Journal of
Mechanical
Science and
Technology

Journal of Mechanical Science and Technology 21 (2007) 1383~1387

Wake Suppression Behind Two Slightly Non-coplanar Cylinders

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(Manuscript Received October 20, 2006; Revised March 30, 2007; Accepted May 2, 2007)

Abstract

We here have found when the two parallel cylinders are arranged slightly non-coplanar, the vortex shedding could be significantly suppressed above Reynolds number of 6000. This finding is unlike the common understanding that the Kármán vortex formation behind the structure can be manipulated when a structure located within the inherently unstable near wake of another structure. It is particularly important for flow control, since the flow-induced vibration of two parallel cylinders can be suppressed effectively with only slightly non-coplanar arrangement.

Keywords: Passive control; Cylinder; Fluid-structure interaction

1. Introduction

The wake interference behind two side-by-side parallel cylinders has been extensively studied in the past (Spivack, 1946; Bearman, 1973; Williamson, 1985; Zdravkovich, 1985; Kim and Durbin, 1988; Peschard and Le Gal, 1996; Sumner et al., 1999) and the main features of the flows have been described through visualization and measurements. It has been well known that the flow patterns behind the bluff bodies depend strongly on the cylinder spacing ratios. The wake patterns were classified into three regimes according to the spacing ratio T/d, where T is the center-to-center distance between the cylinders and d is the diameter of the cylinder Zdravkovich (1985). At large spacing ratio, $T/D \geq 2.2$, two Kármán vortex streets are generated behind each cylinder; at intermediate spacing ratio, $1.2 < T/d < 2.2$, the gap flow between the two cylinders becomes biased, and the biased flow is bistable; at small spacing ratio, $T/d \leq 1.2$, the two cylinders behave like a single bluff body, and the single Kármán vortex street forms in the wake. The nonparallel pair of circular cylinders in a cross flow was also investigated experimentally Hiramoto and Higuchi (2003). It is found that the wake pattern varies in the spanwise direction between the two ends from mostly independent vortex shedding to almost single-body wake structure. In all of the above experiments, the two cylinders are coplanar. It is well known that a structure located within the inherently unstable near wake of another structure can be used to manipulate the Kármán vortex formation behind the structure. Some researchers used small cylinder or plate to control the large cylinder's wake (Roshko, 1955; Strykawski and Sreenivasan, 1990). In this experiment, it is found that a pair of non-coplanar cylinders can also suppress the vortex shedding significantly when they are sufficiently close to each other. It is particularly of practical interest, since it does not need an additional small structure to modify the wake, and the wake can be suppressed effectively with only slightly structural modification.

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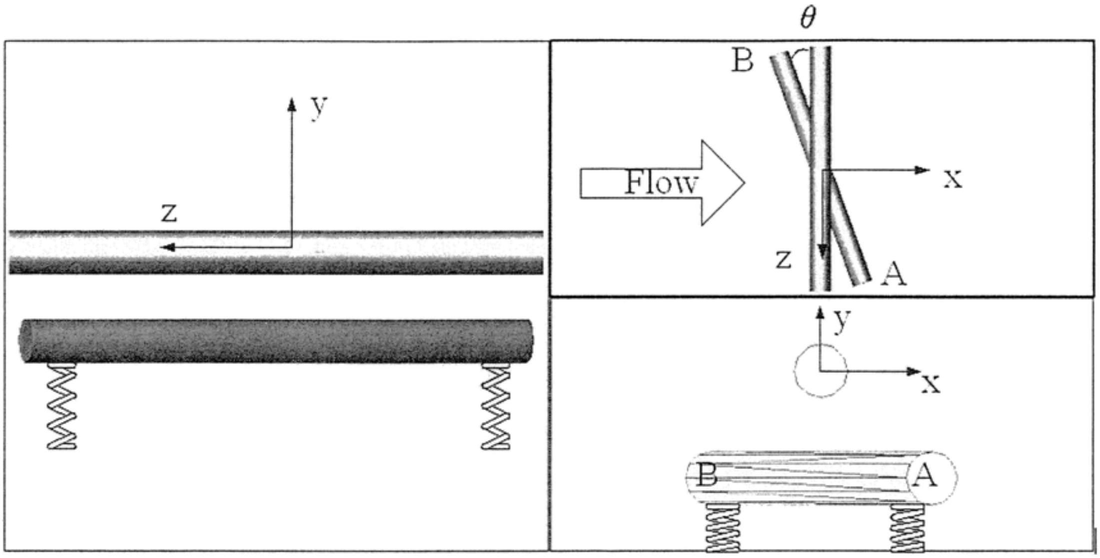


Fig. 1. Experiment setup.

2. Experimental setup

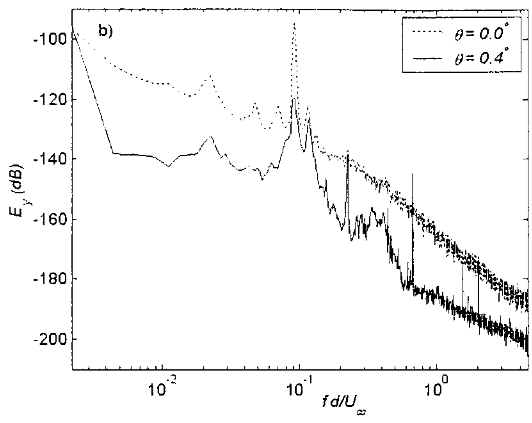
The schematic view of the experiment setup is shown in Fig. 1. Experiments were carried out in a closed-circuit wind tunnel with a 0.6 m×0.6 m square working Sec. 2.4 m-length. The wind speed of the working section can be up to 50 m/s. The streamwise mean velocity uniformity is 0.1% and the turbulence intensity is less than 0.4%. Two identical acrylic tubes with a diameter of $d = 0.025\ m$ were mounted horizontally in a side-by-side arrangement and were placed symmetrically to the mid-plane of the working section. One cylinder was elastically supported by spring and the other was rigidly mounted at both ends. One end of the elastically supported cylinder was slightly moved along streamwise, that led the two cylinder to be non-coplanar and the angle is about $0^{\circ} \sim 0.4^{\circ}$. The transverse spacing ratio was set at $T/d = 1.2$.

A Polytec Series 3000 Dual Beam Laser Vibrometer and a single hot-wire were used to measure the cylinder displacement and flow velocity, respectively. The Vibrometer was focused on the elastically supported cylinder, and hot-wire was placed at $x/d = 4$, $y/d = -1.7$, $z/L = 0$, where L is the length of the cylinder. Hot-wire was operated at an overheat ratio of 1.8 with a constant temperature anemometer. A 12-bit A/D board simultaneously sampled the vibration and flow velocity signals. The velocity field is measured using a Dantec standard PIV2100 system with a Dantec FlowMap Processor. A series of wind tunnel experiments were conducted in the Reynolds number range of 3500 ~ 10000, where Reynolds number $Re = Ud/\nu$; and U is the uniform velocity and ν is the kinematic viscosity.

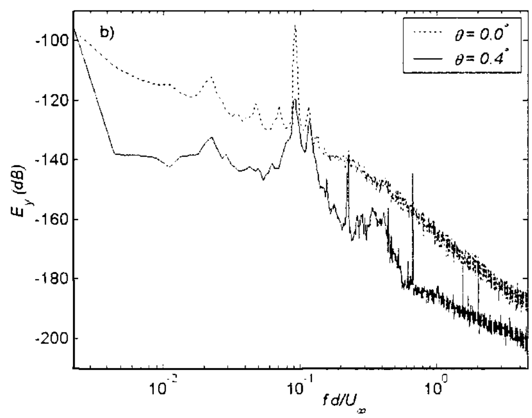
3. Results and discussion

The original objective of this experiment was to study the active control of cylinder arrays. When we carried out the reference test, i.e., without active control, the pair of cylinders behaved like a single bluff body at Re = 3500 ~ 6000, the single Kármán vortex street formed behind the cylinders. However, with increasing Re up to 6600, the vortex disappeared, and the hot wire, laser vibrometer and PIV could not detect any discernable shedding signals. After checking all the electronic connections, we found that the only discrepancy was the elastic support unaligned slightly, i.e., the two cylinders were non-coplanar. After making the two cylinders parallel, the vortex shedding signals appeared immediately. This procedure was repeated several times, it showed the same phenomenon, therefore it ruled out the possibility of initial condition effect. Then we intentionally made the two cylinders non-coplanar, measured more than one hour, and there was no vortex shedding detected.

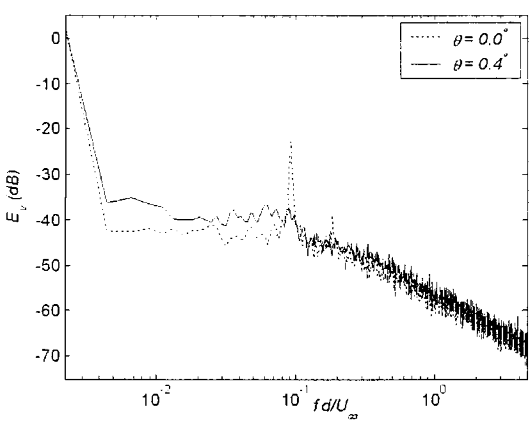
The experiments were carried out at different non-coplanar angles from $\theta = 0 \sim 0.4^{\circ}$. Figures 2(a) and



(a)



(b)



(c)

Fig. 2. Comparison between θ = 0° and 0.4° at *Re* = 9227, (a) Cylinder displacement time history, (b) PSD analysis of displacement, and (c) PSD of velocity at near wake.

2(b) show the time series of cylinder vibration amplitude of the elastically supported cylinder and its power spectra density (PSD) with coplanar and non-coplanar arrangement at *Re = 9227*. When the angle included between the two cylinders $\theta = 0.4^o$, the cylinder vibration is suppressed significantly. From Fig. 2(b), it clearly shows that the vortex shedding at $\theta = 0.0^o$ is locked into the main natural frequency. But at $\theta = 0.4^o$, the PSD at the main natural frequency is reduced more than 20 dB, which is equivalent down to *1%*. Figure 2(c) shows the spectral analysis of streamwise velocity at near wake. There is almost no discernable shedding frequency which can be detected at $\theta = 0.4^o$, and the behavior of the PSD looks just like white noise. The measurement of hotwire in far wake ($x/d = 16$) is also consistent with that of near wake, and the reduced oscillation frequency shifts from 0.092 to 0.081. Moving the hotwire within the spanwise position of $-2.8 < z/d < 2.8$, the same phenomenon was observed.

To investigate the effect of non-planar angle and the crossing location, the two non-coplanar cylinders was set up to cross each other at both the middle span and the end, respectively. As shown in Fig. 3(a), the vortex suppression is strongly dependent on the included angle, but is almost independent of crossing location. With slightly non-coplanar, the root mean square (RMS) vibration of the cylinder is reduced significantly. Figure 3(b) shows the rms value of cylinder's vibrating displacement at different *Re*. For $\theta = 0^o$, there exists a peak at Re = 9227 (f^* = 0.092) where the corresponding shedding frequency coincides with the natural frequency, i.e., the resonance occurs. For $\theta = 0.2^o$, no discernable peak can be found, indicating the vortex shedding has been effectively controlled and there is no resonance occurring around the natural frequency.

Figure 4(a) shows the PSD variation of near wake velocity with different Re at $\theta = 0.2^o$. When $Re < 8000$, the PSD peak at the shedding frequency is quite significant; however, with increasing Re over 8200, the PSD peak is almost disappeared, indicating a suppression of the vortex shedding. The experiment was also carried out for both cylinders were rigidly mounted at both ends as shown in Fig. 4(b), and the similar phenomena were obtained, only the critical *Re* is changed to *Re = 6400*, indicating that the vortex suppression is mainly due to the non-coplanar arrangement, and the elastic cylinder does not affect the vortex suppression.

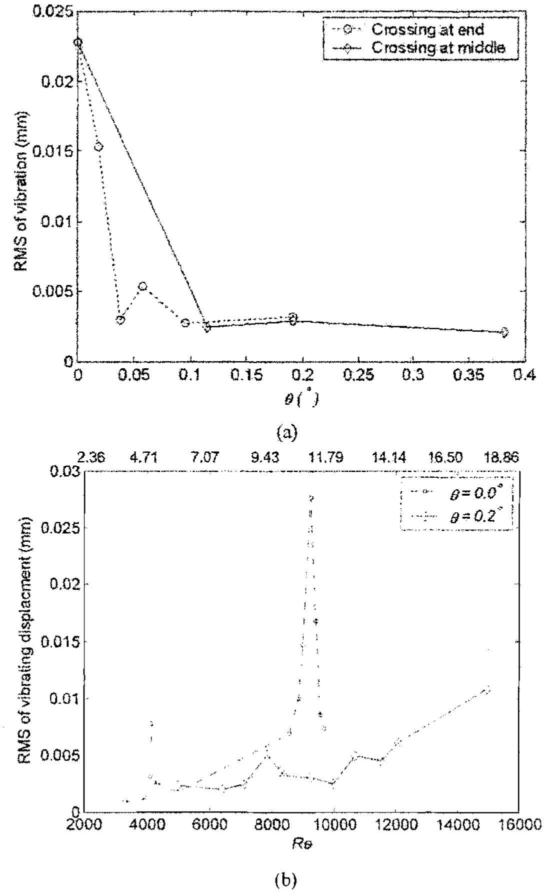


Fig. 3. RMS of vibrating displacement at (a) different angles (Re = 9227), and (b) different Re.

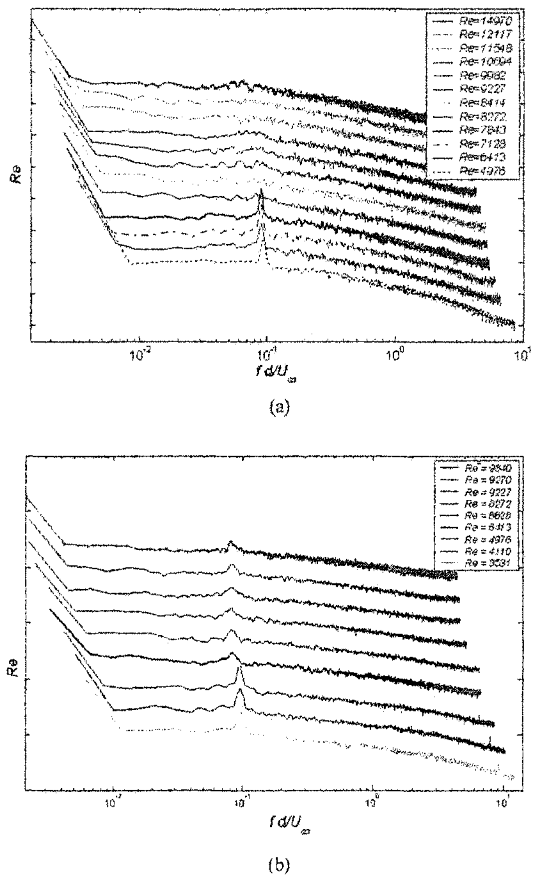


Fig. 4. PSD variation of near wake flow velocity at different Re (θ = $0.2°$). (a) Elastic Support, and (b) Rigidly mounted.

4. Conclusion

In summary, the vortex shedding can be effectively suppressed when the two cylinders are arranged slightly non-coplanar, and it is true for both rigidly and elastically mounted cylinder pair. The vortex suppression occurs at only above certain Re numbers, the critical Re number depends on the cylinder elasticities. The suppression can be taken into effect as the non-coplanar angle is small as $\theta = 0.1^o$. It is of particularly interest in practical flow-induced vibration control, since the vortex shedding can be suppressed as long as the structure is slightly modified.

Acknowledgement

Support given by the Research Grants Council of the Government of the HKSAR under Grant No. PolyU 5305/03E and 5221/05E, and by the Hong Kong Polytechnic University under Central Research Grant No. A-PE53 is gratefully acknowledged.

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