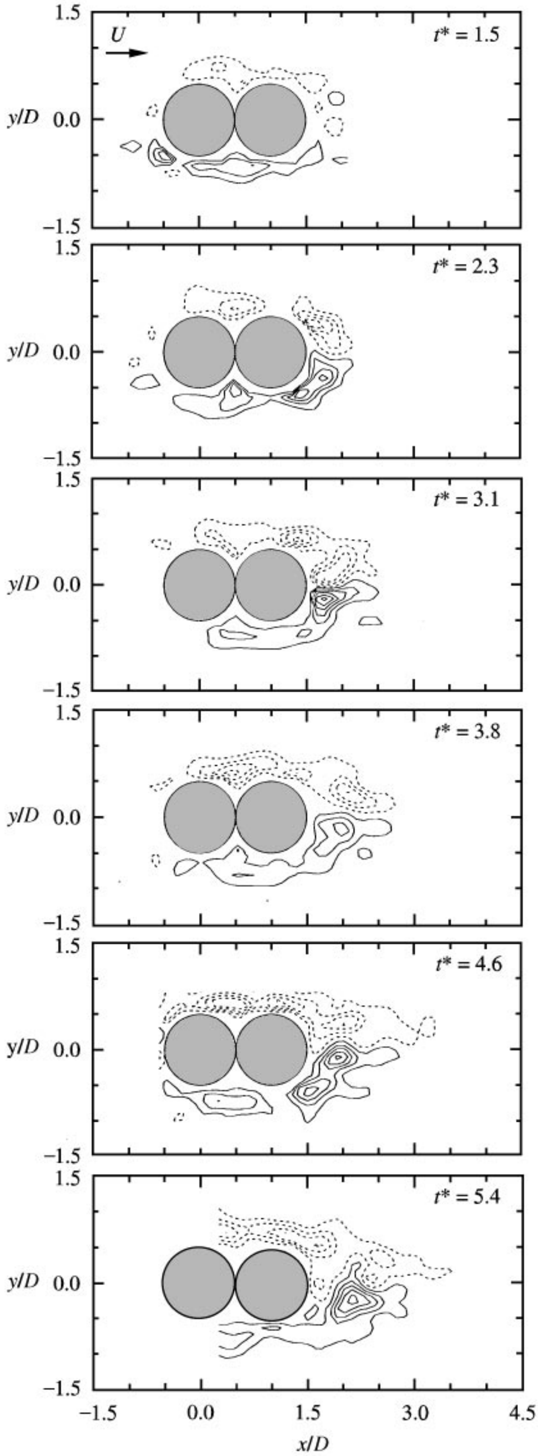

Figure 3. Nondimensional, instantaneous, in-plane vorticity field for two impulsively started tandem cylinders, $L/D = 1{\cdot}0$, Re $= 2400$, $A_p = 0{\cdot}3$. Minimum vorticity contour magnitude 0·75, contour increment 1·5, solid lines represent positive (CCW) vorticity, dashed lines represent negative (CW) vorticity.

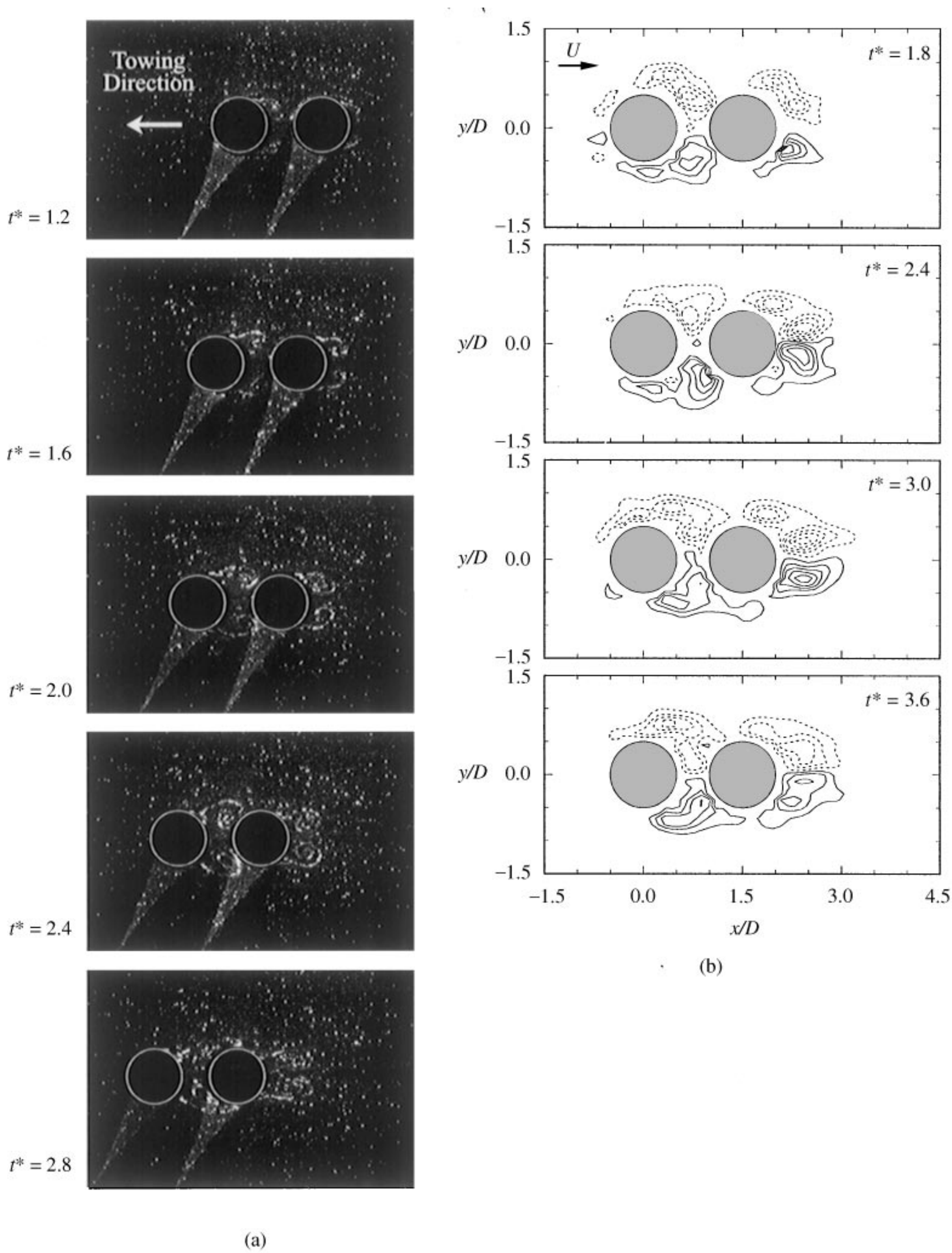

Figure 4. Two impulsively started tandem cylinders at $L/D = 1{\cdot}5$: (a) flow visualization, Re = 1300, $A_p = 0{\cdot}8$; (b) vorticity field, Re = 1900, $A_p = 0{\cdot}3$.

particle image data, using an interrogation window of 32×32 pixels (approximately 10×10 mm, or $0{\cdot}3 \times 0{\cdot}3$ cylinder diameters) with 75% overlap. The size of the interrogation window effectively limits the minimum size of the vortex structures which can be identified in these experiments to approximately 0·3 cylinder diameters. Software developed in-house was then used to compute the in-plane velocity vector field (57×57 vectors) and vorticity field (55 × 55 points) at a spacing of about 2·6 mm (or 0·1 cylinder diameters). The time between successive pairs (or sets of vorticity data) was $\Delta t = 0{\cdot}2$ s.

For each configuration, up to 10 different PIV experiments were conducted, each yielding eight vorticity fields. A time history of the nondimensional, instantaneous, in-plane vorticity field was determined from a single towing of the cylinders however, and no ensemble averaging or phase averaging of data from successive runs was undertaken (nor were these techniques possible with the given experiment set-up). In most cases, there was good correspondence between the flow visualization images and the instantaneous PIV vorticity data. By applying known displacements to a digitized particle image using Adobe Photoshop software, the measurement uncertainty of the velocity and vorticity data could be assessed; the measurement uncertainty of the vorticity was conservatively estimated at 10%.

From the vorticity data, the temporal growth of a recirculation zone was quantified by measurements of the streamwise location of the primary eddy centres from the base of the cylinder, a, the cross-stream spacing of the primary eddy centres, b, and the length of the recirculation zone from the base of the cylinder, L_R (all of which are defined in Figure 1(b)). Measurements of the area of a primary eddy, A, the peak vorticity within a primary eddy, ω_{zp}, and the primary eddy circulation or strength, Γ, were also obtained from the PIV vorticity data. These data were computed by integration of the vorticity field, with 0·5 designated the lowest meaningful magnitude of vorticity.

3. RESULTS AND DISCUSSION

When the cylinders are in contact (Figure 3), they behave as a single bluff body. The flow field is similar to that around a single cylinder (Bouard & Coutanceau 1980; Sumner *et al.* 1997b), and similar to other multiple cylinder configurations when the cylinders are in contact, such as the side-by-side configuration (Sumner *et al.* 1997a). A single quasi-attached recirculation zone forms in the near-wake region of the most downstream cylinder, containing a pair of eddies of equal strength and opposite rotation. The PIV vorticity data show the development of shear layers alongside the cylinders that are contiguous with the recirculation zone in the near-wake region (Figure 3). The shear layers greatly resemble the wrapped shear-layer behaviour observed under steady flow conditions (Igarashi 1981; Ljungkrona & Sundén 1993).

When the tandem cylinders are no longer in contact, but rather there is a gap between them, a recirculation zone forms behind each of the cylinders, with each zone containing a pair of eddies of equal strength and opposite rotation. At intermediate pitch ratios, of $L/D = 1{\cdot}5$ and 2·0, the temporal development of the gap recirculation zone is affected by the presence of the cylinders immediately downstream (Figure 4). The flow pattern suggests that a shear layer reattachment flow pattern may result, once steady flow conditions are established (Igarashi 1981; Ljungkrona & Sundén 1993). Here, the presence of the downstream cylinder constrains the streamwise growth of each gap recirculation zone, as it reaches the leading surface of the next cylinder. When the gap eddies can no longer extend in the streamwise direction, the zones expand symmetrically and laterally into the outer flow. The expansion is less pronounced at higher L/D, since the primary eddies in the gap have greater room to expand in the streamwise direction. Continued development of the flow sees the gap eddies being symmetrically convected about the downstream cylinder. The flow visualization results appear to show that the shed gap eddies are entrained into the shear layers, and then into the near-wake region of the most downstream cylinder, precipitating asymmetry in its recirculation zone. However, further PIV experiments with improved spatial resolution would be needed to verify this behaviour.

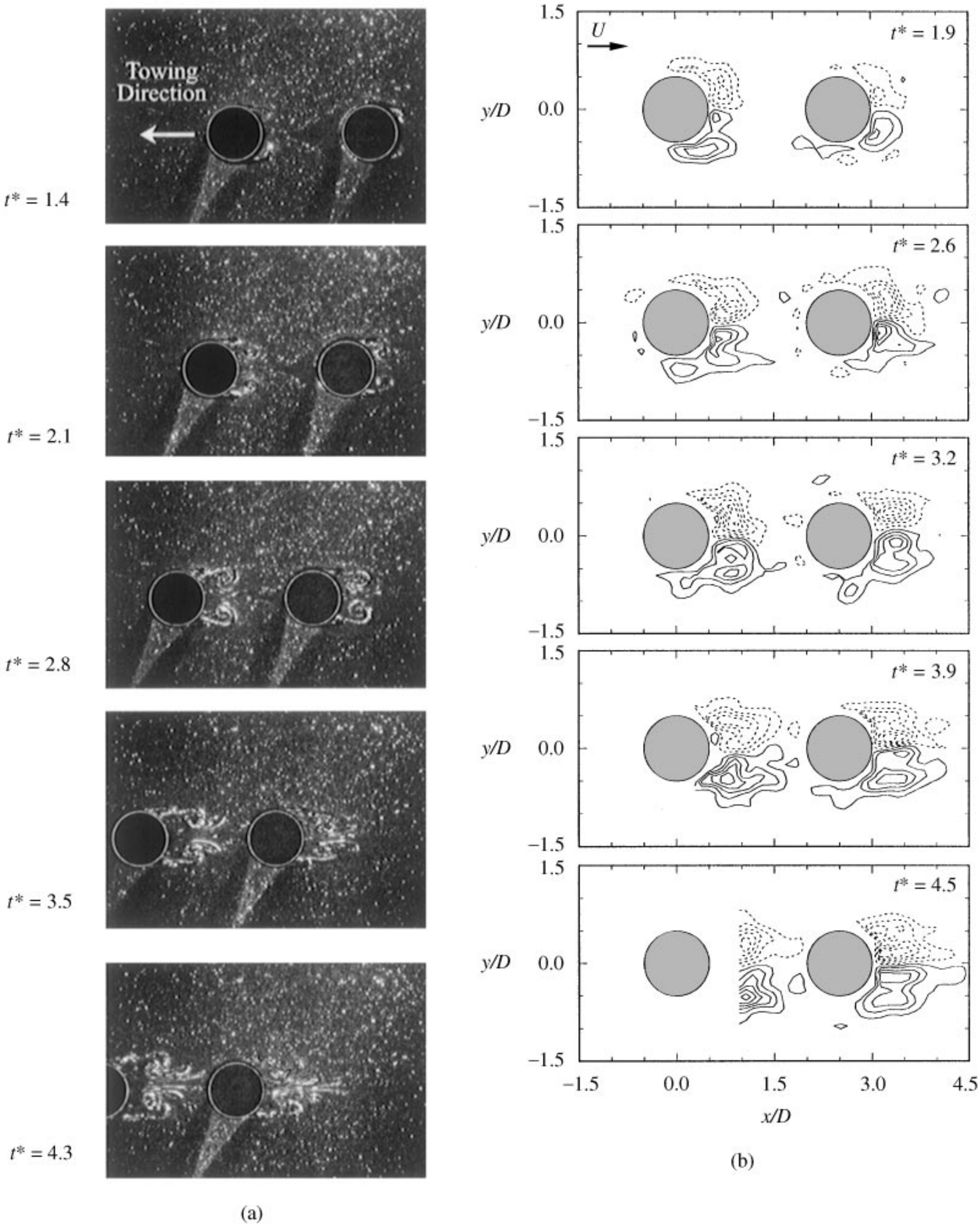

Figure 5. Two impulsively started tandem cylinders at $L/D = 2{\cdot}5$: (a) flow visualization, Re = 2300, $A_p = 0{\cdot}2$; (b) vorticity field, Re = 2100, $A_p = 0{\cdot}3$.

At larger pitch ratios, of $L/D = 2{\cdot}5$ and 3·0, the downstream cylinders have increasingly less influence on the development of the gap recirculation zone, and their growth resembles more that of a single cylinder (Figure 5). Lateral expansion of the gap recirculation zones becomes less evident. In all cases (although not shown here), three-cylinder groups behave in a much similar fashion to the two-cylinder combinations, with recirculation zones forming behind each of the three cylinders.

Some recirculation zone data are presented in Figure 6, for the downstream cylinder of a two-cylinder combination, for $L/D = 1{\cdot}5$ and $3{\cdot}0$. These data show that (i) the positions of the primary eddies, a and b, vary little with the pitch ratio L/D (Figure 6(a, b)); while (ii) the area of the primary eddies, the length of the recirculation zone, the peak vorticity and the circulation (or primary eddy strength), all increase with L/D (Figure 6(c–f)). Similar, but more pronounced, effects (not shown here) are seen for the upstream cylinder.

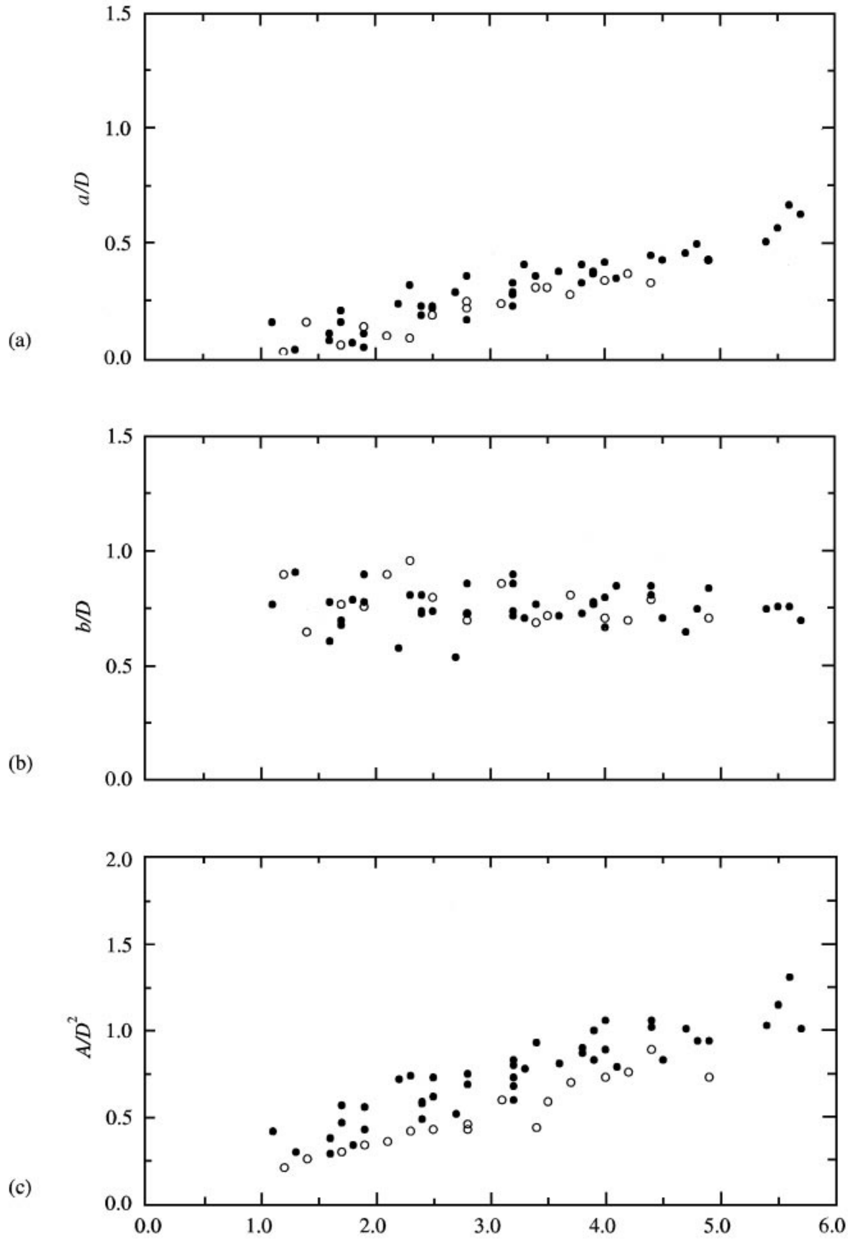

Figure 6, first part. Caption on next page.

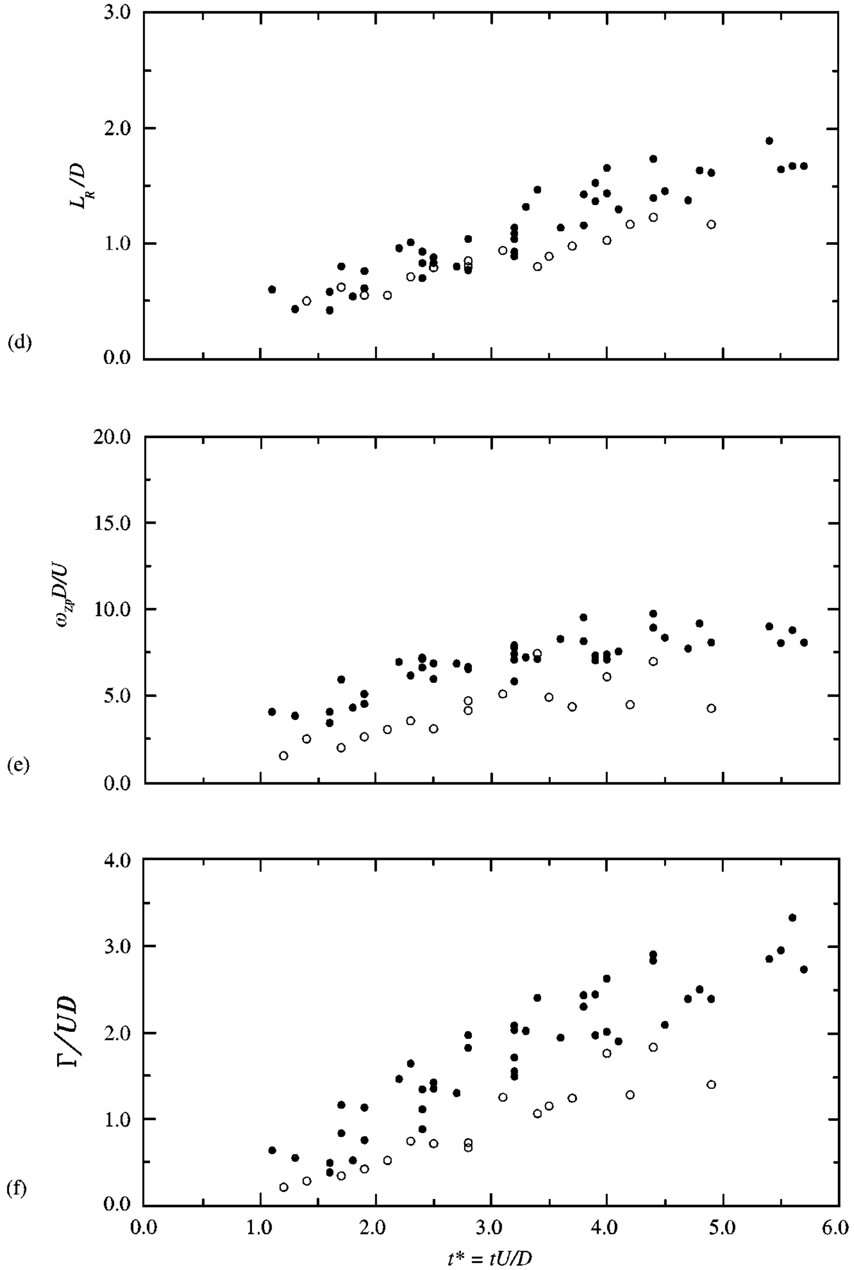

Figure 6. Recirculation zone data for two impulsively started tandem cylinders, downstream cylinder: ○, $L/D = 1{\cdot}5$, Re = 1800–2200, $A_p = 0{\cdot}3$–$0{\cdot}4$; ●, $L/D = 3{\cdot}0$, Re = 1800–2900, $A_p = 0{\cdot}3$–$0{\cdot}6$. (a) Streamwise position of the primary eddies from the base of the cylinder; (b) transverse spacing of the primary eddies; (c) area of a primary eddy; (d) streamwise extent of the recirculation zone from the base of the cylinder; (e) peak vorticity; (f) primary eddy circulation. Vorticity cut-off magnitude is 0·5.

4. CONCLUSIONS

This study is the first known investigation of tandem cylinders in impulsively started cross-flow. Three basic flow patterns were identified, sketched in Figure 7: (i) single

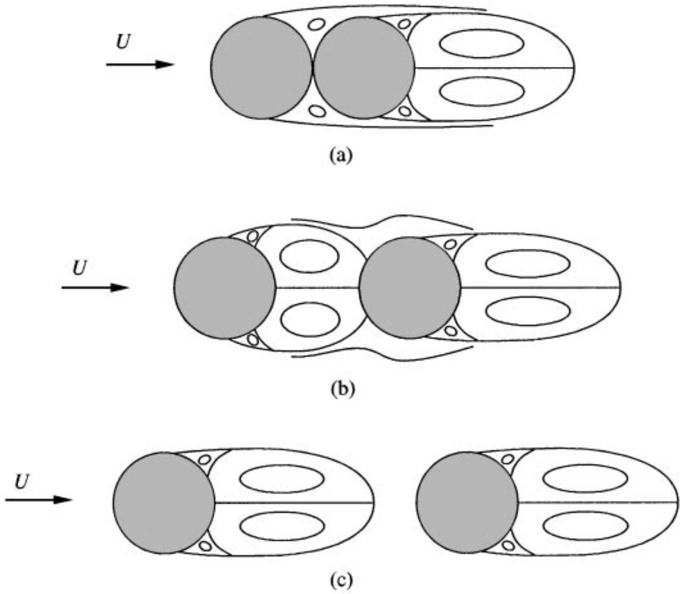

Figure 7. Flow development identified in the present study for two tandem circular cylinders of equal diameter impulsively set into motion, Re = 1200–3800: (a) tandem cylinders in contract; (b) tandem cylinders with a small gap; (c) tandem cylinders with a large gap. Similar patterns are seen for three-cylinder configurations.

bluff-body behaviour when the cylinders are in contact, (ii) constrained streamwise growth and lateral expansion of the gap recirculation zones at small and intermediate L/D, and (iii) independent formation of recirculation zones similar to a single impulsively started circular cylinder at larger L/D.

It is likely that the latter two flow patterns, for which there is a gap between the cylinders, both evolve to a shear-layer-reattachment flow pattern under steady conditions, despite the apparent and increasing independence of the cylinders at the larger pitch ratios.

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