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Interactions of lock-on wake behind side-by-side cylinders of unequal diameter at Reynolds number 600

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ABSTRACT

The flow characteristics, mutual interactions and downstream evolutions of the wakes behind the side-by-side cylinders of unequal diameter are illustrated by flow visualization and Laser Doppler Anemometry. All the experiments are conducted in a recirculating water channel at Reynolds number 600. The gap ratio is 0.75 and the diameter ratio is 2.0. Periodic excitations are applied to the large cylinder with constant excitation amplitude. Within the excitation frequency range studied, the wake behind the large cylinder experiences the primary and the one third sub-harmonics lock-on; whereas the wakes behind the small cylinder are not locked-on. For the wake behind the large cylinder experiencing the primary lock-on, the gap flow becomes unbiased and the gap vortices are observed to interact and shed alternately into the wake behind each cylinder in synchronization with the excitation frequency (the natural vortex shedding frequency of large cylinder). The synchronized flow patterns exist only in the near wake region; in the downstream region, only one wider wake dominated by the excitation frequency is detected. While the wake behind large cylinder is locked-on at the one third sub-harmonics of the excitation frequency, the gap vortices are observed to entrain alternately into the wake behind each cylinder in synchronization with the one third of the excitation frequency (e.g., natural vortex shedding frequency of large cylinder). The synchronized flow patterns exist only in the near wake region; in the downstream region, the wake is relatively weak, less organized and turbulent. For both lock-on cases, the near and the far wake structures change suddenly within a short distance.

1. Introductions

Unsteady flows characteristics over the cylinder couple of various arrangements are of fundamental importance in several industrial applications [25,29,30]. For side-by-side cylinders of equal diameter at low Reynolds numbers, clear pictures showed different degrees of cross-coupling and streamwise evolution between the gap vortices with the free-stream side shear layers. Such interactions lead to dramatic change of the pressure distributions acting on each cylinder [1,18] and thus are important to the loadings of the cylinders. Interaction of the gap vortices with the free-stream side shear layers eventually leads to the formation of a wide and a narrow wakes with different vortex frequencies in the downstream region behind each cylinder. The types of interaction and streamwise evolution are strong function of the gap ratio [5,16,27,28].

When the cylinders are spaced with very small gap ratio, only one single vortex street exists behind the cylinders; and the shedding frequency is about half of that behind a single isolated cylinder at the same Reynolds number. A vortex street behind each cylinder is observed as the gap ratio is equal to or greater than 2.5. In this category, two vortex streets are nearly parallel to each other and may shed in phase or out of phase at random time intervals [1,16,28]. When the two cylinders are spaced with small or intermediate gap ratio, the most well known flow pattern is the stably biased gap flow leading to a narrow and a wide wakes behind the cylinder couple. The high and low characteristic frequencies are detected, respectively, in the far wake regions behind each cylinder. The ratio of the high and low frequencies depends strongly upon the mutual interaction between the gap vortices in the near wake region of both cylinders [27,28]. Besides, Sumner et al. [24] investigated the side-by-side cylinders of equal diameter exposed to the cross flow at Reynolds number 850–1900 and they indicated that there are two distinct vortex shedding frequencies associated with the bi-stable flow structures behind the cylinder couple while the center-to-center distance lied within 1.2D–2.2D. For certain gap ratios, the gap flow may switch intermittently and randomly [1,18,22] toward the wake behind each cylinder. The switching timescale is several orders of magnitude longer than those of the vortex shedding as well as the shear layer instability [14]. Besides, Brun et al. [6] study the role of shear layer instability in the near wake of side-by-side circular cylinders of equal diameter. They found, below a critical Reynolds number (Re < 1700), the gap flow

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Nomenclature

D	diameter of large cylinder, cm
d	diameter of small cylinder, cm
f_e	excitation frequency, Hz
f_n	characteristics frequency of the unperturbed narrow-wake, Hz
f_w	characteristics frequency of the unperturbed wide-wake, Hz
f_{os}	natural shedding frequency behind a single large cylinder, Hz
f_r	frequency measured in the near wake region, Hz
G	gap between two side-by-side cylinders, cm
L	spanwise length of the cylinders, cm
Re	Reynolds number, $\mathrm{Re} = UD/v$
PSD	power spectral density function, cm^2/s
St	Strouhal number, $St_D = f_w D/U$ and $St_d = f_n d/U$
t	time, s
Te	excitation period, s
$\bar{u}$	time-averaged streamwise velocity, cm/s
$\tilde{u}(f)$	streamwise velocity fluctuation at specific frequency, cm/s
U	velocity of uniform stream, cm/s
X, Y, Z	coordinate in the streamwise, transverse, spanwise directions

Greek symbol

$\theta_{\max}$	maximum excitation amplitude, °
$\theta(t)$	angular displacement of the exciting cylinder, °
v	Kinematic viscosity, cm^2/s

is stably biased to one side and two distinct characteristic frequencies are detected. Above this critical Reynolds number, the shear layer instability occurred and the flopping gap flow is observed. Practically, the flow structures behind the cylinder couple with small gap ratios receive more attention because the loadings (mean, fluctuating drag and lift) on the cylinders upstream of the narrow and the wide wakes show significantly different characteristics and magnitudes. Further details of the interactive flow characteristics behind side-by-side cylinders of equal diameters can be found in the review of Sumner [23].

On the other hand, the flow structures behind the side-by-side cylinders of unequal diameters received very little attention. In 1993, Lam et al. [19] measured by hot wire the interaction of flows behind two circular cylinders of diameter ratio 2 in side-by-side arrangement at a gap ratio $T/D = 1.5$ (or $G/D = 0.75$) and Re = $2.5–5.0 \times 10^4$. In their study, the conditional sampling and the phase-averaged techniques are employed to illustrate the evolution of coherent flow structures during the interactions. Later, Ko et al. [15] measured in a wind tunnel the mean base pressure coefficients, the velocity spectra, the energy distributions in the wake region at Re = $2.5–5.0 \times 10^4$. They also provided the flow patterns at Reynolds number 750 and showed that the mutual interactions between gap vortices are much more complicated than those for cylinders of equal diameter. Recently, Gao et al. [9] investigated the wake structures behind two side-by-side circular cylinders of unequal diameter at gap ratios $T/D = 1.2–3.6$ and Re = 1200, 2400 and 4800 by PIV technique. They focused to elucidate the asymmetrical mean flow characteristics within the subcritical Reynolds number regime. They also provide a plausible interpretation for the generation mechanism of the biased gap flow. In addition, for the piggyback pipeline applications in offshore oil and gas exploration, the interactive flows around two circular cylinders of different diameters were also studied both by experiments and simulations [25,30]. In such applications, a small cylinder is usually located at close proximity around the circumference of the large cylinder. The main focus is the forces acting on the large (or main) cylinder while the sizes and the circumferential locations of the small cylinder are changed. To date, very little study has focused on the flows behind the side-by-side cylinder couples of different diameters probably due to the relatively complicated interacting flow structures to which the existing point wise measuring techniques are not sufficient.

The lock-on frequency band, excited by cross-flow perturbation, distributes almost symmetrically about f_{os} which is the natural shedding frequency of Karman vortex street behind a single cylinder. For the perturbation of in-line oscillation, the lock-on frequency band distributes nearly symmetrically about $2f_{os}$ [4,10]. For a perturbation in the form of rotary oscillation, Tokumaru and Dimotakis [26] investigated the lock-on characters and the wake control of a circular cylinder. They clearly indicated that the primary lock-on occurred near the Karman vortex shedding frequency. Lu [20] also studied the flow characteristics behind a rotary oscillating circular cylinder at low Reynolds number and illustrated the timing of vortex formation to interpret the π phase shift across the primary lock-on region. The results are consistent with the π phase shift found by Filler et al. [7] where small-amplitude rotational oscillations were imposed. Baek and Sung [3] studied the flow structures behind a rotary oscillating circular cylinder at Re = 110. They presented the relation of $t_{-Cl\max}$ (the instant at which the lift coefficient attains the negative maximum value) against the forcing Strouhal number across the primary lock-on region and indicated that the rate of change of the phase shift of near wake flow structures depends strongly upon the excitation amplitude. The near wake flow can also be effectively excited at a frequency near the Bloor–Gerard instability frequency of the shear layer at high Reynolds number [7,8]. At small excitation amplitudes, the resonance occurred near f_{os}; whereas the resonant frequency shifted toward lower frequency with increasing amplitude of oscillation [12]. Further, Baek et al. [2] and Lu [20] demonstrated the one third sub-harmonics lock-on of a cylinder wake in terms of a paired or linked vortices and a negligibly small phase shift across the lock-on frequency band.

For the side-by-side cylinders of equal diameter, the lock-on frequency bands were studied by Mahir and Rockwell [21] at large gap ratio. Further, Hanson et al. [11] investigated experimentally the aero-acoustic response of flow structures behind the side-by-side cylinder couple at gap ratio ranging from 1.25 to 3.0. They concluded that within the primary lock-on frequency band, the acoustic response synchronizes the vortex shedding in two wakes and thereby eliminates the bi-stable flow. So far, the lock-on flow characteristics behind the side-by-side cylinder couple of unequal diameter have received very little attentions. It is understandable that, for the side-by-side cylinders of unequal diameter at relatively large gap ratio, the wakes behind the cylinder couple and their lock-on characteristics are similar to those of a single cylinder. Currently, the flow phenomena behind unequal diameter cylinders at small and intermediate gap ratios are still relatively unexplored and thus require further investigations. In the present study, the gap ratio $G/D = 0.75$ and Re = 600 are selected. After some preliminary measurements, the gap flow is considered to be stably biased toward the small cylinder without changeover or switching in this study. Detailed discussion on the gap flow switching phenomenon will be given in Section 3.1.2. While the large cylinder is excited, the wake flow characteristics behind the