Wake Patterns of Two Oscillating Cylinders

Dae Sung Lee*, Man Yeong Ha†, Hyun Sik Yoon**

Abstract

Flows around two oscillating cylinders in side-by-side arrangement at Re=185 are simulated using immersed boundary method. The cylinders oscillate vertically with prescribed sinusoidal function in opposite directions in uniform cross-flow. Flow patterns and drag & lift forces are described by varying distance between two cylinders and oscillating frequency. Time series of flow patterns are investigated along with corresponding drag & lift coefficients.

Key Words : Oscillating Cylinder(진동하는 실린더), Wake pattern(후류 형태)

1. Introduction

Oscillating cylinders in cross or stationary flow are frequently observed in engineering problems such as offshore structure and power cable. Naturally there are a lot of researches on the oscillating cylinders.

Williamson and Roshko(1), Gu et al(2), Guilmineau and Queutey(3) studied flow over single oscillating cylinder. Gu et al(2) investigated flow over an oscillating cylinder where Reynolds number as 185 and 5000 with experiment. The frequency ratios which are defined as oscillating frequency over natural vortex shedding frequency of fixed cylinder were 0.8, 0.9, 1.0, 1.1, 1.12 and 1.2.

Kang(4) investigated flows over two stationary cylinders in side-by-side arrangement at $40 \le \mathrm{Re} \le 160$ and the gap spacing between two cylinders divide by cylinder diameter, g is less than 5. He classified six wake patterns as "anti-phase synchronized" ($g \ge 2$), "in-phase synchronized" ($g \ge 1.5$), "flip-flopping" ($0.4 \le g \le 1.5$), "single bluff-body" ($g \le 0.4$), "deflected" ($50 \le \mathrm{Re} \le 110$ and $0.2 \le g \le 1$) and "steady" wake patterns ($\mathrm{Re} \le 40$ and $g \ge 0.5$).

Mahir and Rockwell(5) experimentally studied flows over two oscillating cylinders in side-by-side arrangement in a cross flow. Two cylinders oscillated independently with variable phase angle between two cylinders' position at Re=160. They varied frequency ratio, phase angle and amplitude and measured velocities in the wake. They focused Fourier transformed velocity in the wake and instantaneous fields and investigated the lock-on phenomenon.

As there are a few results for flows over two oscillating cylinders, wake patterns of two oscillating cylinders will be investigated numerically in this study.

2. Numerical details

The governing equations which are non-dimensionalized by free stream velocity, U and cylinder diameter, D are as follows:

$$\frac{\partial u_i}{\partial x_i} - q = 0 \tag{1}$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial u_i \partial u_j}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{1}{Re}\frac{\partial^2 u_i}{\partial x_j \partial x_j} + f_i \tag{2}$$

Here, q is mass sink/source, f_i is momentum forcing, Re is Reynolds number. Oscillating cylinders are implemented by immersed boundary method of Kim et al(6).

Finite volume method with non-uniform gird is adopted. We used Adams-Bashforth for convection terms, Crank-Nicolson for diffusion terms and central difference for space discretization. Continuity is satisfied with fractional step method(7) for every time step.

Computational domain is -60<x<40 and -60<y<60. Boundary conditions are described in Fig. 1. 900×682 grid points are used and near the cylinder $\Delta x = 0.01$ and $\Delta y = 0.01$ is used.

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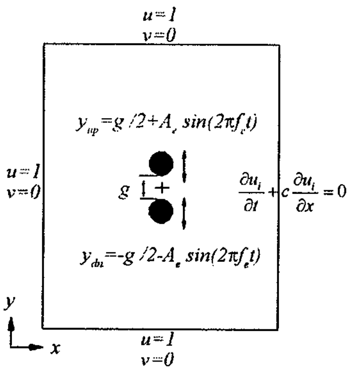


Fig. 1. Computational domains and boundary conditions.

Cylinder oscillation is described in Fig. 1. The Reynolds number is 185 and oscillation amplitude, A_e is 0.2 and frequency, f_e is varied. The natural vortex shedding frequency of one fixed cylinder at Re=185, f_o is 0.192. The frequency ratio, f_e/f_o is 0.8, 1.0 and 1.2 in this study.

3. Results

Two oscillating cylinders have characteristics of oscillation and multiple cylinders with variable gap between cylinders. As cylinders oscillate, the characteristics may differ from those of stationary cylinders and flow pattern of two cylinders is different from that of one cylinder. In this study, the gap between two cylinders is the primary parameter and the oscillation frequency is the secondary parameter and the results will be described in this order.

Firstly, the largest dimensionless gap between two cylinders in this study, for g_o=1.8, dimensionless gap are between 1.4 and 2.2 as the two cylinders oscillates. According to Kang(4), for two stationary cylinders with $1.4 \le g \le 2.2$ at Re=185 shows anti- or in-phase synchronized pattern.

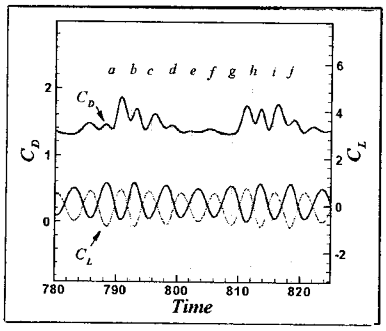


Fig. 2. *Drag and lift coefficients of* g_o=1.8 *and* f_e/f_o=0.8.

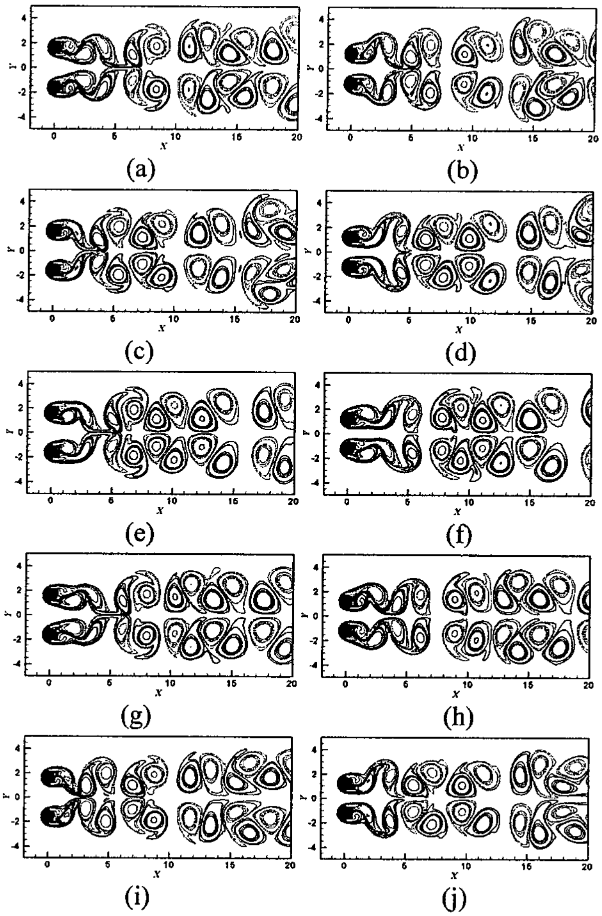


Fig. 3. Times series of instantaneous vorticity fields for g_o=1.8 and f_e/f_o=0.8

Fig. 2 shows time evolution of drag and lift coefficients for upper and lower cylinder for g_o=1.8 and f_e/f_o=0.8. Solid line is for upper cylinder and dashed line is for lower cylinder. Drag coefficient is composed of fluctuating ((a)-(d), (g)-(j)) and rather flat patterns ((d)-(g)). Every index, 'a' - 'j' in Fig. 2 corresponds to indexed instantaneous vorticity field in Fig. 3 which shows instantaneous vorticity fields of two oscillating cylinders when the two cylinders are at the furthest and closest positions in turn. (Hereinafter every instantaneous fields are plotted in this manner) Anti-phase vortex shedding forms two parallel anti-phase streets that are symmetric to the centerline. In Fig 3 (a), outer vortices that are rolled up around the cylinder reach about 1.7 in x-direction. The length of outer vortices keeps increasing in Fig. (a), (c), (e) and (g) and suddenly decreases in (i) and this happens periodically. The structure of wake patterns is kept symmetrically to far downstream without merge. While those phenomenon like modulation is not shown for one oscillation cylinder f_e/f_o=0.8, it can be seen for two oscillating cylinders with interferences between symmetric vortices from two cylinders.

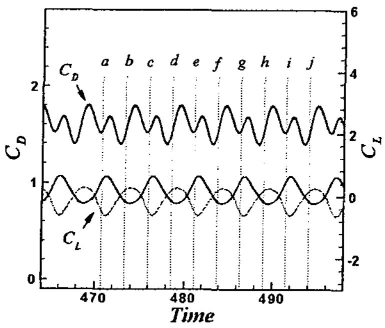
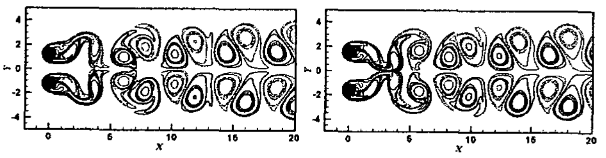


Fig. 4. Drag and lift coefficients of g_o =1.8 and f_e/f_o =1.0



(a) (b)

Fig. 5. Times series of instantaneous vorticity fields for g_o=1.8 and f_e/f_o =1.0

When f_e/f_o =1.0 that is near resonance frequency ratio, Fig. 4 shows very regular drag and lift coefficients. Unlike f_e/f_o =0.8, f_e/f_o =1.0 has same patterns for same furthest positions and closest positions respectively in Fig. 5 which shows instantaneous vorticity fields. Therefore only two instantaneous vorticity fields are shown in Fig. 5. The vortices in the wake keep their symmetric forms without merging or distortion to far down stream.

As oscillating frequency is increased to 1.2, symmetric wake pattern breaks and modulation phenomenon appeared. Even though two stationary cylinders with g_o=1.8 does not have flip-flop pattern, drag coefficients shows flip-flop like pattern because of asymmetry. Fig. 6 shows a part of asymmetric and periodic drag and lift coefficients and points from (a) to (l) make one period. Vortices are asymmetric and some of them are merged and distorted while flowing to downstream.

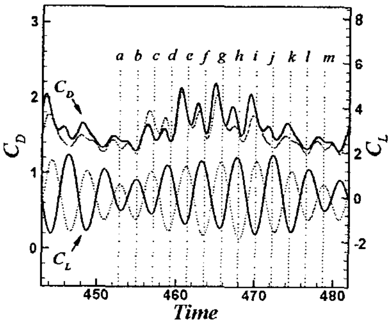
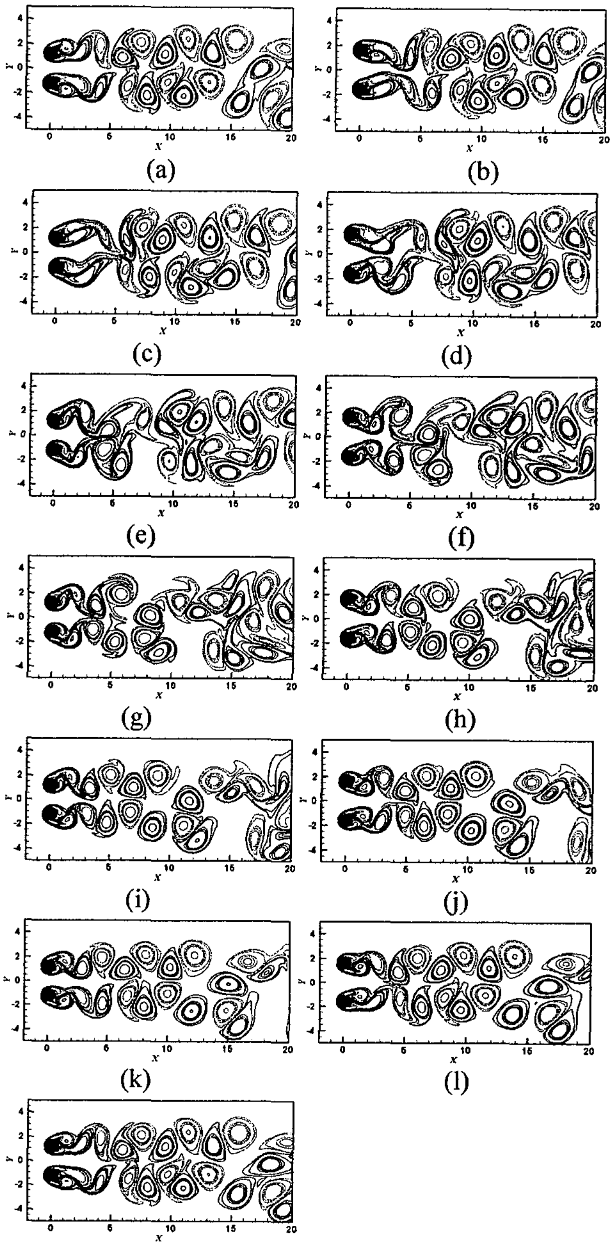


Fig. 6. Drag and lift coefficients of g_o =1.8 and f_e/f_o =1.2



(a) (b) (c) (d) (e) (f) (g) (h) (i) (j) (k) (l) (m)

Fig. 7. Times series of instantaneous vorticity fields for g_o=1.8 and f_e/f_o =1.2

In Fig. 7 (a) and (c), the inner vortices around the cylinders are rather long and they are to be cut by outer vortices, but in (e) they became short suddenly and are going to cut the outer vortices. The position of vortex shedding is switched. It is similar to vortex switching that is found in one oscillating cylinder as frequency ratio is increased over near 1.1(2,3). However, for one oscillating cylinder vortex switching is found as the frequency ratio is increased while it happens for same frequency ratio for two cylinders. The inner vortices are kept short till (k) and (m) has same wake pattern with (a), so (a) – (l) makes one complete period. Comparing with

f_e/f_o =0.8 and f_e/f_o =1.2, they have same phenomenon such as the change of length of vortices around the cylinders and similar history of drag coefficient that has fluctuating and rather flat patterns. For g_o=1.8, in-phase synchronized and deflected pattern are found for $0.8 \le f_e/f_o \le 1.2$.

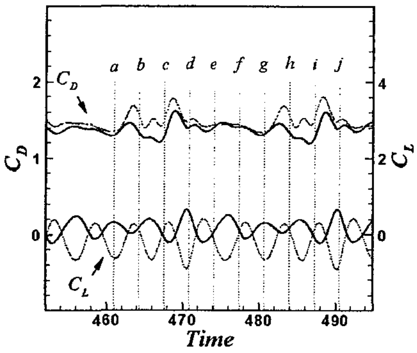
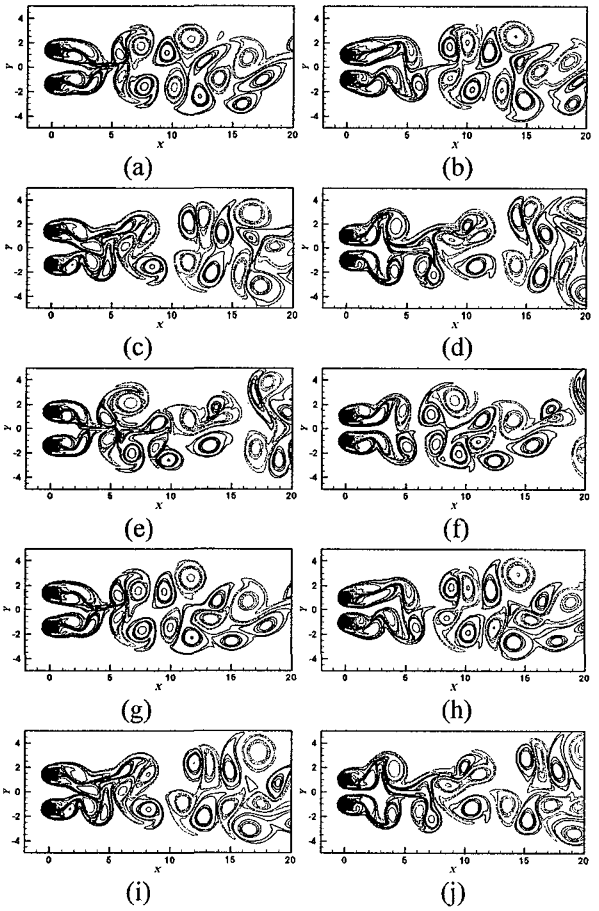


Fig. 8. Drag and lift coefficients of g_o=1.4 and f_e/f_o =0.8



(a) (b) (c) (d) (e) (f) (g) (h) (i) (j)

Fig. 9. Times series of instantaneous vorticity fields for g_o=1.4 and f_e/f_o =0.8

When the g_o is decreased to 1.4, g is between 1.0 and 1.8. That regime includes flip-flop and anti- or in-phase synchronized wake pattern for two stationary cylinders. (4) Time history of drag and lift coefficients of two oscillating cylinders are depicted in Fig. 8 and they are similar to Fig. 2 for g_o =1.8 and f_e/f_o =0.8. However, upper and lower drag coefficients are not same and upper and lower lift coefficients are not symmetric. Fig. 9 (a) and (g) looks very similar to each other and points from (a) to (f) makes one complete period. The outer vortices around the upper cylinder are getting shorter as time goes by in Fig. 9 (a), (c), (e) and get longer again in (g). As g has flip-flop region for two stationary cylinders, also oscillating cylinders have asymmetric wake pattern. However, drag coefficients in Fig. 8 are seemed to be deflected pattern rather than flip-flop pattern. According to Kang(4), it can be inferred that the deflected wake pattern should be another kind of the flip-flopping pattern with extremely large flip-flopping time scale as mentioning Kim and Durbin's observation(8). In their study, the time scale for the flip-flopping exponentially increased with decreasing Reynolds number at high Reynolds numbers and its extrapolation to low Reynolds numbers would give extremely large time scales.

As frequency ratio, f_e/f_o is increased to 1.0, the pattern of drag and lift coefficients and instantaneous vorticity fields are similar to the case of g_o=1.8. So, the figures for f_e/f_o =1.0 are omitted.

Unlike g_o =1.8, even if the frequency ratio is increased to 1.2, the symmetric pattern is kept. Flow over two stationary cylinders is asymmetric for g_o=1.8 and in-phase synchronized for g_o=1.4. The flow pattern is symmetric for two oscillating cylinders with g_o=1.4 and asymmetric for g_o=1.8. The characteristics of stationary flow may affect flow over oscillating cylinders. Fig. 11 (a) and (m) are nearly same and the length of outer vortices keep decreasing through (a) to (k) and (m) shows vortices as long as (a). So, the period is inferred to be from (a) to (l). All characteristics are similar to that of g_o=1.8 except of symmetry of flow pattern. For g_o=1.4, in-phase synchronized and deflected pattern are found for $0.8 \le f_e/f_o \le 1.2$.

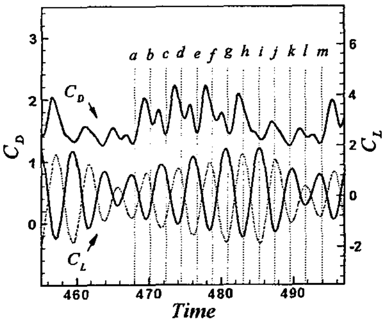
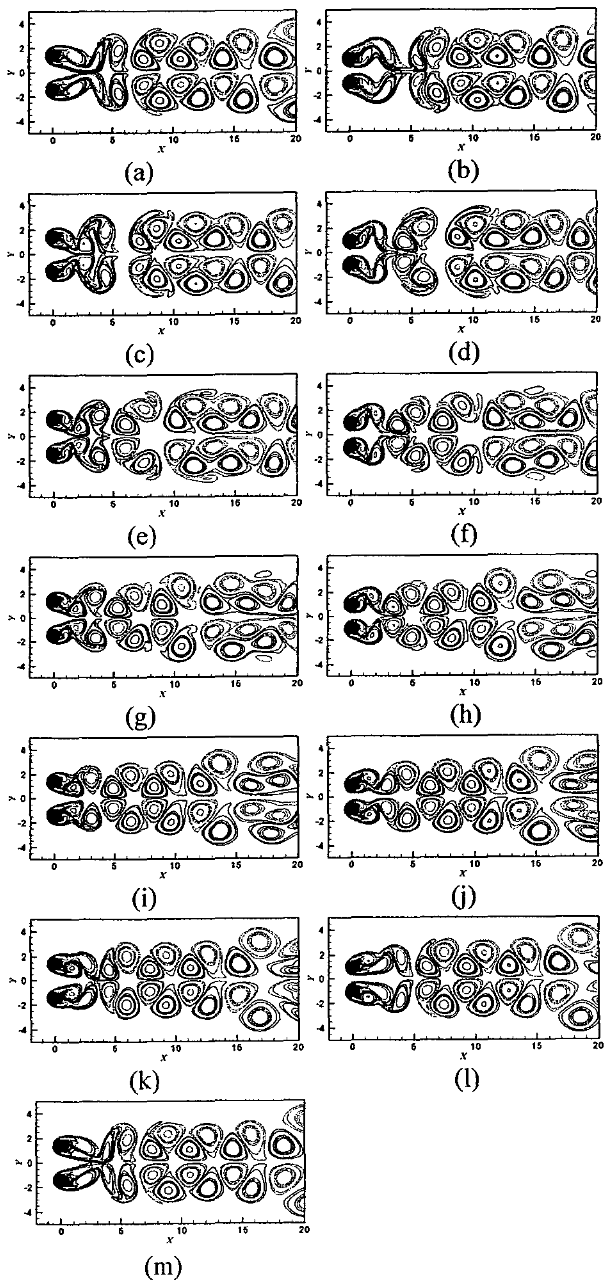


Fig. 10. Drag and lift coefficients of g_o =1.4 and f_e/f_o =1.2



(a) (b) (c) (d) (e) (f) (g) (h) (i) (j) (k) (l) (m)

Fig. 11. Times series of instantaneous vorticity fields for g_o=1.4 and f_e/f_o =1.2

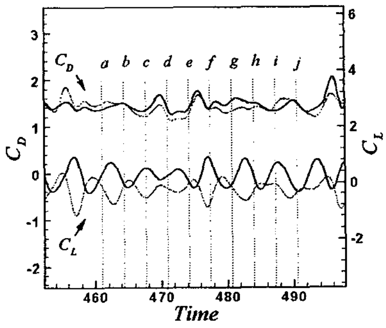
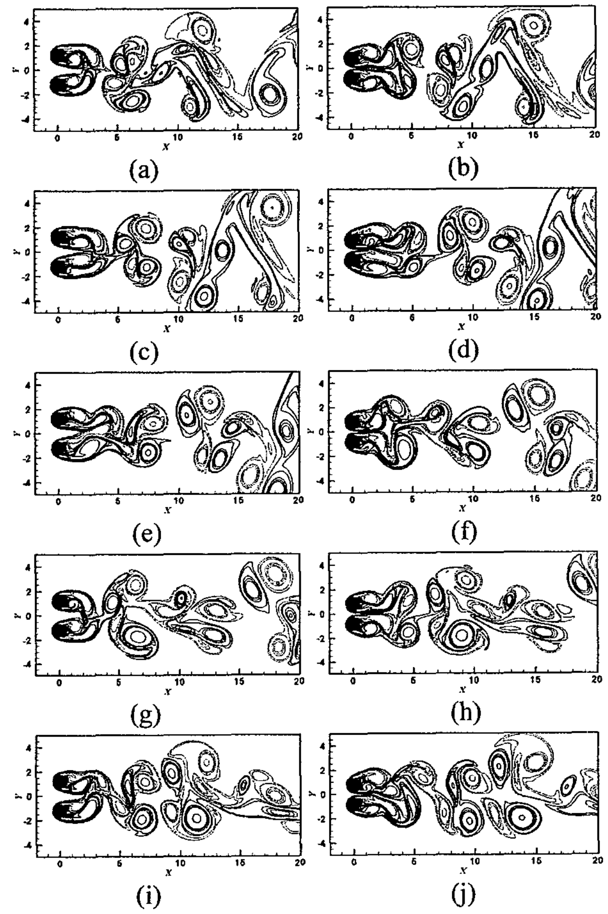


Fig. 12. Drag and lift coefficients of g_o =1.0 and f_e/f_o =0.8



(a) (b) (c) (d) (e) (f) (g) (h) (i) (j)

Fig. 13. Times series of instantaneous vorticity fields for g_o=1.0 and f_e/f_o =0.8

When the g_o is decreased to 1.0, g is between 0.6 and 1.4. That regime includes flip-flop and anti- or in-phase synchronized wake pattern for two stationary cylinders.(4) For f_e/f_o =0.8, drag and lift coefficients are described in Fig. 12 and patterns more irregular comparing with g_o =1.4. According to the drag coefficients, flip-flop pattern can be found but anti- or in-phase synchronized pattern cannot be found. Instantaneous vorticity patterns are shown in Fig. 13. In instantaneous fields, some has symmetric pattern for only near wake and some has deflected near wake pattern. Vortices shed from the cylinders are distorted and merged soon making complex and random wake pattern and periodic pattern is not clear. When the cylinders are in closest positions, they are so close that vortex shedding is interfered from each other. Far downstream is different from those of previous cases which have the form of two row streets.

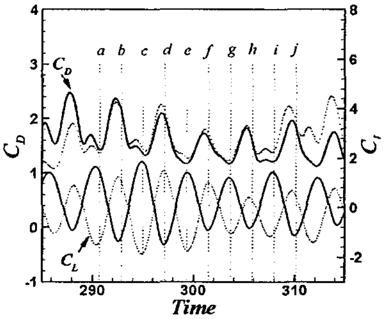


Fig. 14. Drag and lift coefficients of g_o=1.0 and f_e/f_o =1.2

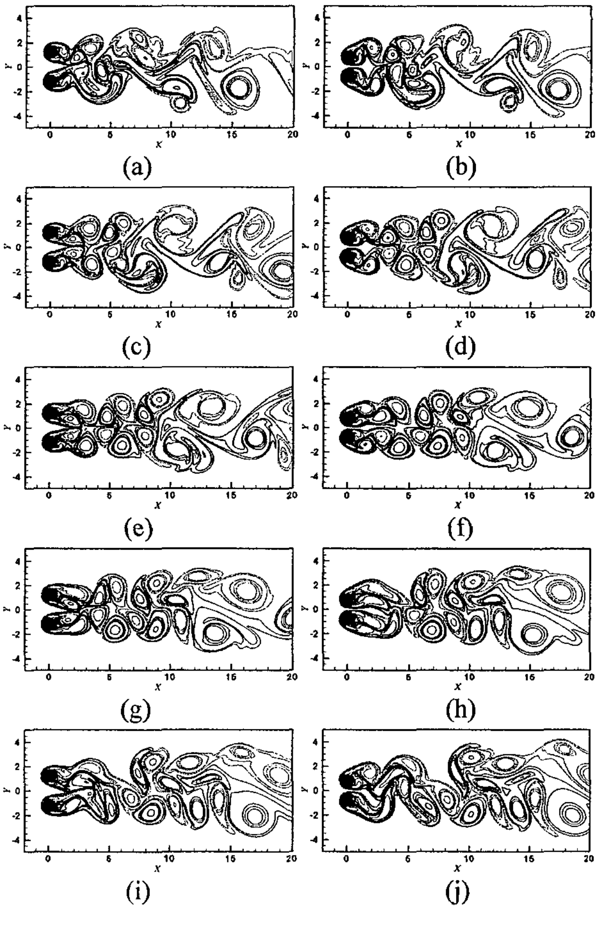


Fig. 15. Times series of instantaneous vorticity fields for g_o=1.0 and f_e/f_o =1.2

For f_e/f_o =1.0, the pattern of drag and lift coefficients and instantaneous vorticity fields are similar to the case of g_o=1.8. So, the figures for f_e/f_o =1.0 are omitted.

When f_e/f_o is increased to 1.2, Fig. 14 and Fig. 15 show drag and lift coefficients and instantaneous vorticity fields respectively. While the wake patterns of g_o=1.4 and 1.8 show periodicity with irregular drag and lift coefficients, g_o=1.0 shows unclear sign of periodicity with rather regular drag and lift coefficients. The vortices near the cylinders are anti-phase synchronized patterns except Fig. 15 (i) that seems to be rather in-phase than anti-phase. Regular vortices near cylinders are keeping their form from (a) to (e), but in (h) the vortices are distorted and merged. After merging of two rows of streets, wake pattern is similar to the single bluff body. For g_o =1.0, single bluff body, flip-flop in-phase synchronized and anti-phased synchronized pattern are found for $0.8 \le f_e/f_o \le 1.2$.

When the g_o is decreased to 0.6, g is between 0.2 and 1.0. That regime includes single bluff body and flip-flop wake patterns for two stationary cylinders.[(4)]

For f_e/f_o is 0.8, as the gap between two cylinders are so small, vortex shedding is suppressed and shed vortices experience interference from each other. So, the drag and lift coefficients are random and asymmetric in Fig. 16. The outer vortices merge right after they shed from the cylinders and form the wake pattern similar to that of single bluff body. In Fig. 17 (a), outer vortex around the upper cylinder cuts the outer vortex of lower cylinder as the two vortices are from the same single bluff body.

Even though f_e/f_o is 1.0, unlike other cases with same frequency ratio, drag and lift coefficients in Fig. 18 are asymmetric and deflected. As the cylinder oscillates with near resonance frequency, the vortex shedding is stronger and far down stream wake pattern in Fig. 19 look like single bluff body than f_e/f_o =0.8.

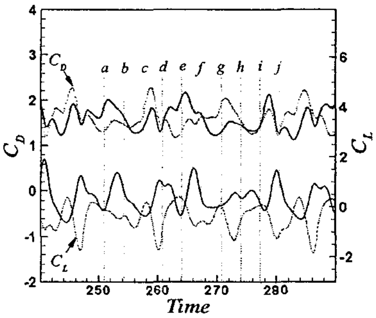


Fig. 16. Drag and lift coefficients of g_o=0.6 and f_e/f_o =0.8

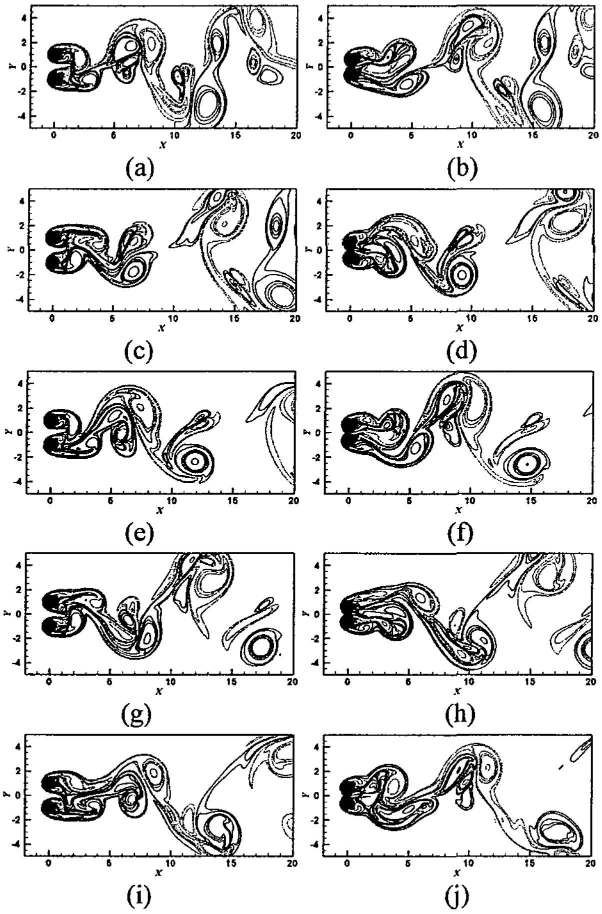

(a) (b) (c) (d) (e) (f) (g) (h) (i) (j)

Fig. 17. Times series of instantaneous vorticity fields for g_o=1.0 and f_e/f_o=0.8

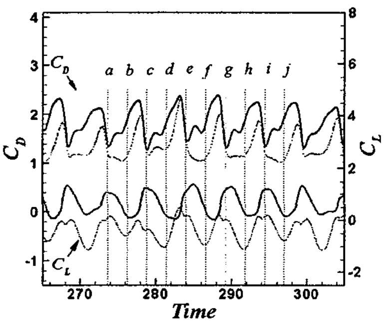


Fig. 18. Drag and lift coefficients of g_o=0.6 and f_e/f_o=1.0

If f_e/f_o is increased to 1.2, general pattern of drag and lift coefficients in Fig. 20 are similar to the case of g_o=1.0 and f_e/f_o=1.2 and now the modulation is nearly disappeared. Wake pattern in Fig. 21 has no symmetric part that are partially found in g_o=1.0.

As g_o is increased, the portion of two row vortex streets is increased. For g_o=1.0, single bluff body, flip-flop pattern are found for $0.8 \leq f_e/f_o \leq 1.2$.

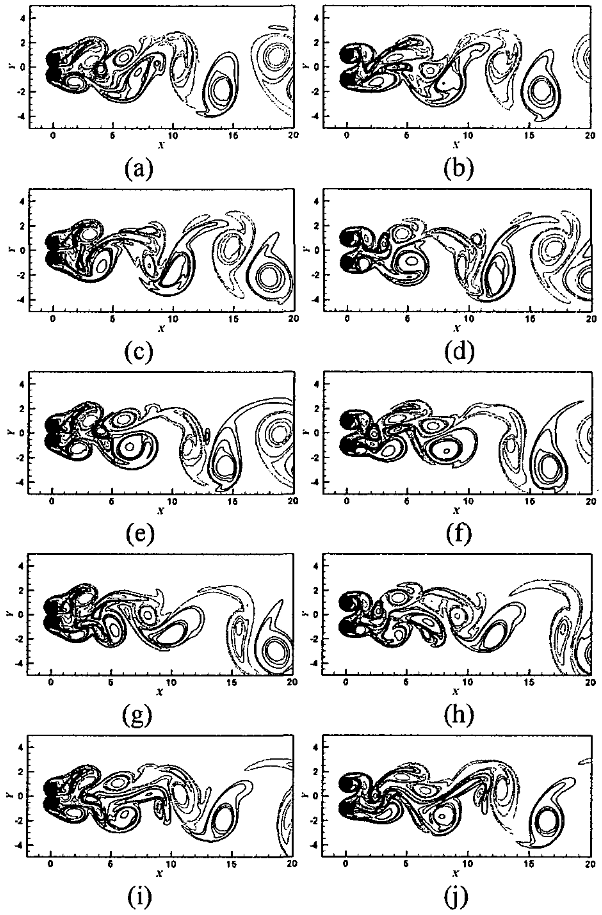

(a) (b) (c) (d) (e) (f) (g) (h) (i) (j)

Fig. 19. Times series of instantaneous vorticity fields for g_o=0.6 and f_e/f_o=1.0

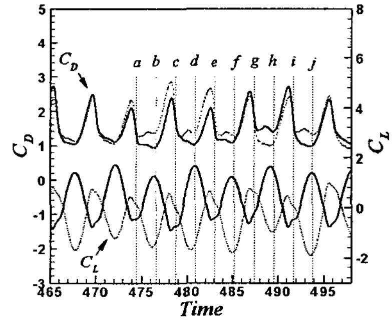
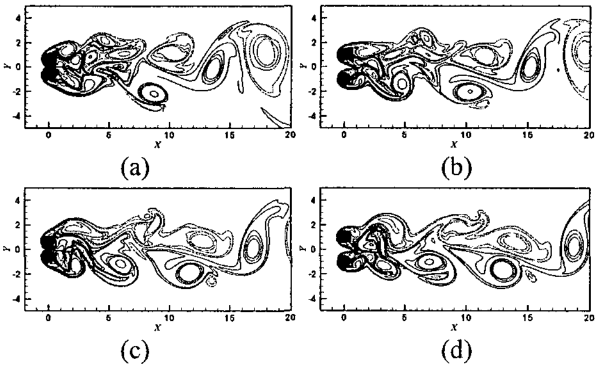


Fig. 20. Drag and lift coefficients of g_o=0.6 and f_e/f_o=1.2


(a) (b) (c) (d)

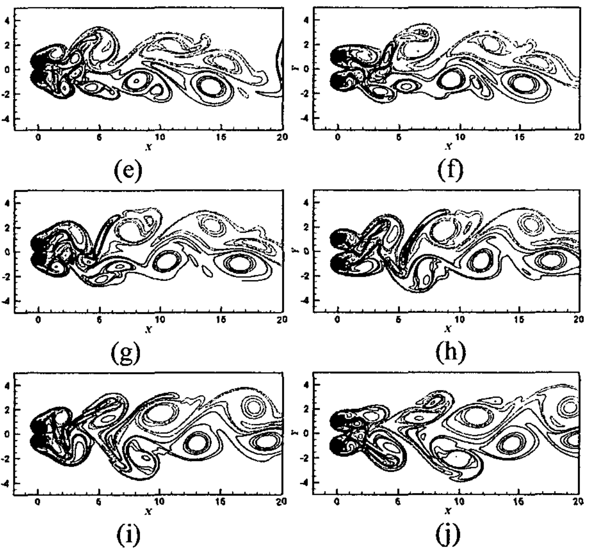


Fig. 21. Times series of instantaneous vorticity fields for g_o=0.6 and f_e/f_o =1.2

4. Conclusions

Wake pattern of two oscillating cylinders are numerically investigated. The dimensionless gap between two cylinders and frequency ratio are the main parameters that determine wake patterns.

Various wake patterns of two stationary cylinders can be found in oscillating cylinders for same dimensionless gap and the also additional patterns can be seen for oscillating cylinders with oscillation effect.

Oscillation frequency has strong effect on the pattern of drag & lift coefficients and also flow patterns except small gap such as g_o =0.6. For f_e/f_o =1.0, near resonance frequency ratio, flow pattern is nearly same for g_o>0.6.

Two oscillating cylinders have different flow patterns from the single oscillating cylinders for same frequency ratio as the vortices interfere together.

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