Vibration Initiation of a Cylinder in the Wake of Another

B. Qin, Y. Liu, Md. Mahbub Alam and Y. Zhou

Abstract This paper presents the cross-flow induced vibration response of a both-end-spring-mounted circular cylinder (diameter *D*) placed in the wake of a rigid circular cylinder of a smaller diameter *d*. The cylinder diameter ratio *d/D* and the spacing ratio *L/d* are 0.4 and 2.0, respectively, where *L* is the distance between the center of the upstream cylinder to the forward stagnation point of the downstream cylinder. The focus is given to investigate how the initiation of the vibration occurs, gaining insight into physics in the transition period where the cylinder starts to vibrate. The transition period can be divided into pre-initial, initial and late transitions. The role of added mass, added damping and work done in the transition process is studied in detail.

Keywords Flow induced vibration · Vibration initiation · Added mass
Energy transfer

1 Introduction

Previous investigations have mostly been concerned with two rigid circular cylinders in tandem [1]. Bokaian and Geoola [2] surveyed flow-induced vibration (FIV) of a cylinder immersed in the wake of a fixed identical upstream cylinder, where the downstream cylinder is free to oscillate laterally. The FIV of a pair of cylinders in tandem has been investigated by Assi et al. [3, 4] for $L/d \geq 4.0$ at $m^* \zeta = 0.018$, where the mechanism of the origin of the downstream cylinder lift forces has been elucidated. Divergent vibration was observed for $L/d = 4.0$ –6.0 with increasing reduced velocity U_r, and constant vibration amplitude was for

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$L/d > 6.0$. A review of the literature indicates that previous investigations have mostly been with two identical diameter cylinders at a low mass-damping $m^* \zeta$ value, where m^* is the mass ratio and ζ is the damping ratio. A systematic study on the influence of the upstream cylinder size (diameter d) on FIV of a downstream cylinder of diameter D has been documented by Alam et al. [5] at $d/D = 0.2$–1.0 and $L/d = 1.0$–5.5. Violent vibrations were generated for $d/D = 0.2$–0.8, $L/d < 1.5$–5.5 depending on d/D. Many issues were unaddressed. For example, how the vibration is initiated? What are the parameters responsible for the instability to generate the vibration? What are their roles? The objectives of the present investigations are to investigate (i) the initiation of vibration and characteristics during the generation of the vibration, and (ii) the roles of added damping, added mass and energy transfer when the cylinder starts to vibrate. $d/D = 0.4$ and $L/d = 2.0$ are chosen for the detailed investigation.

2 Experimental Details

FIV experiments were carried out in a low-speed, closed-circuit wind tunnel. A schematic diagram of the experimental setup is shown in Fig. 1. Investigation was made for $d/D = 0.4$ and $L/d = 2.0$ where violent vibration is erupted. The upstream cylinder was fixed at both ends and the downstream cylinder was allowed to vibrate in the transverse direction only. A standard laser vibrometer was used to measure the vibration displacement (Y) and vibration frequency (f_{osc}) of the downstream cylinder. The ζ, $m^* \zeta$, and natural frequency of the cylinder (f_n) were estimated to be 0.043, 15.05, and 10.23 Hz, respectively. Connecting both pressure scanner and laser vibrometer systems to the same data-acquisition computer enabled simultaneous measurements of lift force and displacement.

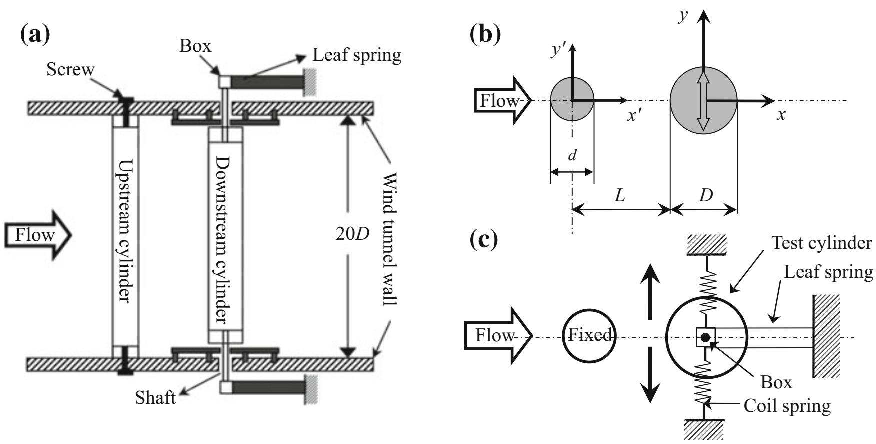

Fig. 1 **a** Experimental setup, **b** definition of symbols, **c** the test cylinder support system

3 Results and Discussion

3.1 Force and Vibration Characteristics

For two tandem cylinders with $d/D < 1$, VE (vortex excitation) is generated for the downstream cylinder at $U_r \approx 5.0$ and a violent vibration divergent with increasing U_r is unveiled at larger U_r, which is excited by the switching gap shear layers from one side to the other of the downstream cylinder [5]. Presently $U_r = 41.4$ corresponding to $A/D = 0.48$ is chosen to investigate the violent vibration initiation.

Two scenarios are examined to investigate the process when the cylinder vibration starts and grows in amplitude. (I) The flow is increased continuously from $U_r =$ (arbitrary) to a value 41.4 and then remains constant. The velocity was increased at a rate of 0.84 m/s/T_n, where $T_n = 1/f_n$. (II) Given a flow that is adequate to produce a large amplitude vibration ($U_r = 41.4$), the cylinder is kept fixed and then suddenly released. In both cases, Y_0/D grows from zero to its stable value, where Y_0 is the displacement amplitude. Time histories of Y/D, lift force coefficient C_L, 20 Hz low-pass-filtered C_L, and f_{osc}/f_n in the transition process for cases I and II are presented in Fig. 2, which is characterized by three stages. In the pre-initial stage, Y_0/D is very small and lift force coefficient C_L is dominated by the fluctuation at the vortex shedding frequency. Meanwhile, f_{osc}/f_n grows gradually. In the initial transition stage, Y_0/D grows rapidly (positive curvature), accompanied by an

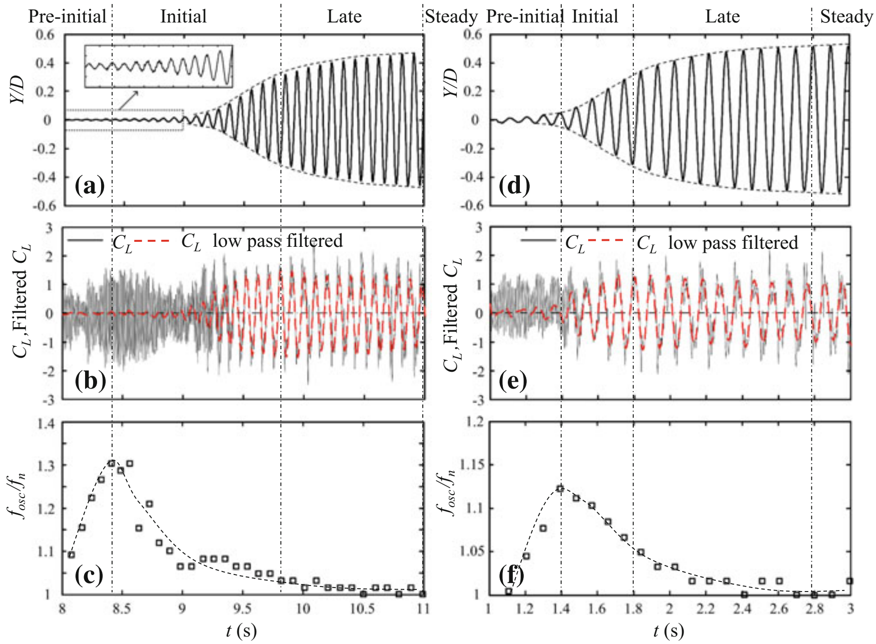

Fig. 2 Time histories of Y/D, C_L and f_{osc}/f_n in the transition process for cases I (**a**–**c**) and II (**d**–**f**). Dashed red lines in (**b**) and (**e**) are 20 Hz low-pass-filtered C_L

exponential rise in C_L amplitude. C_L fluctuation at the shedding frequency weakens and that at the oscillation frequency grows. Meanwhile, f_{osc}/f_n drops. In the late transition stage, the growth in Y_0/D slows down (negative curvature), C_L is dominated by cylinder oscillation frequency and filtered C_L amplitude decreases, along with reduced f_{osc}/f_n.

3.2 *Energy Transfer and Added Mass*

Figure 3a, d shows the variations of energy transferred from the fluid to the cylinder motion W_f, energy dissipated by the structural damping W_d, and total energy transfer W_t ($=W_f + W_d$) calculated over one period. W_f and W_d rise and decline, respectively, in the initial and late transitions, and become invariant after the late transition. W_t grows rapidly in the initial transition regime, reaching a maximum before declining in the late transition regime. $W_t > 0$ means that the energy transferred from the fluid to cylinder is larger than the energy dissipated through the structural damper. Therefore, the excess energy is used to enlarge Y_0/D in the initial regime with $W_t > 0$. In the late transition regime, the slowing down of Y_0/D growth is complemented by W_t declination, essentially $W_t > 0$. As Y_0/D becomes constant, $W_t \approx 0$.

Finally, added mass ratio m_a^* and added (or flow-induced) damping ratio ζ_a variations from estimated C_L in phase with acceleration ($\ddot{Y}$) and velocity ($\ddot{Y}$),

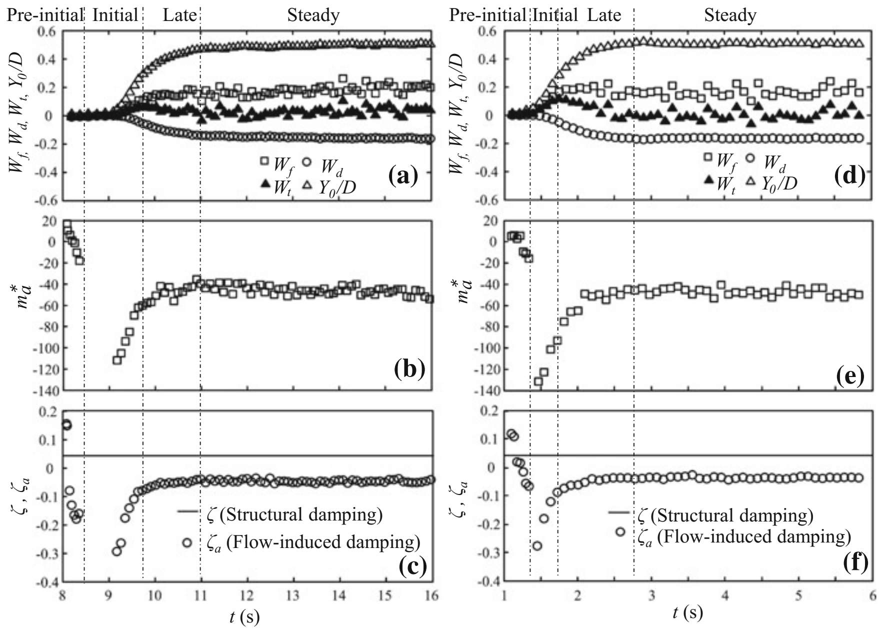

Fig. 3 Time histories of W_f, W_d, W_t, Y_0/D, m_a^* and ζ_a in each period: (**a**–**c**) case I, (**d**–**f**) case II

respectively, are presented in Fig. 3b, c, e, f. For case I, m_a^* and ζ_a are based on the shedding frequency in the pre-initial regime, and on the vibration frequency for other regimes. Interestingly, both m_a^* and ζ_a being positive at $t = 8$ s experiences a drastic drop in the pre-initial regime. It may be inferred that the vibration is initiated by m_a^* and ζ_a being negative at the shedding frequency. At $t = 8.4$–9.0 s, both added mass and added damping cannot be calculated. Then at $t > 9.0$ s, m_a^* and ζ_a experience rapid increases in the initial transition and mild increases in the late transition regime, resulting in a reduced f_{osc}/f_n (Fig. 2c). They attenuate in the steady regime where $m_a^* \approx -47$ and $\zeta_a \approx -0.043$ that is equal in magnitude of the structural damping ζ, i.e., $\zeta + \zeta_a = 0$ (Fig. 3c). A similar observation is made for case II (Fig. 3e, f). Thus, it can be concluded that during the increase of the vibration amplitude, the cylinder sustains an effective negative damping ratio ($\zeta + \zeta_a < 0$), while at the stable vibration amplitude, $\zeta + \zeta_a = 0$.

4 Conclusions

The transition period can be divided into pre-initial, initial and late transitions. In the pre-initial regime, Y_0/D is very small, C_L is dominated by the vortex shedding frequency, f_{osc}/f_n augments, W_t is negligible, and ζ_a and m_a^* both plummet. The Y_0/D increases in the initial transition, with C_L amplitude soaring exponentially, f_{osc}/f_n declining, and both ζ_a and m_a^* escalating. W_t grows rapidly, reaching a maximum before declining in the late transition regime. The growth of W_t thus corresponds to that of Y_0/D. On the other hand, the increase in Y_0/D occurring at a negative curvature characterizes the late transition where C_L amplitude declines, f_{osc}/f_n wanes, and both ζ_a and m_a^* keep rising very slowly. The slowing down (negative curvature) of Y_0/D growth is complemented by W_t declination, essentially $W_t > 0$. As Y_0/D becomes constant, $W_t \approx 0$. The natural vortex shedding becoming dominant in pre-initial transition regime initiates the vibration, both shedding and oscillation frequencies in C_L play role in the initial transition regime, and oscillation frequency takes control in the late transition regime.

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