FLOW-INDUCED INSTABILITY OF A CANTILEVER CYLINDER IN WAKES

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ABSTRACT

This paper presents an investigation on free vibrations of a cantilever-supported circular cylinder of diameter D placed in the wake of another fixed cylinder of diameter d. While D was kept fixed, d was varied as d/D = 0.24, 0.4, 0.6, 0.8, 1.0. The spacing ratio L/d was changed from 1.0 to 5.5, where L is the distance between the center of the upstream cylinder and the forward stagnation point of the downstream cylinder. Flow-induced vibration amplitude, lift force and vortex shedding frequency were measured. A map of vibration regime and hysteresis in vibration amplitude is presented on d/D - L/d plane. The cylinder is found to be susceptible to voilent vibration with an increase in reduced flow velocity U_r at a small L/d or d/D. The increase in the vibration amplitude is accompanied by an increased energy transfer from the flowing fluid to the cylinder. The increased energy transfer is compensated by an increased lift force amplitude. The wake behind the vibrating cylinder undergoes two different scales of vortices associated with natural vortex shedding frequency and vibration frequency, respectively. The vortices associated with the natural shedding frequency decay rapidly with x/D, while those associated with the other grows upto x/D = 20 and then experience a natural decay.

INTRODUCTION

The study of vortex induced vibration of circular cylinders has a long history. An obvious reason for the interest is extensive use of circular cylinder in various engineering fields. Most structures on land and in the ocean are in groups and subjected to fluid flow, such as heat-exchanger tubes, risers and multiple chimney stacks, etc. Two cylinders in tandem represent a good model and the knowledge of the flow around the two cylinders is insightful for understanding that around more structures. Most of the previous investigations have been performed on two fixed circular cylinders in tandem, focusing on flow structures generated, forces acting on them, Strouhal frequencies, etc., (Alam *et al*. 2003, Alam and Zhou 2007). Bokaian and Geoola (1984) investigated two identical diameter cylinders where the upstream cylinder is fixed and the downstream one is both-end-spring-mounted (two-dimensional model) and free to vibrate in the cross-flow direction only, over L/d = 0.59 - 4.5, reduced velocity U_r (= U_∞/Df_n) = 3.8 - 10, where U_∞ is the free-stream velocity and f_n is the natural frequency of the cylinder system. The investigated ranges of L/d and mass-damping parameter $m^*\zeta$ were 0.59 - 4.5 and 0.018 - 0.2, respectively, where m^* is the mass ratio and ζ is the damping ratio. It was found that depending on L/d the downstream cylinder exhibited a galloping (L/d = 0.59), or a combined vortex excitation (VE) and galloping (L/d = 1.0), or separated VE and galloping ($1.5 \le L/d \le 2.5$) or VE (L/d > 2.5). Kim *et al*. (2009a, b) investigated the flow-induced vibration characteristics of two identical circular cylinders, two-dimensional models, in tandem arrangement for L/d = 0.6 - 3.7, U_r = 1.5 - 26 and $m^*\zeta$ = 0.65. Assi et al. (2013) examined vibration of the downstream cylinder for $L/d \ge 4.0$ at mass-dampping ratio $m^*\zeta$ = 0.013. A detailed survey of research relating to flow-induced response of tandem cylinders suggests that previous investigations mostly were performed for (i) two cylinders of an identical diameter, (ii) two-dimensional model (spring mounted at both ends), and (iii) at a low $m^*\zeta$ value. The literatures mainly clarified L/d range where vortex-resonance or galloping persists. There does not seem to have a systematic study on flow-induced responses when the downstream cylinder is cantilevered and the upstream cylinder size (diameter) is changed.

The aim of present work is to examine the flow-induced response of a cantilever circular cylinder submerged in the wake of another of different diameters. Specific objectives are to (i) examine flow-induced response, (ii) investigate shear-layer/vortex interaction between the cylinders including vortex shedding process, (iii) measure lift force on the vibrating cylinder and estimate energy transfer between the fluid and cylinder, and (iv) study the downstream evolution of the wake.

EXPERIMENT AND METHODOLOGY

Experiments were conducted in a closed-circuit wind tunnel with a test section of 1.0×0.8×3.0 m. The turbulent intensity was less than 0.5%. The two cylinders were mounted in the horizontal mid plane of the test section. The upstream cylinder was fixed while the downstream cylinder was cantilever-mounted. Measurements were performed for d/D = 0.24, 0.4, 0.6, 0.8, 1.0, and L/d = 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 5.5, where L is the distance between the center of the upstream cylinder and the forward stagnation of the downstream cylinder. Figure 1 shows a schematic diagram of the experimental setup and the definitions of symbols and coordinates (x', y') and (x, y), with the origins defined at the upstream- and downstream-cylinder centers, respectively. The reduced flow-velocity U_r, based on D and freestream velocity, is varied from 4 to 80. The cylinder vibration amplitude is measured by using a laser vibrometer.

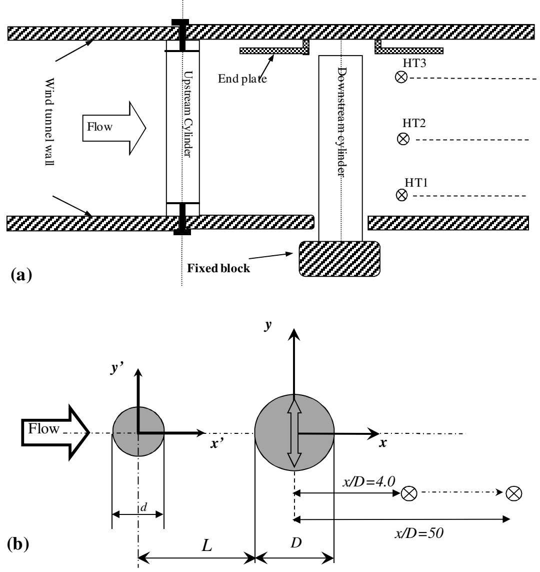

Figure 1. (a) Schematic diagram of experimental setup, (b) definitions of symbols.

Three hot wires as shown in Fig. 1 were used to measure natural vortex shedding frequencies. Furthermore, they were traversed along the streamwise direction to examine the wake evolution. The structural damping ratio ζ was estimated from the logarithmic decrement of the amplitude of vibration in still air, where the cylinder was given an initial displacement and then released to vibrate (Alam and Kim 2009). The natural frequency f_n was obtained by analyzing the power spectrum of the vibration signal. The mass-damping ratio $m^*\zeta$ and f_n are obtained as 7.5 and 11.72 Hz, respectively.

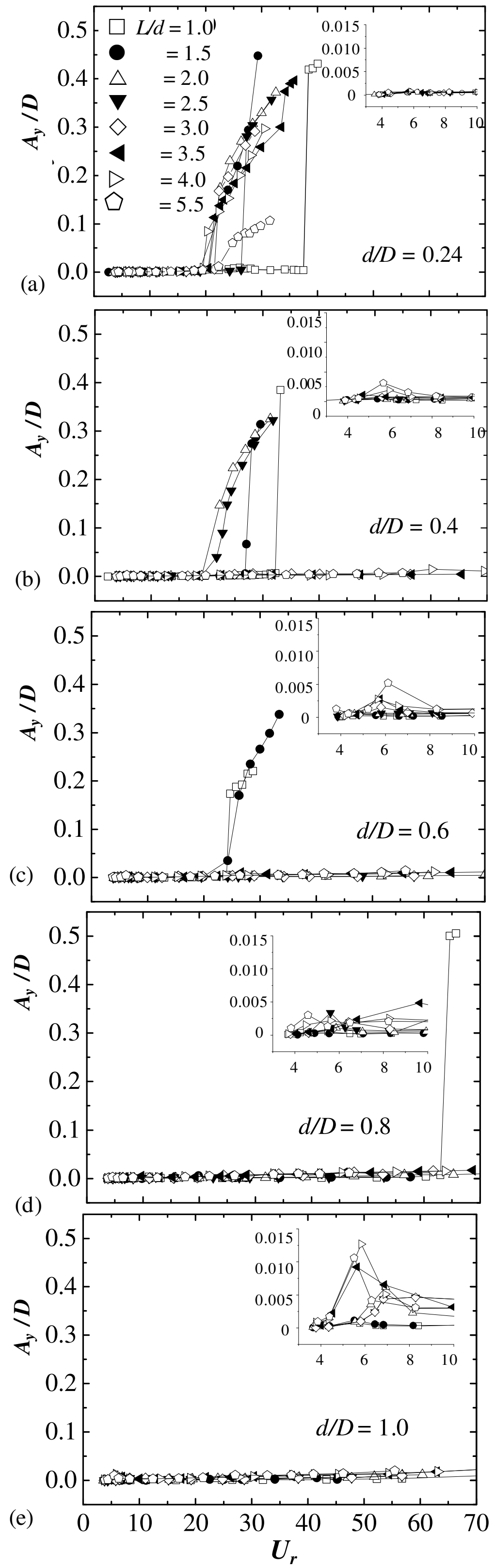

Figure 2. Dependence of A_y/D on U_r at (a) d/D = 0.24, (b) 0.4, (c) 0.6, (d) 0.8, (e) 1.0.

Instantaneous pressure distribution around the cylinder was measured using a pressure scanner, leading to an estimation of the lift force $F_L(t)$ as a function of time. The energy transfer E_f in one cycle of oscillation (displacement $y(t)$) is calculated as,

$$E_f = \int_t^{t+T} F_L(t)dy(t) \tag{1}$$

If $F_L(t)$ and $y(t)$ are assumed to be (but not exactly) sinusoidal (Morse and Williamson 2009), then E_f can be simplified as,

$$E_f = \pi A_L A_y \sin\phi, \tag{2}$$

where A_y is the amplitude of oscillation, A_L is the amplitude of lift force and ϕ is the phase angle between lift and displacement.

RESULTS AND DISCUSSION

Vibration Response

Fig. 2 shows the dependence of normalized vibration amplitudes A_y/D on U_r at d/D = 0.24, 0.4, 0.6, 0.8 and 1.0. At d/D = 0.24, the cylinder vibrates violently at all L/d examined for U_r > 19 - 38 (Fig. 2a). At d/D = 0.4, the violent vibration occurs at L/d = 1.0, 1.5, 2.0 and 2.5 for U_r > 32, 26, 20 and 20, respectively, while at a larger L/d ($\geq$ 3.0) the vibration does not occur (Fig. 2b). The violent vibration occurs only at L/d = 1.0 and 1.5 for d/D = 0.6 (Fig. 2c) and at L/d = 1.0 only for d/D = 0.8 (Fig. 2d). No vibration is generated for d/D = 1.0. Therefore, it indicates that a smaller d/D and a smaller L/d each can cause a higher instability of the flow. As d/D tends to be small, the upstream cylinder wakes narrows, and the shear-layer reattachment position on the downstream cylinder moves toward the front stagnation point. Hence the shear layer is more suspectiable to switch and inducing the vibration. Another interesting feature in the vibration responses is that the vibration amplitude grows rapidly at smaller L/d (particularly near the U_r where cylinder starts to vibrate) but rather mildly at a lager L/d. On the other hand, very tiny humps generated around $U_r \approx 6$ (see the insets) is the sign of vortex excitation (VE). Though the vibration at VE is small due to the remarkably high of $m^*\zeta$, it is relatively larger at a larger d/D or L/d.

Hysteresis in Vibration Response

Fig. 3 shows the typical vibration hysteresis at d/D = 0.4, L/d = 1.0 and d/D = 0.4, L/d = 2.5, with black and red symbols corresponding to U_r increasing and decreasing, respectively. Pronounced hysteresis in vibration amplitude is observed at L/d = 1.0 (Fig. 3a) but not at L/d = 2.5 (Fig. 3b). Note that the vibration amplitude shoots up for the former case (smaller L/d) when U_r is increased and drops monotonically when U_r is reduced. On the contrary, for the latter condition (larger L/d) where the vibration amplitude augments and diminishes monotonically with U_r increasing and decreasing, respectively, hysteresis in amplitude is absent. Taking into account other configurations (not shown), it is concluded that obvious hysteresis in the response is afoot for the cases where amplitude grows abruptly with increasing U_r, i.e., at smaller d/D or L/d. The range of U_r associated with the hysteresis was longer at smaller L/d; for example, for d/D = 0. 4, the hysteresis range of U_r = 20 -33 at L/d = 1.0 and U_r = 20 - 27 at L/d = 1.5; for d/D = 0.24, it was U_r = 20 - 38 at L/d = 1.0 and U_r = 20 - 23 at L/d = 3.0. A summary of vibration response and hysteresis can be presented in on a d/D - L/d plane shown in Fig. 4. What is reflected from the figure is that a smaller d/D or L/d corresponds to violent vibrations and a larger hysteresis.

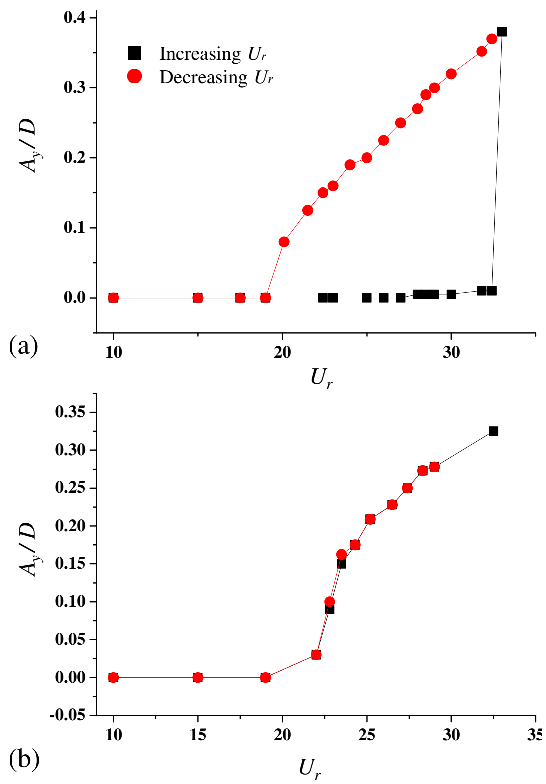

Figure 3. Typical vibration hysteretic response at (a) d/D = 0.4, L/d = 1.0, (b) d/D = 0.4, L/d = 2.5.

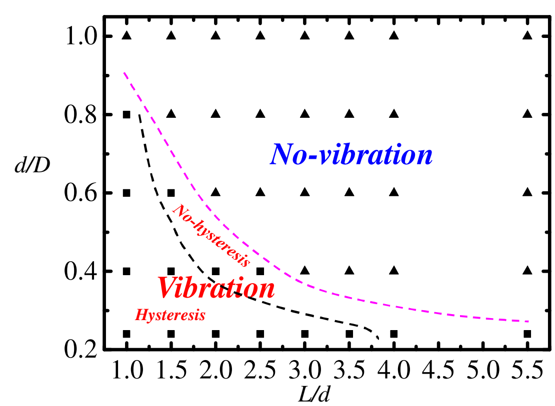

Figure 4. Vibration and hysteresis maps in d/D - L/d plane.

Energy Transfer between Fluid and Cylinder

Fig. 5 shows the dependence on U_r of ϕ, A_y/D, E_f and the amplitude of lift coefficient $C_{L\text{-}amplitude}$ at a representative d/D = 0.24, L/d = 2.5. With an increase in A_y/D from 0 to 0.26, ϕ augments from ≈ 85° to 122°, $C_{L\text{-}amplitude}$ shoots up from 0.2 to 0.95, and E_f grows from 0 to 0.15. Evidently, the increase in A_y results from an increase in E_f , while the latter is contributed by the increased $C_{L\text{-}amplitude}$.

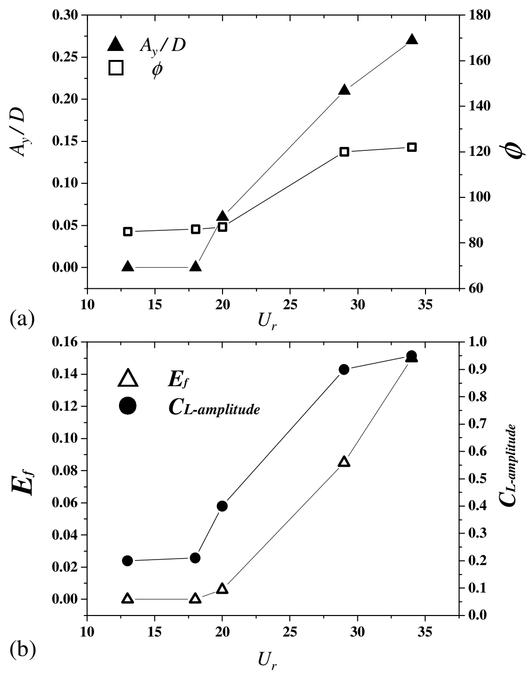

Figure 5. Dependence of (a) phase lag φ, vibration amplitude A_y, (b) energy transfer E_f , lift force coefficient amplitude $C_{L\text{-}amplitude}$ on U_r at d/D = 0.24, L/d = 2.5.

Wake Evolution

Fig. 6 shows the representative power spectra of fluctuating streamwise velocity obtained from the three hotwires (base, midspan and free-end) at d/D = 0.24, L/d = 4.0, U_r = 30 where the hotwire position x/D is traversed from 4 to 50 along the wake. Two peaks are observed in the power spectra at the free-end (Fig. 6a). One peak, stronger, corresponds to the vibration frequency f/f_n = 1.0 and the other, weaker, appearing at smaller x/D only, is the natural vortex shedding frequency. While the vortices associated with the natural shedding frequency decay rapidly with x/D, those associated with the other grow upto x/D = 20 and experince a natural decay, surviving in the x/D range examined.

Similar observation is made on the power spectra at the midspan. Again the peak at the vibration frequency heightens up to x/D = 20. Nevertheless, the shedding frequency peak at smaller x/D is now stronger than the vibration frequency peak (Fig. 6b), as the vibration amplitude is smaller at the midspan than the free-end. At the base, where the vibration amplitude is very small, the vibration frequency peak is very weak at smaller x/D, growing in the whole range of x/D examined, and the other, stronger at x/D < 8, decays rapidly. The observation suggests that only vortices associated with the vibration frequency dominate the wake at large x/D.

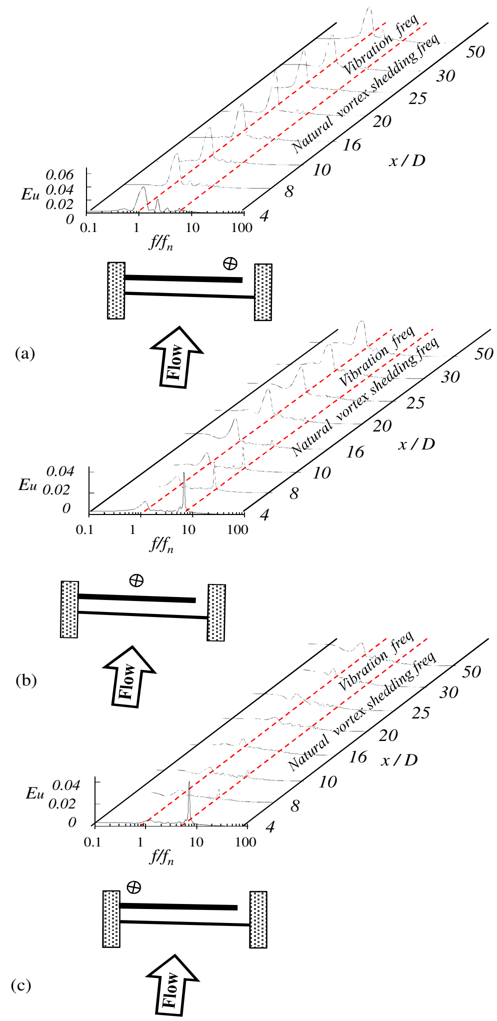

Figure 6. Power spectrum of streamwise velocity at d/D = 0.24, L/d = 4.0, U_r = 30 at (a) free-end, (b) mid-span, (c) base.

CONCLUSIONS

The cylinder vibrates violently for L/d = 1.0 - 5.5 at d/D = 0.24, L/d = 1.0 - 2.5 at d/D = 0.4, L/d = 1.0 - 1.5 at d/D = 0.6, and L/d = 1.0 at d/D = 0.8; the cylinder is susceptible to violent vibration at a smaller L/d or d/D. Apparent hysteresis in the vibration amplitude is observed for the configurations where the vibration amplitude shoots up with an increase in U_r.

The increase in amplitude is accompanied by an increased energy transfer from the flowing fluid to the cylinder. While the phase lag hovering around 90° does not contribute to the energy transfer, an increased lift-force amplitude is responsible for the increased energy transfer.

When the cylinder vibrates, two peaks are observed in the power spectral density function of hotwire-measured fluctuating velocity, corresponding to the natural vortex shedding and vibration frequencies, respectively. While the vortices associated with the natural shedding frequency decay rapidly with *x/D*, those associated with the other grow and then experience natural decay..

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