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Gap ratio effect on flow characteristics behind side-by-side cylinders of diameter ratio two

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ABSTRACT

This study investigates the vortex interaction, the spatial distributions in the flow and the streamwise evolution of the spectral amplitude along the shear layer behind side-by-side cylinders of diameter ratio two at different gap ratios via dye flow visualization and particle image velocimetry (PIV). The frequency responses are measured at Re = 1000, 2000, 5000 as the gap ratio changes. Velocity measurements are made and analyzed at Re = 1000 for gap ratios of 1.25, 0.75 and 0.25. It is found that, as the gap ratio increases, the Strouhal number of the narrow wake decreases monotonously but that of the wide wake increases also in the monotonous way. The gap flow is always stably deflected toward the small cylinder. For side-by-side cylinders of diameter ratio two and Re = 1000, two different vortex interaction scenarios are found leading to two different flow categories. The critical gap ratio for diameter ratio two is slightly smaller than that for equal diameter. The frequency ratio of the narrow and wide wakes depends strongly upon the gap ratio and the diameter ratio; but is independent of the Reynolds number studied. This frequency ratio is related to the ratio of the averaged streamwise distance of the local maxima of each spectral component. For side-by-side cylinders of diameter ratio two, two flow characteristics are modified relative to that of a single cylinder. First, the onset locations of the shear layer instability. Second, the spatial growing rates of the shear layers. For the side-by-side cylinders of diameter two ($D/d = 2$), the influence on the wide wake is more significant but is less pronounced on the narrow wake. Besides, the influences on both the narrow and the wide wakes are even pronounced for $D/d = 1$ than those for $D/d = 2$.

1. Introductions

Unsteady flows passing through the cylinder couple of various arrangements show diversified fluid phenomena within a wide range of Reynolds numbers including the shedding of vortices, the mutual interactions and the loads on these cylinders. The related flow phenomena attracted many researchers because of the fundamental importance in the industrial applications [26,27]. For side-by-side cylinders of equal diameter, the types of vortex interaction and evolution are strong functions of the gap ratio and Reynolds number [2,14,20,23,24]. Such interactions may lead to different vortex frequencies, flow structures far downstream and dramatic change of the loads acting on each cylinder [1,11].

Behind the side-by-side cylinders of equal diameter, the basic flow structures are categorized as follows. First, only one single vortex street exists if they are spaced very closely ($G^* < 0.3$). In this case, the shedding frequency is about half of that behind a single cylinder at the same Reynolds number. Secondly, a vortex street behind each cylinder is observed while the gap ratio (G^*) is equal to or greater than 2.5. These two vortex streets interact very weakly and may shed in phase or out of phase at random time intervals [1,13,23]. Third, while two cylinders are spaced with intermediate gap ratios, the flow structures depend upon the Reynolds numbers, the gap ratio and the experimental conditions [3]. For the gap ratio $0.3 < G^* < 2.0$, formation of a wide and a narrow wakes behind each cylinder is observed [3,24]. The well known flow pattern is the stably biased gap flow. Under some situations, the gap flow may switch upwards or downwards at intermittent and random time intervals [1,8,11,17]. The switching timescale is several orders of magnitude longer than those of the vortex shedding and the shear layer instability [10]. From the practical viewpoints, the third category receives more attention because the loadings (mean, fluctuating drag and lift) on the cylinders upstream of the narrow and the wide wakes exhibit appreciable differences.

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Nomenclature

D, d	diameter of large and small cylinder, m
Dx	delay distance of onset of shear layer instability, m
f	frequency in the flow, Hz
f_{BG}	Gerrard–Bloor instability frequency, Hz
f_n	characteristic frequency of narrow-wake, Hz
f_w	characteristic frequency of wide-wake, Hz
f_{sL}	shedding frequency behind a single cylinder of diameter D, Hz
f_{ss}	shedding frequency behind a single cylinder of diameter d, Hz
G	gap between two cylinders, m
L	streamwise distance between the centers of two cylinders, m
t	time, s
T_n	period of narrow wake, s
T_w	period of wide wake, s
$\bar{u}$	time mean local streamwise velocity, m/s
$\tilde{u}(f)$	root-mean square value of velocity fluctuation at frequency f, m/s
$\tilde{u}_m(f)$	local spectral amplitude of $\tilde{u}(f)$ along each shear layer, m/s
$\tilde{u}_o(f)$	spectral amplitude of $\tilde{u}(f)$ at $X = 0$ at frequency f, m/s
U	uniform inflow velocity, m/s
$U_{\max}$	maximum mean velocity across the shear layer, m/s
$U_{\min}$	minimum mean velocity across the shear layer, m/s
W	spanwise dimension of cylinders, m
X, Y, Z	coordinate in the streamwise, transverse, spanwise directions
$y_{1/2}$	coordinate where the streamwise mean velocity equals $(U_{\max} + U_{\min})/2$, m
ν	kinematic viscosity, m^2/s
$\theta(x)$	local momentum thickness along the shear layer, m
k	complex wave number, $k = k_r - ik_i$, 1/m

Non-dimensional parameter

Dx^*	streamwise delay distance of the onset of shear layer instability, Dx/D.
f^*	frequency in the flow, f/f_{sL}
f_w^*	frequency of wide wake, f_w/f_{sL}
f_n^*	frequency of narrow wake, f_n/f_{sL}
G^*	gap ratio, G/D
L^*	longitudinal distance, L/D
Re	Reynolds number, $\mathrm{Re} = UD/\nu$
St	Strouhal number, $\mathrm{St}_n = f_n d/U$, $\mathrm{St}_w = f_w D/U$, $\mathrm{St}_d = f_{ss} d/U$ and $\mathrm{St}_D = f_{sL} D/U$
t^*	instant within the cycle, $t^* = t/T_w$
U^+	mean velocity across the separating shear layer, $(\bar{u} - U_{\min})/(U_{\max} - U_{\min})$
$u^*(f)$	root-mean square value of velocity fluctuating at frequency f, $\tilde{u}(f)/U$
$u_m^*(f)$	maximum amplitude of $u^*(f)$ along each shear layer, $\tilde{u}_m(f)/U$
$u_0^*(f)$	spectral amplitude of $u^*(f)$ at $X = 0$ at frequency f, $\tilde{u}_o(f)/U$
y^+	local elevation, $y^+ = (y - y_{1/2})/\theta(x)$
$y_{1/2}^*$	local elevation of the shear layer, $y_{1/2}/D$

For the cylinder couple of diameter ratio two, Lam et al. [15] and Ko et al. [12] measured in a wind tunnel the mean base pressure coefficients, the velocity spectra, the energy distributions in the wake region at $G^* = 0.75$, $L^* = 0.0$ and $G^* = 0.4$, $L^* = 0.25$, respectively, for $\mathrm{Re} = 5.0 \times 10^4$ based on the diameter of the large cylinder. Lam et al. [15] revealed the detailed interaction mechanism between the vortices of the deflected gap flow and those along the free stream sides by hot wire through the conditional average technique. Ko et al. [12] pointed out that the interactions between the gap vortices with outer vortices played an important role in the downstream development of the wakes. Both results showed that the interactions between gap vortices are more complicated than those for cylinders of equal diameter. Recently, Gao et al. [4] investigated the wake structure behind two side-by-side circular cylinders of diameter ratio 1.5 at three intermediate gap ratios by PIV technique. They focused on elucidating the asymmetrical mean flow characteristics for Re = 1200, 2400 and 4800. They found the changeover of the gap flow at $G^* = 0.45$ and Re = 1200 and provide a plausible interpretation, which is similar to that of Brun et al. [3], to explain the generation mechanism of the biased gap flow. To date, very little study has been focused on this subject probably due to the relatively complicated interacting flow structures or insufficient analyzing techniques.

In the present study, the Reynolds number 1000 is selected because the vortex formation length behind the large cylinder is the longest and the wake behind is more likely to be affected by the proximity of a small cylinder. The vortex formation length is defined as the streamwise distance between the cylinder center and the location where the spectral amplitude of velocity fluctuation reaches the maximum. In our preliminary studies for $D/d \geqslant 4$ arranged side-by-side, the small cylinder merely provides local disturbance and minor modification on the neighboring separating shear layer of the large cylinder. For the case of diameter ratio two, the small cylinder is expected to affect the separating shear layers of the large cylinder and vice versa, leading to different flow categories far downstream. So far, the vortex interaction and the influencing mechanisms are still relatively unexplored and require further investigations. Thus, in this study, the flow structures behind the side-by-side cylinders of diameter ratio two ($D/d = 2$) spaced at three gap ratios ($G^* = 0.25$, 0.75 and 1.25) are studied by the PIV system. The frequencies are measured on the free stream sides along the shear layer of both cylinders at Re = 1000, 2000 and 5000 to show the variation trends of the Strouhal numbers as the gap ratio changes. Velocity measurements are made and processed for Re = 1000 to demonstrate the spatial distributions of the spectral amplitude over the flow domain for different gap ratios. Also, the spatial growth and the delay distance of the onset of the shear layer instability along the outer shear layers of both cylinders are analyzed to disclose the mechanism leading to different frequencies of the narrow and the wide wakes.

2. Experimental system and techniques

2.1. Coordinate system and flow parameters

Fig. 1 defines the flow parameters and the coordinate system of the side-by-side cylinders of diameter ratio two placed in a uniform stream of magnitude U. For the two-cylinder system, the origin is located at the center of small cylinder with diameter d (d = 1 cm). The diameter of large cylinder is denoted as D. The characteristic frequencies of the narrow and wide wakes are defined by f_n and f_w, respectively. In this study, the diameter D and the vortex shedding frequency f_{sL} of a single cylinder with diameter D are employed as the reference length and frequency. The positive X and Y directions are defined along the inflow direction and upward normal to the incoming flow, respectively. The plane at $Z = 0$