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Wake Flow Behaviour behind a Smaller Cylinder Oscillating in the Wake of an Upstream Stationary Cylinder

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Abstract

The flow patterns around a cylinder oscillating freely in the wake of a larger cylinder upstream were investigated using the particle image velocimetry (PIV) technique. The upstream cylinder was fixed at both ends while the downstream smaller cylinder was held by springs such that it was free to oscillate in the transverse direction. The flow patterns, amplitudes of oscillation and vortex shedding frequencies were compared with those of a single cylinder. In the presence of the upstream cylinder, the three parameters characterising the oscillation response of the smaller cylinder - amplitude of oscillation, vortex shedding frequency and Reynolds stresses - were greatly reduced. While their magnitude increased with gap ratio, these three parameters were still smaller than the corresponding magnitudes for a single oscillating cylinder. The peak values of turbulence statistics such as Reynolds shear stress and normal stress behind the oscillating downstream cylinder were similarly reduced, and increased with gap ratios.

Keywords: Oscillating cylinder; gap ratio; PIV; oscillation amplitude; vortex shedding frequency; turbulence statistics.

1. Introduction

Flow-induced vibration of two circular cylinders in tandem arrangement features heavily in fluid dynamics and ocean engineering applications like risers, mooring lines, bridge piers and tube bundles in heat exchangers. The investigation on flow-induced vibration has drawn considerable attention due to the increasing risk of fatigue failure in engineering structures, from causes such as amplified vibration amplitude and increased current drag. The wake downstream of a pair of cylinders is more complex than that of an isolated oscillating cylinder, due to interference by the forced vibration of the cylinder, non-uniformity of the oncoming flow, unsteadiness of its own wake and also the relative location of the cylinders (Li *et al*, 1992; Zdravkovich, 1985). There are only a handful of reported studies that deal with unequal cylinders as most experimental and numerical investigations focused on cylinders of equal diameter (Bokaian and Geoola, 1984; Brika and Laneville, 1999; Hover and Triantafyllou, 2001; Li *et al*, 1992; Mahir and Rockwell, 1996; Papaioannou *et al*, 2008; Prasanth and Mittal, 2009).

Tanida *et al* (1973) investigated the stability of an oscillating cylinder in uniform flow or in a wake at Reynolds number from 40 to 10^4. They found that when the cylinder motion and the vortex shedding are synchronized, the transverse oscillation of the cylinder may become unstable. Using particle image velocimetry (PIV), Assi *et al* (2006) investigated flow-induced oscillations of circular cylinders arranged in tandem, where the upstream cylinder was fixed and the downstream cylinder was mounted on an elastic base, allowing the latter to oscillate transversely. The interference phenomenon of galloping was observed for cylinder spacings of 2*D*-5.6*D* (centre-to-centre, where *D* was the cylinder diameter), and the observed peak amplitude for the downstream cylinder was about 50% higher than that of an isolated cylinder under the same flow conditions. Price *et al* (2007) experimentally investigated the cross-flow past a pair of staggered circular cylinders, with the upstream cylinder subject to forced harmonic oscillation transverse to the flow direction. They demonstrated that oscillation of the upstream cylinder causes considerable modification of the flow patterns around the cylinders, such as strong periodicities in the frequency of the oscillating cylinder and the existence of sub- and superharmonic resonances. Xu *et al* (2008) considered the effect of a longitudinally oscillating cylinder on the two-dimensionality of flow around a downstream cylinder using a pair of hot-wires. They found that the spanwise correlation of the flow depended not only on the oscillation but also on the flow regimes. Kim *et al* (2009) investigated flow-induced vibration characteristics of two circular cylinders in tandem arrangement under three different experimental conditions. Five regimes were identified depending on the spacing ratio *L/D* (where *L* is the centre-to-centre spacing, *D* is the cylinder diameter), fluctuating lift forces and vibration characteristics of the cylinders.

To date, many studies have been devoted to flow past two tandem cylinders with equal diameter to address flow behaviors behind the cylinder-pair such as vortex shedding patterns, oscillation responses etc. However, considerably less attention has been paid to investigate the flow behavior behind a cylinder-pair with unequal diameters, and especially so for the case of which the downstream smaller cylinder undergoing oscillations in the complex wake of an upstream larger cylinder. Igarashi (1982) stressed the importance of establishing the characteristics of a flow around two cylinders of different diameters, but as mentioned earlier, most of the reported studies on oscillating cylinders in tandem arrangement focused on a cylinder-pair with equal diameter, and only a handful of investigations have been carried out for a cylinder-pair with unequal diameters. Sayers and Saban (1994) investigated vortex shedding frequencies from two adjacent cylinders with the larger cylinder upstream of the smaller one. Their results indicated that over a range of diameter ratios, the vortex shedding frequency of the downstream cylinder was locked at a value twice that of the upstream cylinder. However if the diameter ratio was less than two, the vortex shedding frequencies were the same for both cylinders. Lam and To (2003) investigated flow-induced vibration of a flexible circular cylinder located in the vicinity of a larger cylinder and subjected to cross-flow, and found that the response was different from that of two equal cylinders. The induced excitation associated with a larger upstream cylinder was of a higher level and there was a factor of two between the natural shedding frequencies of the two cylinders.

Therefore, this present study aims to address the knowledge gap on the effects of an upstream larger cylinder on the downstream oscillating cylinder and the response on diameter ratio to supplement the findings reported by others. The particle image velocimetry technique was used to capture the flow field behind these two cylinders, and captured the instantaneous flow patterns and spatial distributions of turbulence statistics at different gap ratios. The effects of gap ratio on the oscillation amplitude and vortex shedding frequency of the downstream cylinder were examined and presented herein.

2. Experimental set-up

Experiments were conducted in a re-circulating open water channel, with a test section 6*m* long and $0.3m \times 0.4m$ ($W \times H$) in cross-section at the Maritime Research Center, Nanyang Technological University. Two smooth polypropylene cylinders of diameters *D*=16*mm* and *d*=12*mm* (*D* and *d* are the larger and smaller tube diameters, respectively) were mounted horizontally in the channel. The larger tube was placed in the test-section and secured to the side walls to minimize the possibility of vibrations, the smaller cylinder (length *L*=278*mm*, corresponding aspect ratio *AR*=23) was mounted elastically with 8 springs to ensure that the tube was free to oscillate in the cross-flow direction only. The net stiffness of all 8 springs was 48 *N/m*. The mass ratio $m^* = m/\left(\rho d^2\right)$(where *m* is the mass of the cylinder, and *ρ* is the water density) of the oscillating smaller cylinder was 1.16, very close to unity.

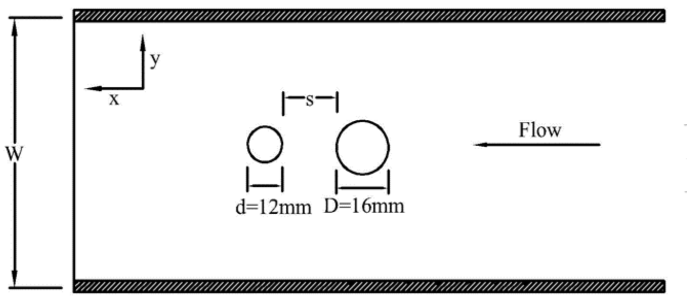

Figure 1. Schematic of the experimental setup, top view.

A sketch of the experimental arrangement is shown in Fig.1, where *s* is the spacing between the two cylinders, and the coordinates *x*, *y* denote the streamwise and transverse directions respectively. The stilling chamber upstream of the cylinder arrangement was fitted with perforated steel plates and a honeycomb-screen to ensure laminar flow into the test section.

Measurements were carried out using a PIV system (Lavision model). A Quantel System double cavity Nd: YAG laser (power~120MJ per pulse, duration ~5ns) was used to illuminate the flow field. Compromising between the requirements of recording a large field of view and resolving detailed flow structures, the viewing area was chosen to be $150mm \times 132mm$. The particle images were recorded using a 12-bit charge-coupled device (CCD) camera, which had a resolution of $1.6K \times 1.2K$ pixels and a frame rate of 15*Hz*.

The particle displacement was calculated using a cross-correlation algorithm with the standard Gaussian sub-pixel fit, structured as an iterative multi-grid method. The processing procedure included two passes, starting with a grid size of 64×64 pixels, then stepping down to 32×32 pixels with 50% overlap. The final spatial resolution was then $1.25mm \times 1.25mm$. For each experiment a set of 1050 images, used to calculate instantaneous flow fields, were acquired at a frequency of 15*Hz* (i.e. 70*s* worth of recordings).

The neutrally-buoyant hollow glass spheres ($10 \sim 15\mu m$ diameter) were seeded in the flow as tracer particles. The time delay between double pulses was set to be $470\mu s$. To give a better understanding of the interference of the presence of an upstream larger cylinder on the oscillation responses of the elastically mounted cylinder, the free-stream velocity was chosen to be $U = 0.6m/s$, with Reynolds number $\mathrm{Re} = Ud/\upsilon$ of 7200 (where *U* is the free-stream velocity, *d* is the diameter of smaller cylinder and υ is the kinematic viscosity), for which large oscillating amplitude of the downstream cylinder was observed. Considering the limitation of the water channel, different gap ratios *s/D*=0.5, 2.0, 3.0, 5.0 (where *s* is the distance between the surfaces of two cylinders) were adopted to investigate the effects of relative location of two unequal-sized cylinders on the flow behaviors and oscillation responses. The diameter ratio used in this experiment was kept to *d/D*=3/4 to supplement the diameter ratio reported in similar investigations by others, such as Igarashi (1982), Lam and To (2003), Zhao *et al* (2007). In the present study, the natural frequency of the single oscillating cylinder f_n was about 7.1 Hz, and the reduced velocity $U_r = U / f_n D$ was equal to 7.

3. Discussion and Results

3.1 A single oscillating cylinder

When a cylinder is free to oscillate in the wake of another upstream cylinder, the flow characteristics are modified significantly from if the upstream cylinder were absent. In order to acquire a better understanding of these differences, the instantaneous flow patterns for a single cylinder (Fig. 2) and two tandem cylinders (Figs. 3-6) have to be compared. This subsection presents the experimental results for a single oscillating cylinder, while following subsections present the results for a pair of cylinders with different spacing. In all cases, the oscillating cylinders' diameters are kept the same.

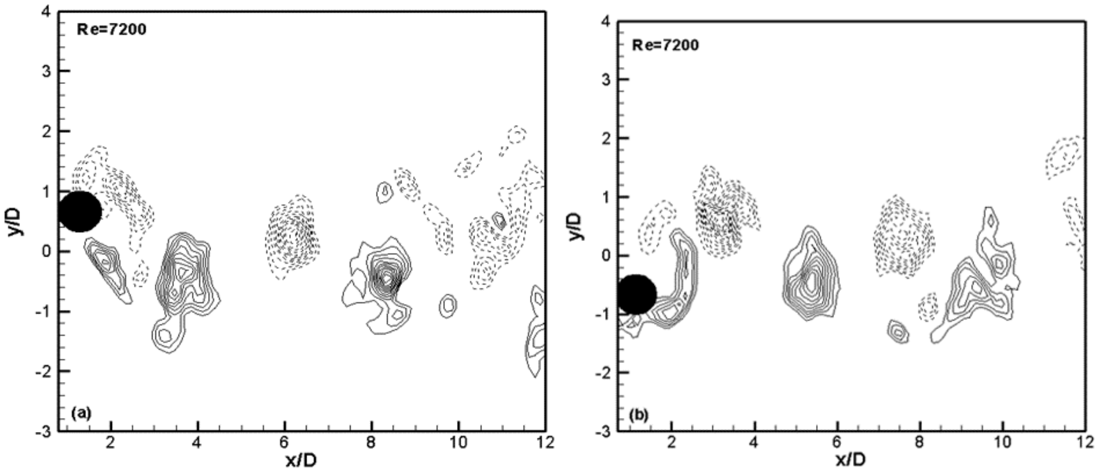

Figure 2. Flow visualisations employing a PIV system for a single oscillating cylinder, Re=7200, at its (a) highest position; (b) lowest position.

Fig. 2 shows the instantaneous vorticity contours behind a single oscillating cylinder at Re=7200. Solid lines and dashed lines represent positive and negative values, respectively, and the increment between contours is 0.2. It can be seen from Fig. 2 that regular 2S vortex shedding modes (two single vortices per cycle) are observed behind the oscillating cylinder, which is consistent with the results obtained by Govardhan & Williamson (2000) and Williamson & Roshko (1988).

As shown in Fig. 2, the maximum oscillation amplitude is approximately 0.6*D*. When the cylinder oscillates to its highest position (*y/D*=0.6), large-scale vortices are shed from the lower side of the cylinder and move downstream. A low-pressure region forms below the cylinder, pulling it downwards. On the other hand, when the cylinder oscillates to its lowest position (*y/D*=-0.6), large-scale vortices are shed from the upper side of the cylinder and the low-pressure region is formed above to pull the cylinder back upwards. By adopting the method outlined by Scarano and Reithmuller (1999), the uncertainty analysis of the instantaneous result such as the fractional error for the highest and lowest positions of the single oscillating cylinder was calculated from the 1050 PIV snapshots, using the following formula:

$$\varepsilon_{\mu} = \frac{Z_c \cdot \sigma}{\mu \cdot \sqrt{N}} \quad (1)$$

where Z_c is the confidence coefficient (95% confidence interval in this study), σ is the variance of the highest or lowest location, μ is the mean.

The uncertainties for the highest and lowest positions of the single oscillating cylinder were estimated, to be 1.3% and 2% respectively.

3.2 Wake interference on the downstream oscillating cylinder

In this section the experimental results obtained for a pair of cylinders in which only the smaller cylinder downstream is allowed to oscillate, are presented. The spacing *s* between the cylinders are varied, and the effects of changing this parameter on the oscillation characteristics such as flow pattern, oscillation amplitude, vortex shedding frequency and Reynolds stress distributions are discussed below.

3.2.1 Effect of gap ratio on the flow pattern and oscillation amplitude

Figs. 3-6 show the instantaneous vorticity contours when the downstream cylinder oscillates between its highest and lowest positions at different gap ratios *s/d*. When *s/d*=0.5 (shown in Fig. 3), the smaller cylinder is completely immersed in the wake of the upstream larger cylinder. No vortex shedding is observed in the gap between the two cylinders, which indicates that the wake from the upstream stationary cylinder is more pronounced compared to the downstream cylinder. The oscillation amplitude of the downstream cylinder is about 0.13*d*, greatly reduced from the 0.6*d* of the single cylinder by the presence of the larger cylinder, which is consistent with the results reported by Lam and To (2003).

When the gap ratio *s/d* increases to 2.0 (Fig. 4), the oscillation amplitude of the smaller cylinder increases to about 0.17*d*. Similar to that observed at *s/d*=0.5, the downstream cylinder is still immersed in the wake of the larger cylinder upstream. The shear layers separating from the upstream cylinder appear to be stretched in the streamwise direction, and the behaviour of the vortices behind the oscillating cylinder is more complex.

When *s/d* increases to 3.0, as shown in Fig. 5, the oscillation amplitude of the downstream cylinder increases to about 0.2*d*. Unlike at *s/d*=0.5 and 2.0, when the downstream cylinder oscillates to its highest position, a counterclockwise vortex shed from the upstream cylinder is observed to attach to the upper side of the downstream cylinder; conversely when the downstream cylinder oscillates to its lowest position, the shear layer from the lower side of the upstream cylinder attaches to the lower side of the downstream cylinder.

Finally when the gap ratio *s/d* =5.0, (Fig. 6), the oscillation amplitude increases to about 0.5*d*. It appears that although the oscillation amplitude of the downstream cylinder increases with gap ratio *s/d*, it is still smaller than that of a single oscillating cylinder. Vortex shedding is observed

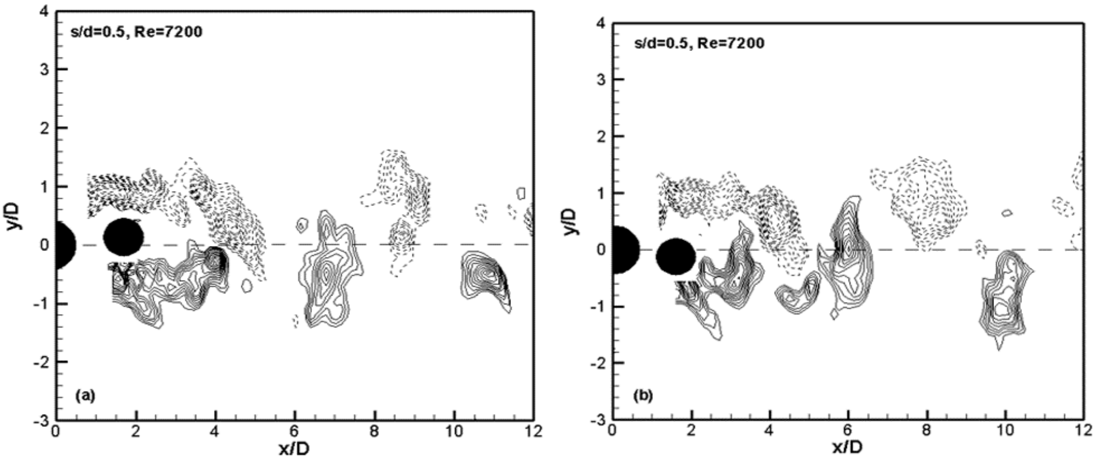

Figure 3. Instantaneous vorticity contours behind two tandem circular cylinders with unequal diameters (*D/d*=4/3) at Re=7200, *s/d*=0.5, for the downstream cylinder at its (a) highest position; (b) lowest position.

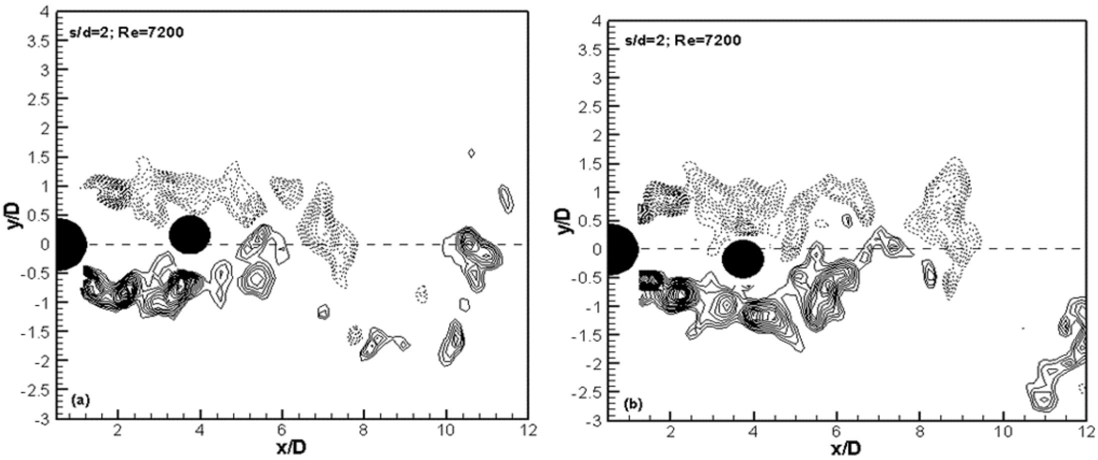

Figure 4. Instantaneous vorticity contours behind two tandem circular cylinders with unequal diameters (*D/d*=4/3) at Re=7200, *s/d*=2.0, for the downstream cylinder at its (a) highest position; (b) lowest position.

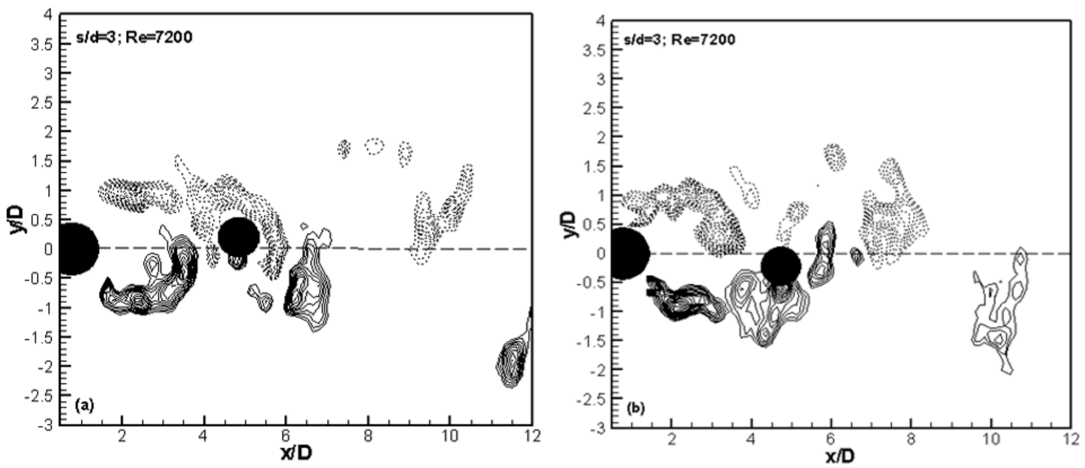

Figure 5. Instantaneous vorticity contours behind two tandem circular cylinders with unequal diameters (*D/d*=4/3) at Re=7200, *s/d*=3.0, for the downstream cylinder at its (a) highest position; (b) lowest position.

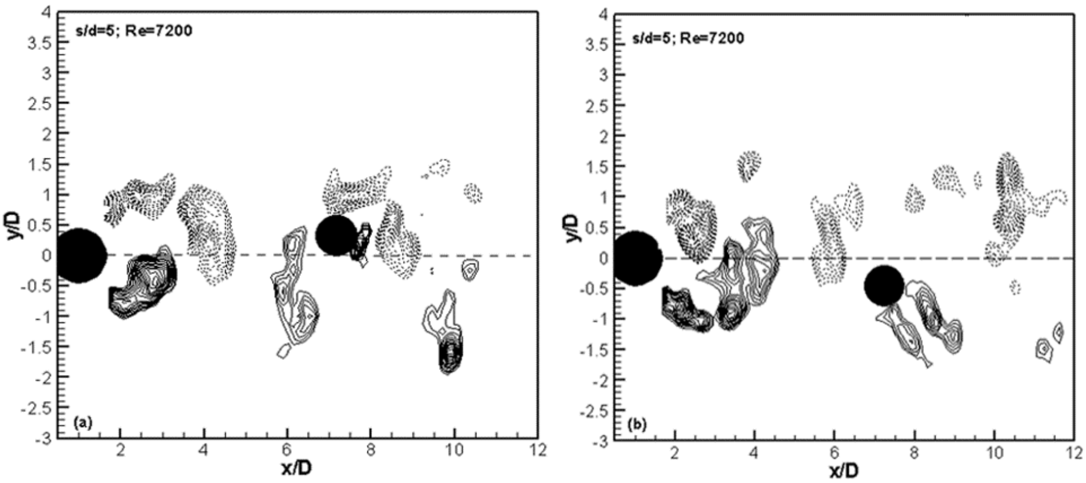

Figure 6. Instantaneous vorticity contours behind two tandem circular cylinders with unequal diameters (*D/d*=4/3) at Re=7200, *s/d*=5.0, for the downstream cylinder at its (a) highest position; (b) lowest position.

from both cylinders. When the oscillating cylinder reaches its highest position (Fig.6 (a)), negative vortices are shed from the upper side of the cylinder and move downstream, while on the other hand, when the cylinder moves to its lowest position (Fig.6 (b)), positive vortices are shed from the lower side of the downstream cylinder. Due to the combination of interactions between the wakes and both cylinders, the vortices behind the downstream oscillating cylinder become unsteady and disorganized.

Comparing the instantaneous flow patterns from a single cylinder and that downstream oscillating cylinder, it can be concluded that the larger upstream cylinder produces significant effect on the oscillation response of the cylinder downstream, causing a great reduction in the oscillation amplitude. The present study also showed that the variation of the oscillating amplitude with gap ratio is very different from the results on two equal-sized cylinders (Papaioannou *et al*, 2008) in which the oscillation amplitude of the downstream smaller cylinder increases with the gap ratio. However, for the cases of two equal-sized cylinders, Papaioannou *et al* (2008) found that the maximum transverse oscillation amplitude of the downstream cylinder is higher at *s/d*=1.5 and 2.5 than that at *s/d*=4.0 over all reduced velocities. This is especially so for the case of U_r=7.1, in which the maximum oscillation amplitude of the downstream cylinder occurs at the small gap ratio *s/d*=1.5. The findings of this study showed that the maximum oscillation amplitude for the downstream cylinder is observed at the large gap ratio *s/d*=5.0 for the two unequal cylinders.

In terms of the flow patterns behind the tandem cylinders with unequal diameters, it can be concluded that different flow patterns are observed at different gap ratio: a single bluff body at small gap ratio *s/d*=0.5 and 2.0; alternating impingement of shear layers on the upper and lower side of the downstream cylinder at medium gap ratios *s/d*= 3.0 and co-shedding at large gap ratio *s/d*=5.0. Different from the cases of two equal-sized cylinders (Assi *et al*, 2006), the flow patterns of a single bluff body is observed behind two unequal-sized cylinders instead of the vortex impingement phenomenon under the same gap ratio and Reynolds number. This may be caused by the large width of shear layers separated from the upstream larger cylinder, which engulf the entire downstream cylinder in its wake.

3.2.2 Effect of gap ratio on vortex shedding frequency

In this section the focus is on how the presence of the stationary upstream cylinder affects the vortex shedding frequency of the smaller, oscillating cylinder downstream, and how that difference varies with the cylinder spacing.

Fig. 7 shows the power spectrum of velocity fluctuations for a single oscillating cylinder at Re=7200. A peak is observed at $f = 6.97Hz$, with a corresponding low non-dimensional frequency of $St = fd/U = 0.14$. It appears that the vortex shedding frequency is approximately equal to the natural frequency of the oscillating cylinder ($f / f_n \approx 1.0$), indicating the occurrence of lock-in phenomenon at this Reynolds number.

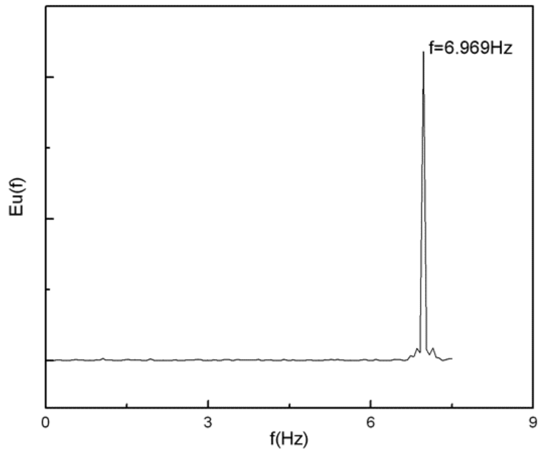

Figure 7. Power spectrum of velocity fluctuations behind a single oscillating cylinder.

The power spectrum of velocity fluctuations for two tandem cylinders at different gap ratios are shown in Figs. 8-11. At a small gap ratio *s/d*=0.5 (Fig. 8), a small pronounced peak is observed at $f \approx 4.78$ Hz ($St_D = fD/U \approx 0.13$) behind the downstream oscillating cylinder at various locations. Compared to the case of an isolated oscillating cylinder, the vortex shedding frequency behind the downstream oscillating cylinder decreases outside the synchronization region, and was observed to be 0.67 f_n (or 2/3 f_n). With larger *s/d* (= 2.0), as shown in Fig.9, a dominant peak is observed at around $f \approx 5.82$ Hz ($St_D = fD/U \approx 0.16$) from the power spectrum. The vortex shedding frequency *f* behind the oscillating cylinder increases to about 0.8 f_n. Different from the cases at smaller gap ratio *s/d*=0.5 and 2.0, when *s/d* increases to 3.0 as shown in Fig. 10, a significant peak at $f \approx 6.20\,Hz$ ($St_D = fD/U \approx 0.17$) is observed from the power spectrum in the

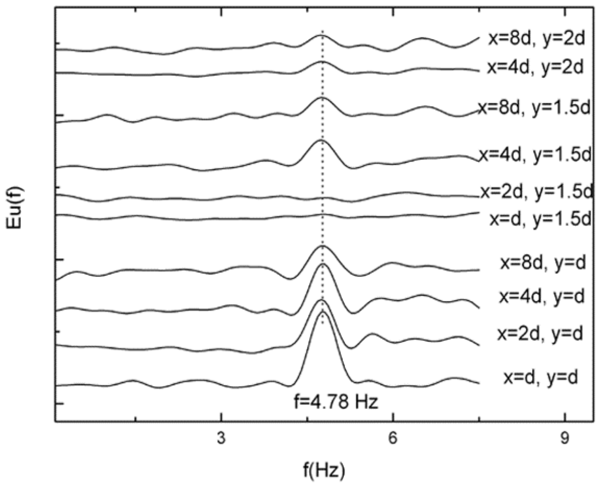

Figure 8. Power spectrum of velocity fluctuations at different locations behind the downstream cylinder for *s/d*=0.5.

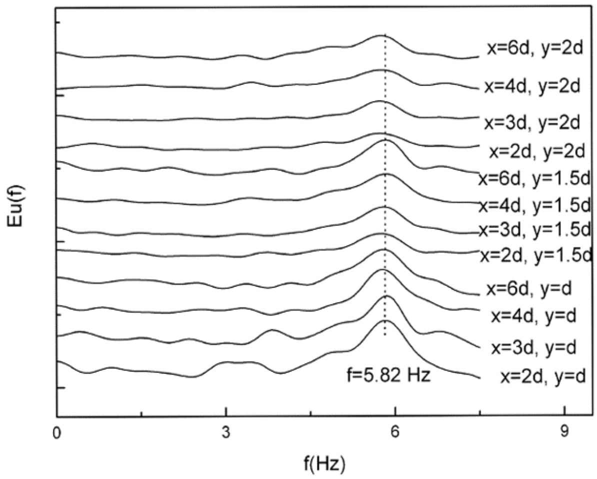

Figure 9. Power spectrum of velocity fluctuations at different locations behind the downstream cylinder for *s/d*=2.0.

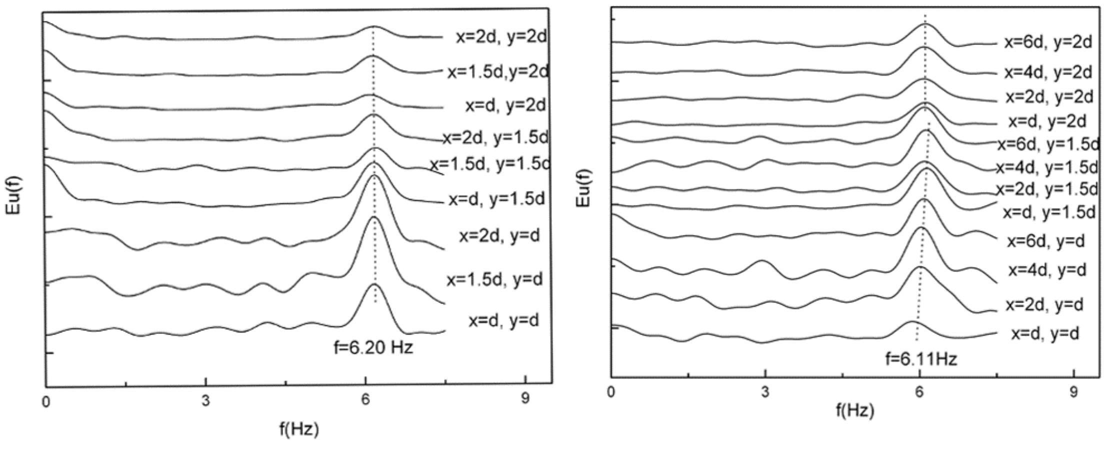

Figure 10. Power spectrum of velocity fluctuations at different locations behind the downstream cylinder for *s/d*=3.0. (a) between the cylinders; (b) behind the downstream cylinder.

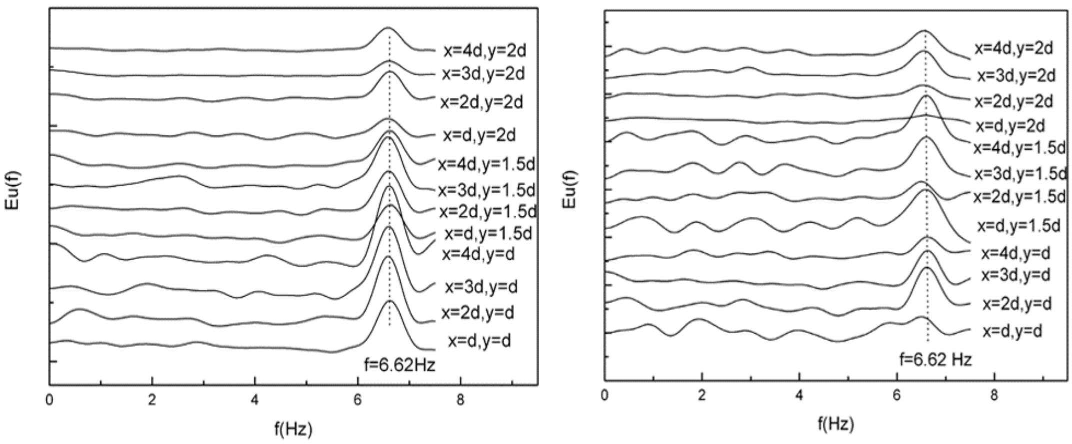

Figure 11. Power spectrum of velocity fluctuations at different locations behind the downstream cylinder for *s/d*=5.0, (a) between the cylinders; (b) behind the downstream cylinder.

gap between the cylinder-pair. A second peak at $f \approx 6.11\,\text{Hz}$ ($St_d = fd/U \approx 0.12$) is observed behind the downstream cylinder, which is about 0.86 f_n. The presence of vortex shedding frequency in the gap between two cylinders is also indicative of the occurrence of alternating vortex impingement phenomenon behind the upstream larger cylinder.

Fig. 11 shows the power spectrum of velocity fluctuations for a spacing of *s/d*=5.0. It can be observed that the vortex shedding frequencies from both cylinders increase with gap ratio, and approach to an identical frequency - a significant peak at $f \approx 6.62$ Hz, or about 0.93 of the natural frequency of the single oscillating cylinder. The progressive increase of vortex shedding frequencies from both cylinders indicates that the effect of upstream larger cylinder on the oscillating responses of the downstream smaller cylinder decreases at the large gap ratio *s/d*=5.0, and the downstream cylinder behaves as an isolated oscillating cylinder, independent of the upstream cylinder.

In terms of the power spectrum of velocity fluctuations, it is also observed that due to the presence of the upstream larger cylinder, the vortex shedding phenomenon behind the oscillating downstream cylinder is significantly suppressed, as reflected in the reduced oscillating amplitudes. The vortex shedding frequency behind the downstream oscillating cylinder increases with the gap ratio, although the magnitude is still smaller than that of isolated single cylinder. Tanida *et al* (1973) reported that in the case of two equal-sized cylinders and at high Reynolds number, synchronization occurred irrespective of the cylinder spacing. However, in the present study, synchronization of the cylinder motion and the vortex shedding was not observed for the two unequal-sized cylinders. But synchronization of the vortex shedding frequencies from both cylinders was observed under the co-shedding flow conditions.

3.2.3 Reynolds stress distributions

In this section the Reynolds stress distributions behind a single oscillating cylinder are compared to that behind two cylinders of unequal diameter in tandem, in order to investigate the effect of the stationary upstream cylinder on the near wake of the oscillating downstream cylinder. Figs. 12-16 (a), (b), (c) show the lateral distributions of the Reynolds normal stresses $\overline{u^2}/U^2$, $\overline{v^2}/U^2$ and shear stress $\overline{uv}/U^2$ at *x/d* =2 for a single oscillating cylinder, and a downstream oscillating cylinder in the wake of an upstream stationary cylinder, respectively. For a single oscillating cylinder (Fig. 12), two peaks are observed in the lateral distribution of the Reynolds normal stress $\overline{u^2}/U^2$, and seem to be symmetric about the *y/d*=0 axis, while the Reynolds shear stress $\overline{uv}/U^2$ distribution is anti-symmetric about the *y/d*=0 axis.

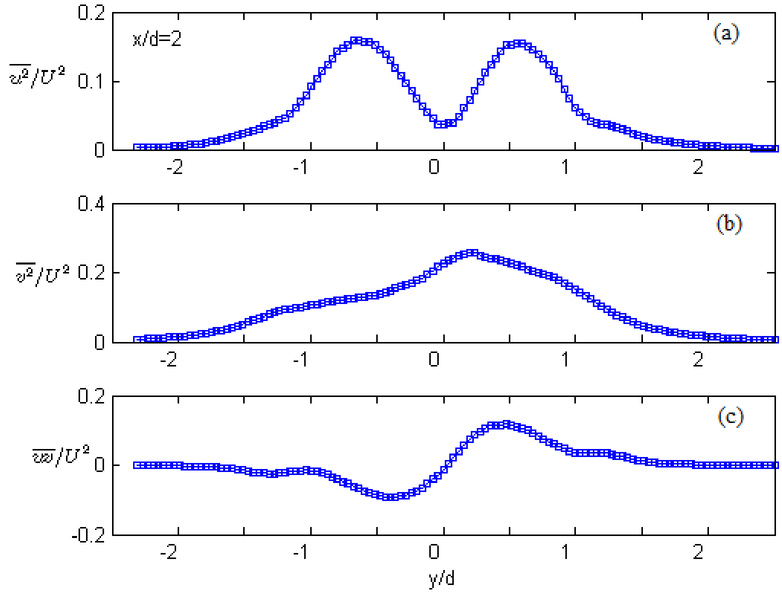

Figure 12. Lateral distribution of Reynolds normal stresses and shear stress at *x/d*=2.0 for a single oscillating cylinder.

When the oscillating cylinder is located in the wake of an upstream larger cylinder, as is the case for all four systems in Figs. 13-16, the lateral distributions of the Reynolds normal stresses $\overline{u^2}/U^2$ and $\overline{v^2}/U^2$ are symmetrical about the *y/d*=0 axis, while the Reynolds shear stress $\overline{uv}/U^2$ is anti-symmetrical. This is similar to the case of a single oscillating cylinder. However, unlike the case of a single oscillating cylinder, different peak values of the Reynolds normal stress $\overline{u^2}/U^2$ are observed for the downstream oscillating cylinder at these four gap ratios s/d=0.5, 2.0, 3.0 and 5.0.

So *et al* (2000) stressed that the behavior of double-peak of $\overline{u^2}/U^2$ for the free vibration of an elastic cylinder in a cross flow contributed to the alternating nature of the shed vortices and the formation of a distinct Karman vortex street. However, in the present study, as can be observed in Figs.13-15, when the downstream cylinder oscillates in the cross-flow direction, the wake becomes unsteady, a mass of fluid is mixed and the momentum exchange rate will be increased in such a way that double peaks of $\overline{u^2}/U^2$ appear. It can also be seen that the double peaks

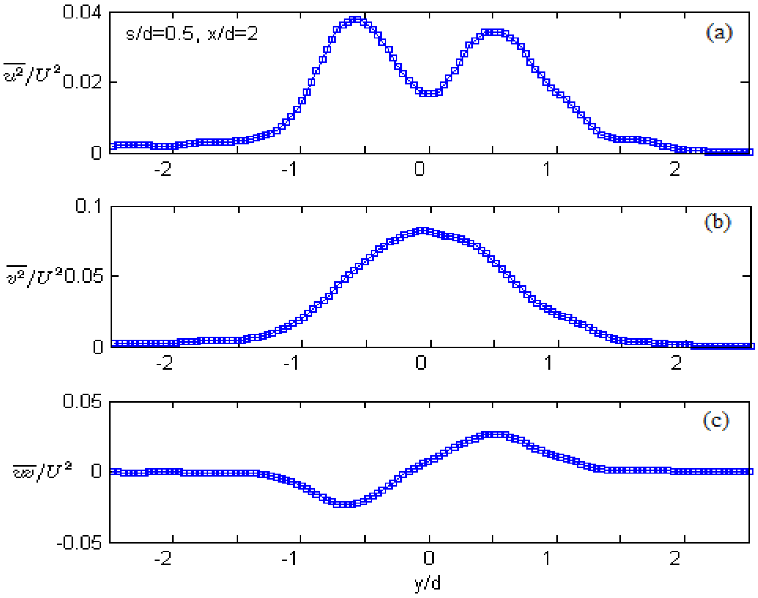

Figure 13. Lateral distribution of Reynolds normal stresses and shear stress at *x/d*=2.0 behind the downstream oscillating cylinder for *s/d*=0.5.

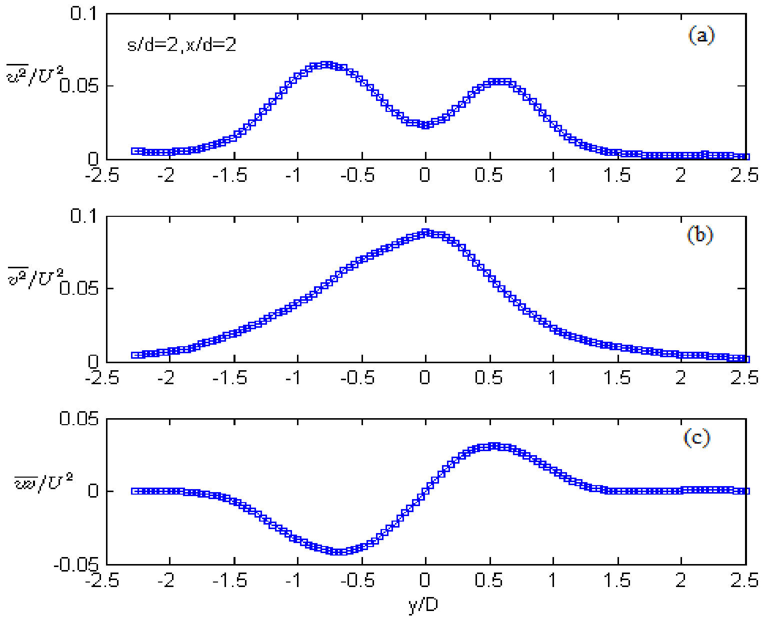

Figure 14. Lateral distribution of Reynolds normal stresses and shear stress at *x/d*=2.0 behind the downstream oscillating cylinder for *s/d*=2.0.

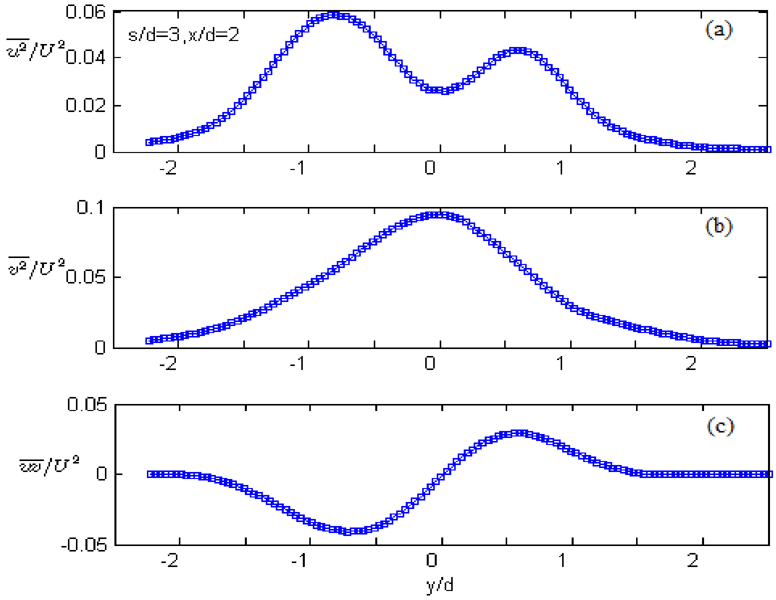

Figure 15. Lateral distribution of Reynolds normal stresses and shear stress at *x/d*=2.0 behind the downstream oscillating cylinder for *s/d*=3.0.

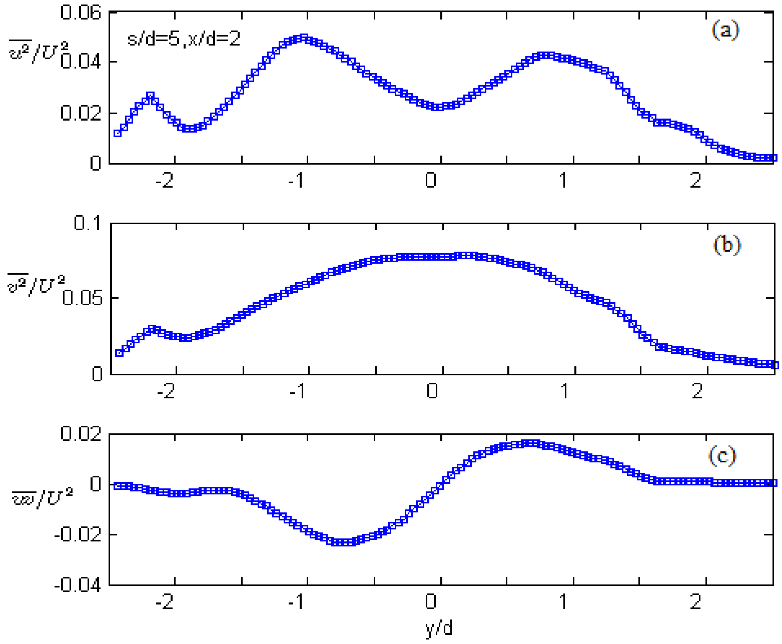

Figure 16. Lateral distribution of Reynolds normal stresses and shear stress at *x/d*=2.0 behind the downstream oscillating cylinder for *s/d*=5.0.

of $\overline{u^2}/U^2$ with different values are observed at *s/d*=0.5, 2.0 and 3.0, while three peaks are observed at the larger gap ratio *s/d*=5.0 shown in Fig.16. The presence of different peak of $\overline{u^2}/U^2$ may arise from the inevitable experimental errors caused by the small misalignment of the two cylinders or the small difference of spring stiffness between the up and down directions. On the other hand, the inconsistency of the double peaks of $\overline{u^2}/U^2$ could possibly come about as a result of the complex wake interference of larger upstream cylinder, where the vortices shed from the upstream cylinder impinge on the smaller downstream cylinder and merge with the wake behind the oscillating cylinder, thus inducing the asymmetry of double peaks of $\overline{u^2}/U^2$.

Moreover, as shown in Figs.13-16, the peak values of $\overline{u^2}/U^2$, $\overline{v^2}/U^2$ and $\overline{uv}/U^2$ for the downstream oscillating cylinder are much smaller than that of a single oscillating cylinder. For instance, at *s/d*=3.0, the peak values of $\overline{u^2}/U^2$, $\overline{v^2}/U^2$ and $\overline{uv}/U^2$ decrease to about 37.86%, 47.76% and 24.98% of that for a single oscillating cylinder. The gap ratios also have significant effects on the Reynolds stress field. For example, with increasing *s/d*, the gradient of the $\overline{v^2}/U^2$ distribution increases and reaches a maximum value of 0.095 at *s/d*=3.0, and then decreases to 0.078 at *s/d*=5.0.

It can be concluded that the upstream cylinder has a significant effect on the peak values of Reynolds stresses, and so do the gap ratios. When $s/d \leq 3.0$, the peak values of the Reynolds stress increase with the gap ratio, however, when $s/d > 3.0$, the peak values decrease and the distribution gradients become smaller.

4. Conclusions

The flow behaviour of the oscillating cylinder in the wake of an upstream larger cylinder was investigated using the PIV technique. Instantaneous flow patterns at the oscillation extrema were presented to highlight the differences between a tandem cylinder-pair and a single cylinder, as well as how these differences change as the spacing between the cylinder-pair increases. The results show that the oscillation response of the smaller cylinder is significantly affected by the upstream larger cylinder, causing a great reduction in both the oscillation amplitude and vortex shedding frequency. As the gap ratio increases, the oscillation amplitude and vortex shedding frequency increases, but for the range of spacing investigated, both parameters are smaller than that observed for a single oscillating cylinder. As a result of the interference caused by the upstream larger cylinder, the peak values of the Reynolds stresses are also reduced, but they too increase with the gap ratios. These differences are significant in that the turbulent mixing arises from the oscillation of the downstream cylinder.

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