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Flow visualization behind a streamwise oscillating cylinder and a stationary cylinder in tandem arrangement

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Abstract : Interference is investigated between a stationary cylinder wake and that of a downstream streamwise oscillating cylinder. Experiments were carried out in a water tunnel. A laser-induced fluorescence technique was used to visualize the flow structure behind two inline circular cylinders of identical diameter d. The downstream cylinder was forced to oscillate harmonically at the amplitude of $0.5d$ and the frequency ratio $f_e/f_s = 1.8$, where f_e is the oscillation frequency of the downstream cylinder and f_s is the vortex shedding frequency from an isolated stationary cylinder. The investigation was conducted for the cylinder center-to-center spacing $L/d = 2.5 \sim 4.5$. Two flow regimes have been identified, i.e. the 'single-cylinder shedding regime' at $L/d \leq 3.5$ and the 'two-cylinder shedding regime' at $L/d > 3.5$. At small L/d, the upstream cylinder does not appear to shed vortices; vortices are symmetrically formed behind the downstream cylinder as a result of interactions between the shear layers separated from the upstream cylinder and the oscillation of the downstream cylinder. This is drastically different from that behind two stationary cylinders at $L/d \leq 3.5$, where vortices are shed alternately from the downstream cylinder only. At $L/d = 4.5$, both upstream and downstream cylinders shed vortices. This is true with or without the oscillation of the downstream cylinder. The flow structure is now totally different from that at $L/d = 3.5$. The vortices are shed alternately from the upstream cylinder; a staggered spatial arrangement of vortices occurs behind the downstream cylinder.

Keywords : Interference, LIF, Tandem, Streamwise Oscillation, Wake.

1. Introduction

Flow behind multiple structures in a cross flow is frequently seen in engineering. Examples include heat exchangers, offshore structures, power transmission lines and high-rise buildings. When the Reynolds number exceeds a critical value, the boundary layer separates from a structure in a flip-flop manner. The alternate flow separation from the structure in turn produces a fluid excitation force, which may induce a structural oscillation up to a significant magnitude. This oscillation will surely influence the flow behind the structure and even flow upstream. It is therefore of both fundamental and practical interests to investigate how an oscillating cylinder alter an upstream cylinder wake.

The simplest case of the multiple structures is a two-cylinder system, which may have side-by-side, in-tandem or staggered arrangements. The structural oscillation can be transverse or streamwise or a combination of both. Previous studies mostly focused on the transverse oscillation of a single or two cylinders (e.g. Bearman, 1984; Williamson and Roshko, 1988; Ongoren and Rockwell, 1988a; Griffin and Hall, 1991; Zhou et al., 2001; Lai et al., 2003; Zhang et al., 2003). This is perhaps because the lift force on a structure is in many cases, say in an isolated cylinder case (e.g. Chen, 1987), one order of magnitude larger than the drag force. Subsequently the lateral structural oscillation prevails against that in the streamwise direction. However, the drag force is also significant; it could even exceed the lift, in particular in the context of multiple cylinders. There have been relatively few studies involving a streamwise oscillating cylinder in a cross flow.

The characterizations of the wake vortex patterns complement study of the unsteady loading on a cylinder oscillating in the in-line direction at small amplitude, addressed experimentally by Tanida, Okajima and Watanabe (1973). Griffin and Ramberg (1976) studied the vortex formation around an isolated cylinder, which oscillated at small amplitude in the streamwise direction, at the onset of 'lock-on'. Here, lock-on refers to the situation where the vortex shedding frequency coincides with that of structural oscillation. Ongoren and Rockwell (1988b) investigated the flow patterns behind a cylinder oscillating in the streamwise direction at the oscillation amplitude $A/d = 0.13$ and the frequency ratio $f_e/f_s = 0.5 \sim 4.0$, where f_e is the oscillation or excitation frequency of the downstream cylinder and f_s is the vortex shedding frequency of an isolated stationary cylinder. Two basic modes of vortex formation were identified, i.e. the symmetrical (in-phase) and the anti-symmetrical (out of phase) vortex formation from either side of the cylinder. Li et al. (1992) conducted a direct numerical simulation (DNS) of an oscillating cylinder in the wake of an upstream cylinder. They identified two flow regimes. In the 'vortex formation regime' at large cylinder-to-cylinder center spacing L/d, vortex streets developed behind both cylinders. The street generated by the upstream cylinder was important compared to the forced oscillation and dominated the flow, resulting in a very small zone of synchronization. In the 'vortex suppression regime' at small L/d, this street became weak and had little effect on the downstream cylinder wake. Recently, Cetiner and Rockwell (2001) studied the lock-on state of a streamwise oscillating cylinder in a cross flow ($f_e/f_s = 0.5 \sim 3.0$). It was found that the time-dependent transverse force was phase-locked to the cylinder motion and the vortex system occurred both upstream and downstream of the cylinder. In spite of these studies, the possible impact of the streamwise structural oscillation on the flow field is far from complete. For example, how would the flow be affected if a streamwise oscillating cylinder is immersed in a stationary-cylinder wake? What is the dominant flow structure when the cylinder oscillation is locked on with the vortex shedding? How would the flow structure change in the absence of the lock-on phenomenon? These issues are interesting and motivate the present investigation.

This work aims to investigate interference between a stationary cylinder and a downstream streamwise oscillating cylinder, specifically, to address the issues raised above. The interference is possibly affected by a number of dimensionless parameters, including L/d, f_e/f_s and the Reynolds number Re. The investigation will focus on the effect of L/d on the flow structure due to limitation on pages. A laser-induced fluorescence (LIF) technique is employed to visualize the flow structure behind the stationary and the downstream oscillating cylinder. The flow structure is compared with that behind two stationary cylinders.

2. Experimental Details

The LIF measurements were carried out in a water tunnel, as described in Zhang and Zhou (2001). The tunnel has a square working section (0.15m × 0.15m) of 0.5m long. The working section is made up of four 0.02m thick perspex panels. A regulator valve controls the flow speed and the maximum velocity attained is about 0.32m/s in the working section. The free stream turbulence intensity is estimated to be about 0.5%.

Two inline acrylic circular tubes of an identical diameter $d = 0.01$ *m* were cantilever-supported in the horizontal mid-plane of the working section. The gap between the cylinder free end and the working section wall was about 0.5 mm, thus resulting in a blockage of about 7%. The downstream cylinder, driven by a D.C. motor through a linkage system, oscillated harmonically in the streamwise direction. The D. C. motor was controlled by a microcomputer so that the oscillating frequency of the cylinder could be precisely obtained. The structural oscillation amplitude was fixed at $A/d = 0.5$ and f_e/f_s investigated were 0 and 1.8. Dye (Rhodamine 6G 99%), which has a faint red color and becomes metallic green when excited by laser, was introduced through one injection pinhole (0.25 mm) located at the mid-span of each cylinder at 90°, both clockwise and anti-clockwise, respectively, from the leading stagnation point. The injection of dye was adjusted by the relative height between dye and pinhole, and a valve. A thin laser sheet, which was generated by laser beam sweeping, provided illumination over $0 \le x/d \le 10$ at the vertical mid-plane of the working section. A Spectra-Physics Stabilite 2017 Argon Ion laser source with a maximum power output of 4 watts was used to generate the laser beam. The dye-marked vortex streets were recorded by a professional digital video camcorder (JVC GY-DV500E) at a framing rate of 25 frames per second. Measurements were carried out for $L/d = 2.5$, 3.5 and 4.5 and Re ($\equiv \frac{U_\infty d}{\nu}$) = 300, where U_∞ is the free-stream velocity and ν is the kinematic viscosity.

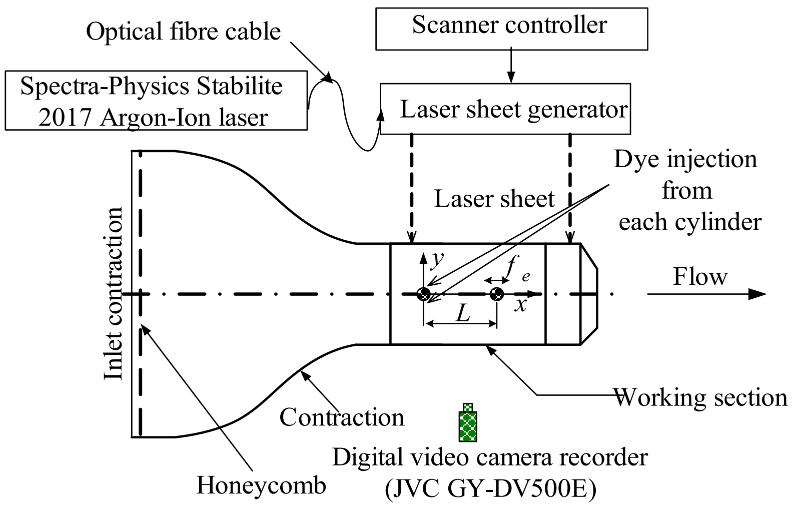

Fig.1. Experimental setup for Laser-illuminated flow visualization in the water tunnel.

3. Flow Structure behind Stationary Cylinders

Zdravkovich (1987) categorized the flow around two inline stationary cylinders into three flow regimes for $L/d < 6$. At $L/d < 1.2 \sim 1.8$, the free shear layers from the upstream cylinder do not reattach on the downstream cylinder; they roll up to form the vortex street behind the downstream cylinder. For $1.2 \sim 1.8 < L/d < 3.4 \sim 3.8$, there is again no vortex shedding from the upstream cylinder, but the free shear layers from the upstream cylinder reattach on the downstream cylinder. A vortex street is generated behind the downstream cylinder. As L/d exceeds $3.4 \sim 3.8$, i.e. the critical spacing, vortices are generated from both cylinders. Furthermore, the shedding of vortices from the two cylinders is synchronized. A binary vortex street is developed behind the downstream cylinder. Igarashi (1981) proposed a similar classification. Nevertheless, the LIF measurements were conducted presently for two stationary cylinders of $L/d = 2.5$ and 4.5, which covered two flow regimes, to provide data for comparison with that when the downstream cylinder oscillates. Experiments were

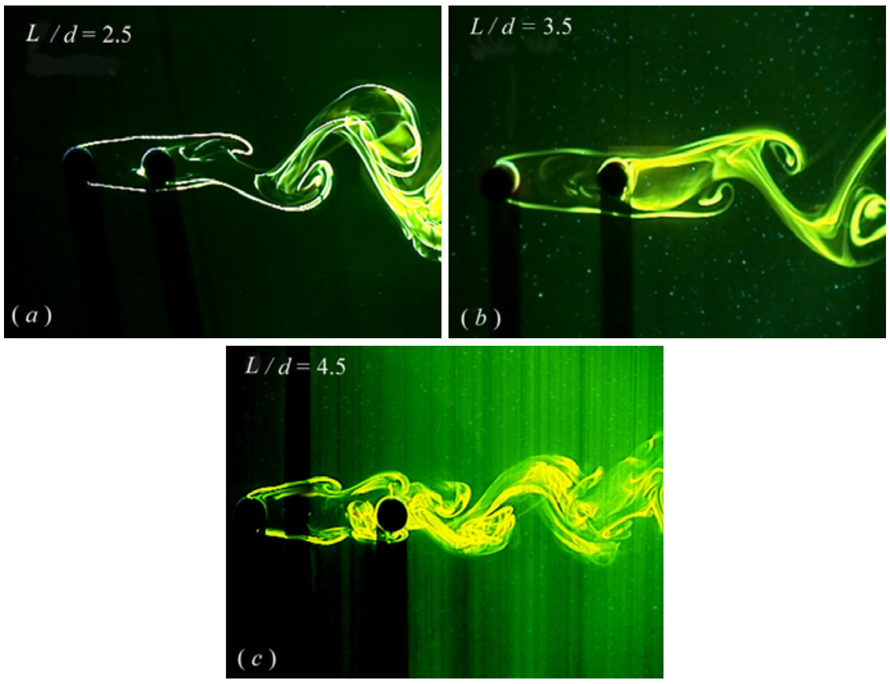

Fig. 2. Typical flow structures behind two inline stationary cylinders at various *L/d* (f_e/f_s = 0, Re = 300).

also carried out at *L/d* = 3.5 in order to examine the flow structure near the critical *L/d*.

Figure 2 shows typical photographs from the LIF flow visualization for *L/d* = 2.5, 3.5 and 4.5 at Re = 300. Evidently, vortices are shed only from the downstream cylinder for *L/d* = 2.5 and 3.5 since the two *L/d* values fall into the same flow regime. At *L/d* = 4.5, vortices are shed from both cylinders. The observation agrees with previous reports (e.g. Igarashi 1981; Zdravkovich 1987).

4. Downstream Cylinder Oscillation Effect on the Flow Structure

When the downstream cylinder oscillates, the flow structure is dependent on not only *L/d* but also Re, f_e/f_s and *A/d*. This section is largely devoted to the flow behaviors at different *L/d*. The effect of other parameters will be reported in a more extensive paper. It has been seen that in the case of stationary cylinders at *L/d* = 3.5 and Re = 300, vortices are alternately shed from the downstream cylinder but not from the upstream cylinder. This is completely different when the downstream cylinder oscillates.

Figure 3 presents the sequential photographs of various phases in a typical cycle of the cylinder oscillation for *L/d* = 2.5, f_e/f_s = 1.8 and Re = 300. The specific phases are indicated in a drawing where t and X represent time and the streamwise displacement from the reference position (X = 0) of the downstream cylinder, respectively. The maximum displacement A is 0.5d. Note that the shear layers from the upstream cylinder now appear rolling up to form vortices near the downstream cylinder probably as a result of interaction between the shear layers and the oscillation of the downstream cylinder. Furthermore, the vortices from both cylinders occur symmetrically about the flow centerline. The symmetrical vortex street behind the downstream cylinder does not seem to be stable though; it quickly collapsed, and a staggered vortex street emerged downstream. The frequencies of the vortices shed from the cylinders were estimated by means of counting consecutive vortices (about 20 pairs) for a certain period. It has been verified that the vortex shedding frequency, $f_{s,d}$ from the downstream cylinder is identical to that, $f_{s,u}$, from the upstream cylinder, both locking on with f_e. A similar observation is made for *L/d* = 3.5 (Fig. 4).

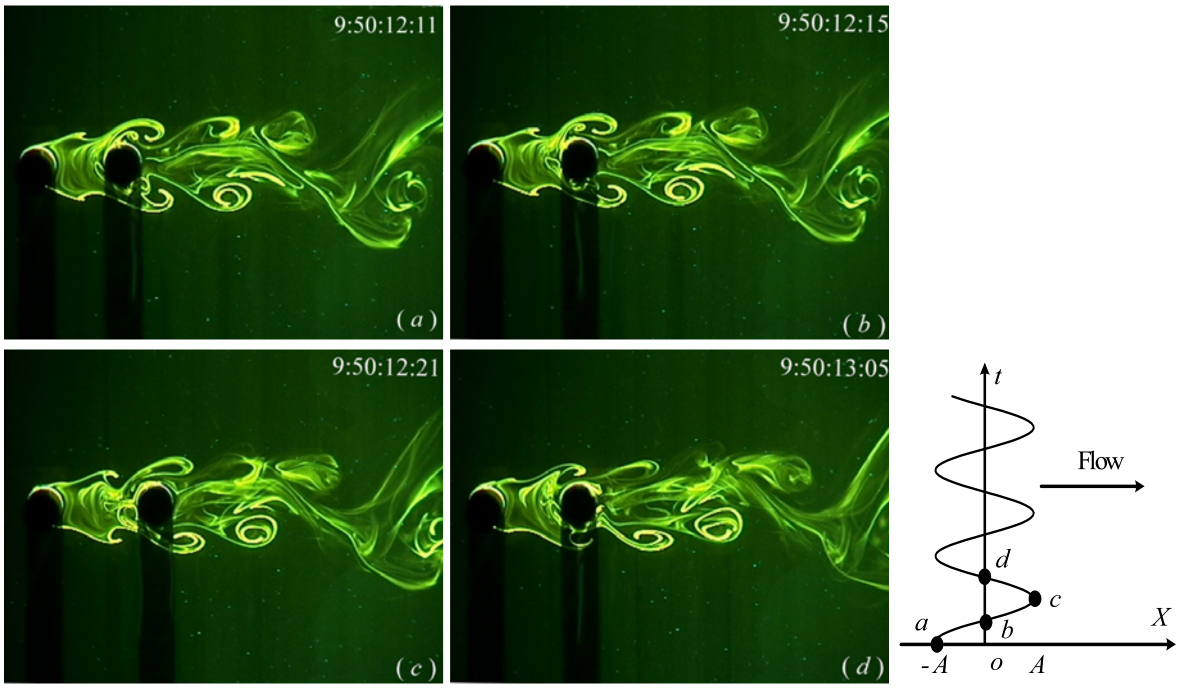

Fig. 3. Symmetric vortex formation from two inline cylinders at *L/d* = 2.5 in one oscillation cycle (the downstream cylinder oscillates at *A/d* = 0.5). Re = 300 and f_e/f_s = 1.8.

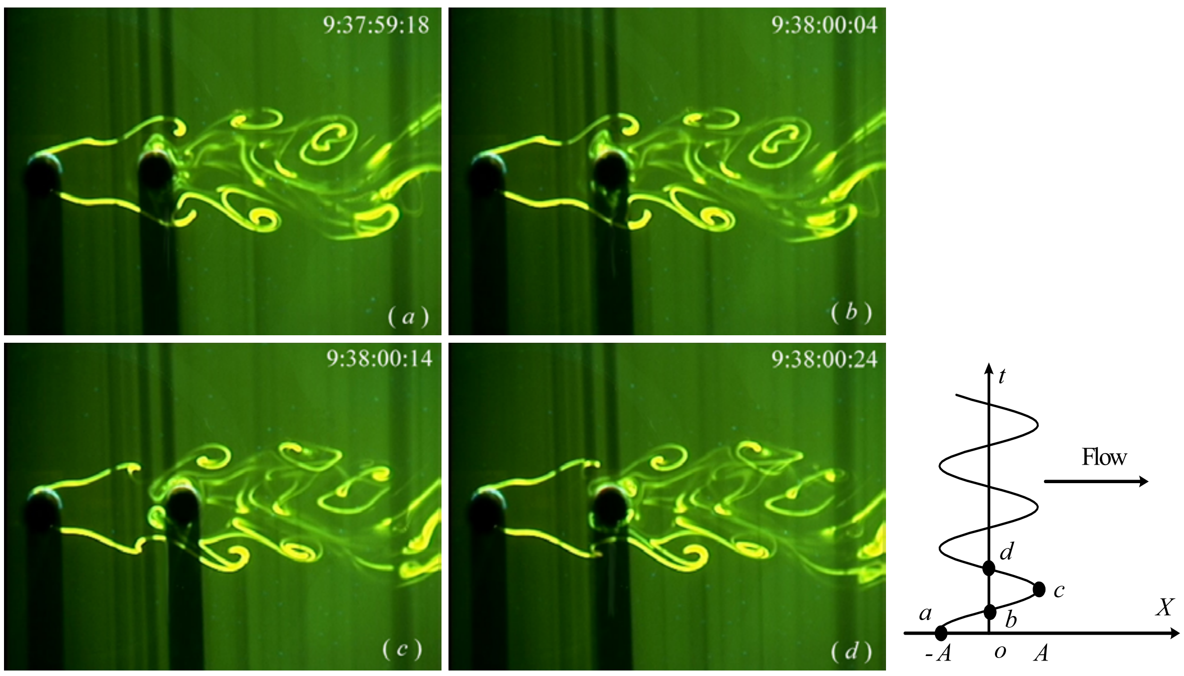

Fig. 4. Symmetric vortex formation from two inline cylinders at *L/d* = 3.5 in one oscillation cycle (the downstream cylinder oscillates at *A/d* = 0.5). Re=300 and f_e/f_s = 1.8.

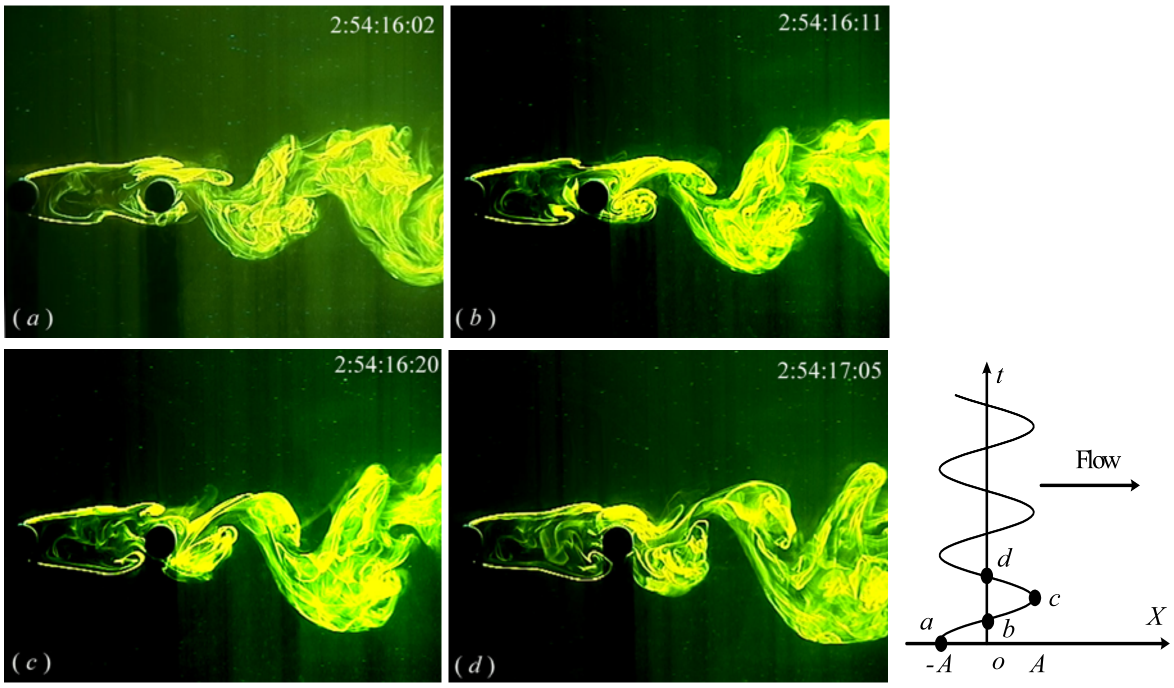

Fig. 5 Anti-symmetric vortex formation from two inline cylinders at L/d = 4.5 (downstream cylinder oscillates at A/d = 0.5). Re = 300 and f_e/f_s = 1.8.

As L/d reaches 4.5, both upstream and downstream cylinder shed vortices (Fig. 5), rather similar to the case of the stationary cylinders. The wake width however increases substantially. The flow structure is totally different from that when $L/d \leq 3.5$. The vortices are shed alternately from each side of either cylinder; a staggered arrangement of vortices occurs behind the downstream cylinder. The vortex shedding frequency of the downstream cylinder is still locked on the frequency of oscillation. However, the vortex shedding frequency of the upstream cylinder is only a half of that of the downstream cylinder.

When a streamwise oscillating cylinder is placed in the near wake of a stationary cylinder, the excitation motion by the oscillating cylinder may dominate, in particular at a small L/d. Subsequently the free shear layers separated from the upstream cylinder as well as those from the downstream cylinder may lock on with the downstream cylinder oscillation. Therefore, we see a symmetrical vortex shedding from the downstream cylinder (Figs. 3 and 4). On the other hand, for a large L/d, the excitation of the oscillating cylinder may not be strong enough to alter vortex shedding from the upstream cylinder. Thus, the classical vortex shedding occurs, namely, vortices are shed alternately from either side of the upstream cylinder. The spatially anti-symmetrically arranged vortices subsequently impose an alternate excitation force on the downstream oscillating cylinder, which suppresses the symmetrical vortex shedding, induces alternate vortex shedding. The scenario corroborates Li et al. (1992)'s finding that at a large L/d, the street generated by the upstream cylinder was important compared to the forced oscillation and dominated the flow, but at small L/d this street became weak and had little effect on the downstream cylinder wake.

5. Conclusion

The interference between the wakes of a stationary cylinder and an inline downstream cylinder that oscillates in the streamwise direction has been investigated based on flow-visualization. With the oscillation of the downstream cylinder fixed at A/d = 0.5 and f_e/f_s = 1.8, the investigation focuses on the effect of L/d on the flow structure. Two flow regimes have been identified, i.e. the 'single-cylinder shedding regime' and 'two-cylinder shedding regime'. At a small L/d, the streamwise oscillation of the downstream cylinder dominates. The shear layers separated from the upstream cylinder do not have sufficient space to develop into vortices, while those from the downstream cylinder are shed symmetrically to form a symmetrical vortex street. The flow structure is in distinct contrast with the case of two stationary cylinders where vortices are shed alternately from the downstream cylinder. As L/d increases, the oscillation effect on the shear layer separation from upstream cylinder impairs so that the alternate vortex shedding resumes. The anti-symmetrically arranged vortices generated by the upstream cylinder may subsequently impose an alternate excitation on the downstream oscillating cylinder, which suppresses the symmetrical vortex shedding, inducing alternate shedding.

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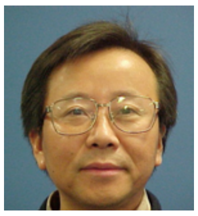

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