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Brief communication

Flow-induced vibration of a flexibly mounted circular cylinder in the proximity of a larger cylinder downstream

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Abstract

A flexibly mounted circular cylinder is placed upstream of a stationary cylinder twice as large. Flow-induced vibration response of the small cylinder is measured with the interfering cylinder placed at 57 relative locations. In most situations, reduced-amplitude vibration or even no vibration is observed. Lock-in resonance remains the dominant vibration behavior, but the reduced velocity of peak lock-in is found to shift to a value higher or lower than the isolated cylinder value, depending on the lateral separation between the two cylinders. When the flexible cylinder is located just in front of the large cylinder, galloping-type vibration of very large amplitude occurs at reduced velocities above 12. Mechanisms of flow-induced vibration are discussed with the aid of flow visualizations. The present study supplements a previous paper reporting amplified vibration of the flexible cylinder with the interfering cylinder placed in various upstream locations.

Keywords: Circular cylinder; Flow-induced vibration; Flow interference; Vortex shedding

1. Introduction

Flow-induced vibration of a circular cylinder is usually studied by exposing a flexibly mounted long circular cylinder in a uniform and smooth cross-flow. Large-amplitude lock-in vibration occurs at reduced velocities around 6 when the frequency of vortex shedding from the cylinder matches the natural frequency of the cylinder mounting system (Belvins, 1994). Presence of another cylinder in the vicinity can significantly modify the vibration response of the flexibly mounted cylinder. When a circular cylinder of the same size is placed upstream of the flexibly mounted cylinder, cross-flow vibration of the latter is found to occur over a wider range of reduced velocities (Tanida et al., 1973; King and Johns, 1976; Bokaian and Geoola, 1984; Assi et al., 2006).

In an earlier paper, the authors have investigated the modifications of vibration response of a flexibly mounted circular cylinder with interference from a twice-as-large cylinder placed upstream (Lam and To, 2003). In the staggered arrangement when the flexible cylinder is located near the edge of the large cylinder wake, large-amplitude vibration occurs over a broad range of reduced velocities and the vibration response characteristics are modified dramatically. The most severe vibration is found when the small cylinder is located just at the edge of the large cylinder wake. A gap

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flow passes intermittently and periodically between the two cylinders as the small cylinder vibrates in the lateral direction to allow and stop the gap flow. At larger lateral separations, flow always passes between the cylinders, but streamlines are bent towards the large cylinder wake. This results in a wider wake behind the small cylinder, making its lock-in resonance occur at a reduced velocity higher than 6. At small lateral separations, flow passes the two cylinders as a single body and lock-in resonance of the smaller cylinder occurs around reduced velocity 12 instead of 6. At this reduced velocity, vibration of the smaller cylinder resonates with the vortex shedding frequency of the larger cylinder. Similar resonance at reduced velocity 12, though at much lower amplitudes, is observed when the cylinders are in the tandem and near-tandem arrangement.

In this Brief Communication, we report results of experiments in which the flexibly mounted circular cylinder is located upstream of the larger cylinder. The results complement our earlier paper to cover all possible locations of the interfering cylinder. The flow is relevant to the engineering application of a slender and flexible prismatic structure like a tall chimney being located in the vicinity of a larger and stiffer structure. The effect of a downstream interfering cylinder on flow-induced vibration of a flexible cylinder has been reported in Gowda and Sreedharan (1994). That study covered part of the present configuration of an interfering cylinder twice the size of the flexible cylinder, but discussion was made mainly on other smaller sizes of the interfering cylinder being studied.

2. Experimental techniques

The experimental set-up and procedures were the same as in our previous study and have been described in Lam and To (2003). Two rigid aluminum cylinders, diameters $D = 3.2$ cm and $d = 1.6$ cm, were mounted horizontally in the wind tunnel test-section. They were bounded by two square end-plates 30 cm wide. The effective lengths of both cylinders were 32 cm and the cylinder aspect ratios were 10 and 20. The large cylinder was firmly mounted, while the small cylinder was elastically mounted. The smaller cylinder was made hollow, except for a 6 cm long short section at mid-span. Both ends of the short solid section were connected to a rigid frame outside the wind tunnel using tensioned piano

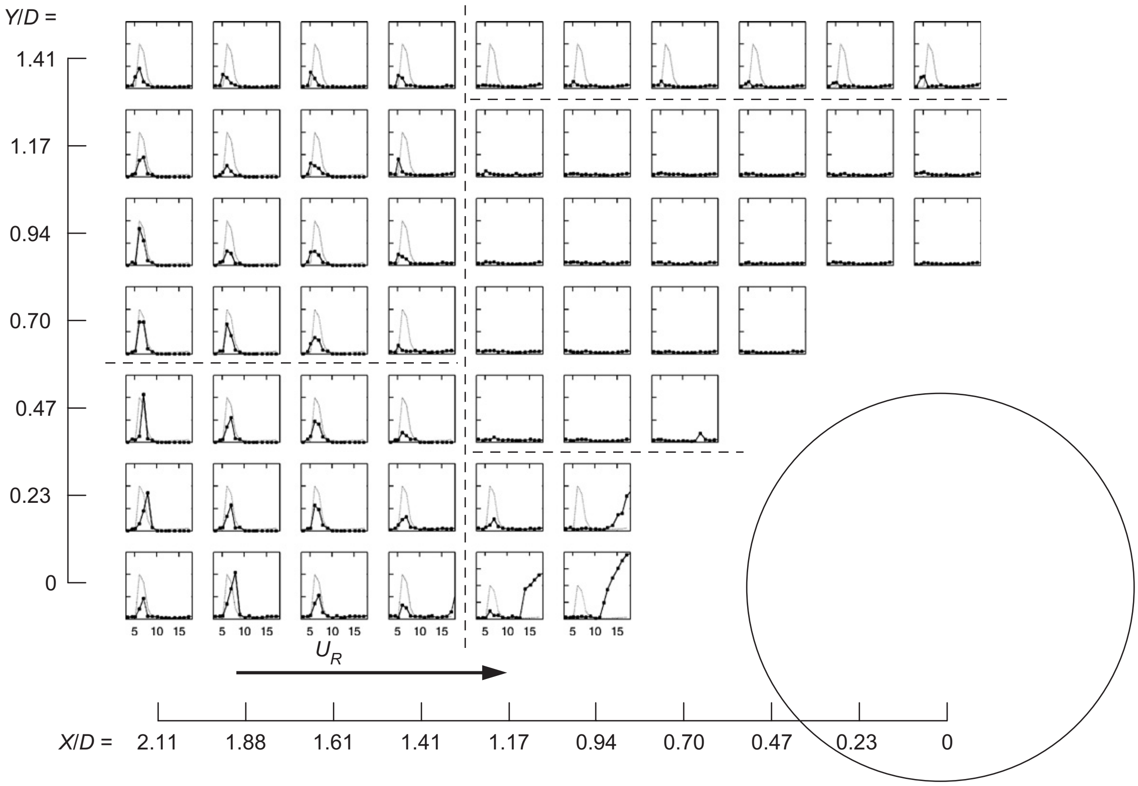

Fig. 1. Vibration response curves of a small flexible cylinder placed upstream, at (X, Y), of a large cylinder. Regions of different response behavior are noted.

wires. Together with a drag wire, the most dominant mode of cylinder vibration was the vertical up-and-down motion. The natural frequency of coherent vertical cross-flow vibration of the cylinder was measured at $f_n = 10.5\,\text{Hz}$ and the damping ratio was about 0.002. A large number of relative positions of the two cylinders were tested. We mainly report response characteristics of the small cylinder with the interfering large cylinder placed in 57 different downstream locations. Separations between the two cylinders covered seven values of lateral distances Y between centers of the two cylinders from $Y/D = 0$ to 1.41. The small cylinder was placed at 10 different upstream longitudinal distances X to the large cylinder from $X/D = 0$ to 2.11 (Fig. 1). Fourteen locations of the interfering cylinder have been studied in Gowda and Sreedharan (1994) with $X/D \leqslant 3.5$ and $Y/D < 1.5$. Our 57 cylinder positions cover 8 of those 14 locations.

At each separation between the two cylinders, experiments were performed at a number of free-stream velocities U corresponding to reduced velocities between $U_R = U/f_n d = 3$ and 20. The Reynolds number varied between $\text{Re} = Ud/v = 540$ and 3600. At each velocity, root-mean-square (r.m.s.) vibration amplitude, y_{rms}, of the small cylinder was measured with a non-contact displacement sensor (EMIC Corp.) after the cylinder vibration had become steady. As in Lam and To (2003), smoke visualizations were carried out at some selected flow cases. With a laser sheet and a laser shutter, visualizations were made at selected vibration positions of the small cylinder.

3. Results and discussion

Fig. 1 shows the vibration response of the flexible cylinder at 57 positions upstream of the large cylinder. Each response curve is a plot of normalized vibration amplitude against reduced velocity U_R. The normalized vibration amplitude is calculated by dividing y_{rms} by the largest r.m.s. vibration amplitude of the isolated small cylinder at peak lock-in. The response curve of the isolated cylinder is included in most plots for easy comparison. In the absence of the interfering cylinder, lock-in resonance of the isolated cylinder occurs between $U_R = 5$ and 8 with peak vibration amplitude occurring at $U_R = 6.1$.

Unlike the situation of the flexible cylinder being downstream in Lam and To (2003), flow-induced vibration of the small cylinder is generally suppressed by the interfering large cylinder placed downstream. Almost no vibration is induced at all velocities for Y/D between 0.47 and 1.17 and $X/D \leqslant 1.17$ (Fig. 1). Only at the close-tandem or near-tandem arrangement that large-amplitude vibration of the small cylinder is observed, but it only occurs at higher reduced velocities $U_R > 10$. In all other arrangement positions at large values of X/D or Y/D, vibration amplitude at lock-in is lower than the single cylinder case.

Results of the side-by-side arrangement have been discussed in Lam and To (2003). Lock-in vibration can only occur when the flexible cylinder is not too close to the large cylinder ($Y/D \geqslant 1.41$) and peak lock-in occurs at reduced velocity lower than $U_R = 6.1$ for the isolated cylinder. This is because, when flow passes between the cylinders, the streamlines are bent towards the small cylinder side. This leads to a reduction in the wake width behind the small cylinder and raises the vortex shedding frequency. A similar shift in the reduced velocity for peak lock-in has been reported in Gowda and Sreedharan (1994) and shown in Fig. 7 of that study.

When the flexible cylinder is upstream of the large cylinder and laterally separated from the latter at $Y/D \geqslant 0.70$, vibration response curves with characteristics similar to that of the side-by-side arrangement ($X/D = 0$, $Y/D \geqslant 1.41$) are observed at $X/D \geqslant 1.41$ (Fig. 1). Those curves show a similar lowering of the peak lock-in reduced velocity from the single isolated cylinder value of $U_R = 6.1$. Flow visualizations, not shown here, show that a wake region can be formed behind the small cylinder, but it has a smaller wake width than the isolated cylinder. This is due to the presence of the large cylinder downstream so that streamlines at one side of the small cylinder wake are bent inwards to flow over the large cylinder. At the largest lateral separation shown in Fig. 1, that is $Y/D = 1.41$, low-amplitude lock-in resonant vibration is observed around $U_R \approx 5$ for all longitudinal separations, but the amplitudes are much lower than the isolated cylinder case. Results at larger lateral separations, not shown here, show that the vibration response returns towards the isolated cylinder case.

Fig. 2(a) shows the smoke visualizations of flow past the cylinders at $(X/D, Y/D) = (1.17, 0.94)$ at which the flexible cylinder shows almost no vibration at all reduced velocities. Flow passes between the two cylinders in a large oblique direction, leaving a triangle-shaped wake behind the small cylinder. With this wake, vortex shedding cannot occur from the small cylinder. A similar flow pattern is observed for other arrangement positions in Fig. 1 where the cylinders are very close together and no vibration occurs on the flexible cylinder. The role of ''vortex formation length'' has been discussed in Lam and To (2003), and in Fig. 2(a) the distance from the small cylinder to the large cylinder is clearly shorter than the vortex formation length so that vortex shedding is not possible from the small cylinder. Similar findings of total vibration suppression are reported in Gowda and Sreedharan (1994).

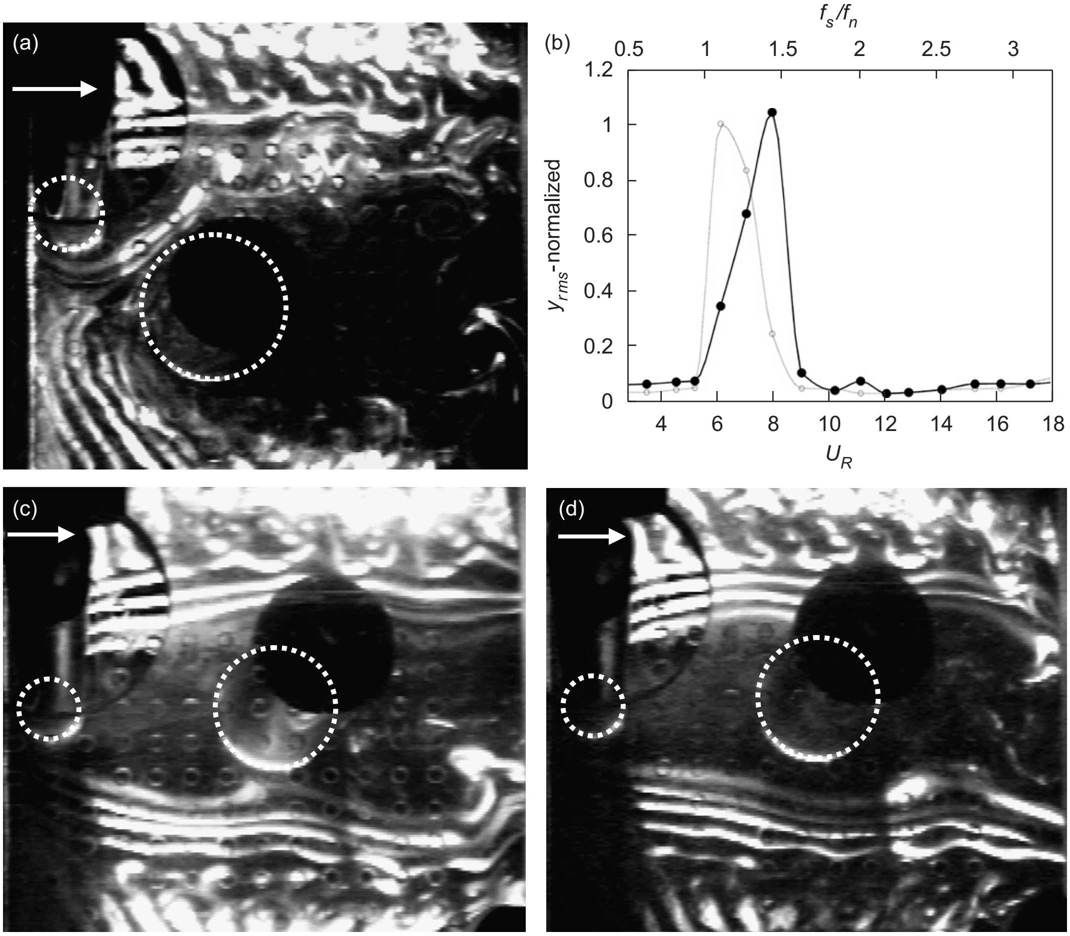

Fig. 2. (a) Distortion of the small cylinder wake at $(X/D, Y/D) = (1.17, 0.94)$: smoke image at $U_R = 6.1$. (b–d) Widening of the small cylinder wake at $(X/D, Y/D) = (1.88, 0)$: (b) response curve, that of the isolated single cylinder shown by the broken line; (c) smoke image at $U_R = 6.1$ while the cylinder is at lower extreme position; and (d) smoke image while the cylinder is at upper extreme position.

When the flexible cylinder is located in front of the large cylinder ($Y/D \leqslant 0.47$), vibration response curves of the lock-in type are observed at $X/D \geqslant 1.41$ (Fig. 1). Contrary to the results at larger lateral separations, the reduced velocity of peak lock-in is found to be higher than $U_R = 6.1$. This is clearly shown by the response curve at $(X/D, Y/D) = (1.88, 0)$ in Fig. 2(b). An axis showing the frequency ratio f_s/f_n is added in the figure as in Lam and To (2003). Without interference, the small cylinder will shed vortices at the natural vortex shedding frequency f_s which is proportional to the free-stream velocity U. The smoke images in Figs. 2(c) and (d) show the typical flow patterns past the cylinders at this cylinder arrangement while the small cylinder moves to its two extreme positions at $U_R = 6.1$. In Fig. 2(c), the smoke trace from the lower side of the small cylinder shows a saddle point near the large cylinder. The saddle point marks the "vortex formation length". In the other extreme position, the saddle point occurs at the upper smoke trace. This is hidden by the large cylinder in Fig. 2(d) but its presence can be revealed by curving of the smoke traces. Actually, the two flow patterns are good mirror images of each other. Flow visualizations at other locations show similar flow patterns. Vortex shedding occurs from the small cylinder when the separation between the cylinders is not too much shorter than the vortex formation length. Presence of the downstream large cylinder makes the small cylinder wake wider than the isolated cylinder case. The resulting lower vortex shedding frequency is responsible for the shifting of reduced velocity of peak lock-in to values higher than $U_R = 6.1$. This widening of the small cylinder wake and increase in the reduced velocity of peak lock-in are not reported in Gowda and Sreedharan (1994).

Flow-induced vibration of a flexibly mounted circular cylinder placed upstream of a fixed cylinder of the same size has been studied in Bokaian and Geoola (1984). Rigorous vibration is observed for most relative positions between

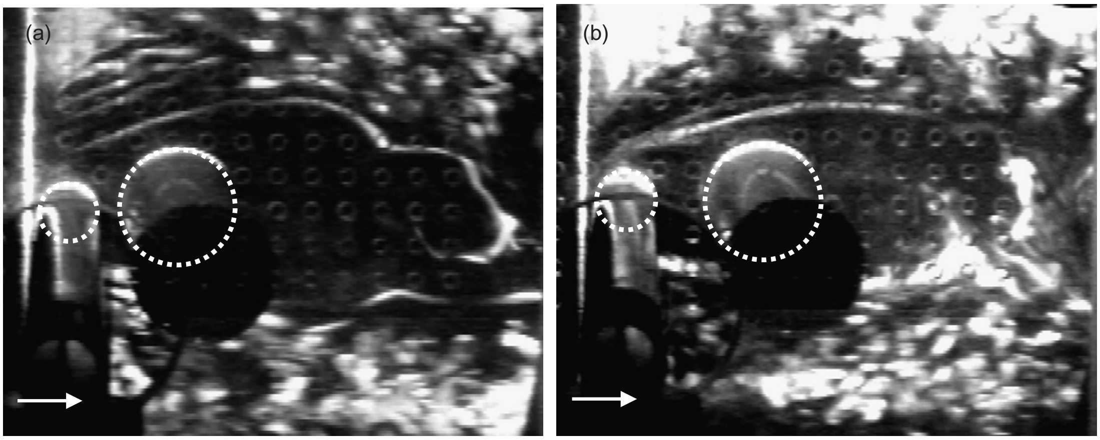

Fig. 3. Large-amplitude vibration at close-tandem arrangement: $U_R = 12.0$, cylinder at upper extreme position. (a) $(X/D, Y/D) = (0.94, 0)$ and (b) $(X/D, Y/D) = (1.17, 0)$.

cylinders. When the cylinders are separated by a small lateral distance, flow passes the upstream flexible cylinder and then over the downstream cylinder as a single body. The wake width is larger than that of the isolated cylinder and peak lock-in is found to occur at a reduced velocity higher than the isolated cylinder value. A similar flow pattern and excitation mechanism are relevant to our observations in Figs. 2(b)–(d). In Bokaian and Geoola (1984), the reduced velocity of lock-in resonance becomes lower than the isolated cylinder value when the lateral separation between cylinders increases beyond $Y/D > 1$. It is because this lateral separation opens a gap between the two cylinders, through which some flow passes. The wake width behind the upstream flexible cylinder is made narrower by the gap flow and thus a higher vortex shedding frequency results. A similar mechanism is responsible for our observation of higher reduced velocities of peak lock-in for $Y/D \geqslant 0.70$ (Fig. 1). For the case of two cylinders of the same size, the effect of the downstream cylinder on modification of the upstream cylinder wake is not as destructive as our situation in Fig. 2(a). Thus, Bokaian and Geoola (1984) found that lock-in vibration can still occur on the upstream cylinder at small longitudinal distances between cylinders, while no vibration occurs on our small upstream cylinder.

The most notable interference effect occurs when the small cylinder is located just in front of the large cylinder. Large-amplitude vibration occurs at high reduced velocities (Fig. 1). Fig. 3 shows the smoke visualizations at two locations $(X/D, Y/D) = (0.94, 0)$ and (1.17, 0). Flow passes the two cylinders as a solid body with the vortex shedding frequency scaled by the size of the large cylinder. The excitation force on the small cylinder in the lateral direction thus originates from the single-body wake. The frequency of excitation is expected to match the natural frequency of small cylinder vibration at $U_R = 6.1 \times D/d = 12.2$. Large-amplitude vibration is observed to start approximately from this value of reduced velocity. The vibration amplitude then increases with further increase of U_R and reaches almost constant levels at $U_R > 18$. For two cylinders of the same size, Bokaian and Geoola (1984) found similar response characteristics on the upstream flexible cylinder for $X/D < 2$. Due to the equal size of the cylinders, large-amplitude vibration was found to start at a reduced velocity of about 6 and this was described as the onset of galloping vibration. For a flexible cylinder upstream of a larger cylinder, Gowda and Sreedharan (1994) reported similar severe vibration at one close-tandem arrangement corresponding to $(X/D, Y/D) = (1.175, 0)$. Proximity-induced galloping was proposed in that paper as the excitation mechanism. In our study, this galloping-type vibration disappears when the longitudinal separation becomes larger at $X/D \geqslant 1.41$.

4. Conclusions

We have measured flow-induced vibration response of a flexibly mounted circular cylinder under the interference of a stationary cylinder twice as large and located downstream. This is to complement our previous investigation in which amplified vibration is found on the flexible cylinder with the interfering cylinder placed in many upstream locations (Lam and To, 2003). In the present study, we found that vibration of the flexible cylinder is reduced in amplitude or even suppressed when it is placed upstream of the large cylinder. The vibration response curves at most locations show a resonant lock-in vibration range at reduced velocities near 6, as for an isolated flexible cylinder. The only exception is when the small cylinder is located just in front of the large cylinder. Very large amplitude vibration then occurs at reduced velocities above 12.

When the longitudinal separation between the cylinders is sufficiently large at $X/D \geqslant 1.41$, the small cylinder can develop its own wake with vortex shedding, and lock-in resonance occurs. However, the presence of the large cylinder downstream is found to modify the shape of the small cylinder wake and thus change its vortex shedding frequency. At smaller lateral separations where the small cylinder is within the streamwise projection of the large cylinder, flow passes around the small cylinder and then the large cylinder like a single body (Fig. 2). The small cylinder wake width becomes larger than the isolated cylinder case and the vortex shedding frequency is reduced. As a result, peak lock-in occurs at a reduced velocity higher than the isolated cylinder case ($U_R = 6.1$). When the lateral separation is larger, $Y/D \geqslant 0.70$, there is flow passing between the cylinders. After passing the small cylinder, the flow streamlines are bent inwards in order to flow around the downstream large cylinder. This reduces the width of the small cylinder wake and peak lock-in occurs at $U_R < 6.1$. When the longitudinal separation between the cylinders is much less than the vortex formation length of the small cylinder, the small cylinder wake is greatly distorted and no vortex shedding can occur (Fig. 2(a)). Almost no vibration is observed on the small cylinder at all reduced velocities.

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