109 Fluid Forces Acting on Two Side-by-Side Circular Cylinders
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Fluid forces acting on two stationary circular cylinders in a side-by-side arrangement were investigated experimentally in a uniform flow at a Reynolds number of 5.5×10^{3}. For a spacing ratio of T/D<1.5 (T, spacing between the cylinders; D, diameter), the gap flow was biased to one side, resulting in the formation of a narrower wake behind one cylinder and a wider wake behind the other. Steady and fluctuating fluid forces acting on the cylinders were decomposed for the narrower wake and the wider wake flow patterns. For T/D>0.20, the action of lift forces on both cylinders was in an outward direction (repulsive); however, for T/D=0.10, the action of lift force on the cylinder associated with the narrower wake was inward and that on the other cylinder was outward. Steady drag and fluctuating fluid forces were comparatively higher for the narrower wake. For T/D=0.10-0.20 and 1.2-1.50, the mean drag induced by the narrower wake and the wider wake was greater than that of a single cylinder.

Key words: Fluid Forces, Circular Cylinders, Side-by-side Arrangement

1. INTRODUCTION
It is important to understand the interaction of multiple structures in flow to avoid detrimental vibration. In the bistable flow regime of two side-by-side cylinders, as the gap flow randomly switches from one side to the other, it is difficult to measure the fluid forces induced by the narrower wake and the wider wake separately. In order to make modes sufficiently stable, Zdravkovich & Pridden [1] slightly staggered the cylinders and measured steady fluid forces acting on them. They found that the sum of drag of the cylinders in the bistable flow regime was always less than twice the drag of a single cylinder and lift forces acting on the cylinders were always repulsive. However, results obtained by Hori [2] showed that, for T/D=0.2, 1.0, and 2.0, the sum of the drag of the cylinder pair was greater than that of the two cylinders in isolation. The data obtained in previous studies on steady fluid force are inconsistent, and there have been few studies pertaining to unsteady fluid force acting on two cylinders. The focus of this study was on determination of the characteristics of steady and fluctuating fluid forces acting on two side-by-side circular cylinders.

2. EXPERIMENTAL DETAILS
Experiments were conducted in a closed-circuit wind tunnel with a test section of 300×1200 mm. The cylinders used as test models were made of brass and were each 49 mm in diameter. The geometric blockage ratio and aspect ratio at the test section were 4% and 6, respectively. Fluid forces acting on a cylinder were measured by using two load cells installed inside a cylinder. To measure the surface pressure during experiments, a semiconductor pressure transducer (Toyoda PD104K) with a range of ±10 kPa was used. The pressure transducer responded to pressure fluctuation up to 500 Hz with a gain factor of 1±0.06, the phase lag being negligible.

3. RESULTS AND DISCUSSION

3.1. Steady Fluid Forces
The variation in drag coefficient, C_D and lift coefficient, C_L of two side-by-side cylinders as a function of spacing ratio are shown in Fig. 1. Two values of C_D for two different flow patterns (mode 'NW' and mode 'WW') on a cylinder were decomposed by using conditional sampling technique in the digitally stored data. For T/D>1.5, the gap flow was not biased and the same drag forces acted on the both cylinders. In the bistable flow regime, T/D=0.10-1.50, the difference between magnitudes of C_D for mode 'NW' and mode 'WW' is larger for small spacing. The magnitude of C_D at T/D=0.10 for mode 'NW' is 1.69 which is 1.5-times greater than that of a single cylinder.

In the case of lift force [Fig. 1(b)], repulsive (outward-direction) force was considered as positive, and
attractive (inward-direction) force was considered as negative. The lift force coefficients at $T/D=0.10$ are interesting. The coefficients are $-0.12$ and $0.65$ for modes 'NW' and 'WW', respectively; i.e., there is a large difference between the values, and attractive force is also possible for two side-by-side cylinders in the bistable flow regime.

In order to determine the nature of the flow pattern that induced negative lift force on the cylinder, the pressure coefficient, $C_p$, was also evaluated separately for modes 'NW' and 'WW' at $T/D=0.10$, and the results are shown in Fig. 2(a). It can be seen in the figure that the stagnation point (positive pressure region) shifts toward the inner side at $330^\circ$ instead of $0^\circ$, and this is a cause of repulsive lift force. The pressure at the inside surface toward which gap flow is biased (mode 'NW') is more negative than that of the mode 'WW'. Thus, in the case of mode 'NW', resultant pressure force normal to the free-stream flow is inward (negative $C_L$).

![Fig. 2. (a) Pressure coefficient, $C_p$, distributions for $T/D=0.10$, (b) flow visualization pattern for $T/D=0.10$.](image)

The flow visualization pattern ([Fig. 2(b)]) supports the pressure distribution shown in Fig. 2(a). The flow pattern shows that an earlier separation of the gap flow occurs from the lower cylinder (positive $C_L$) and that the gap flow is directed along the surface of the upper cylinder, and finally the gap flow separates from the cylinder in the base region. The lift force acting on the cylinders can also be explained in light of circulation, which is defined as the line integral about a close path (periphery of the cylinder) of the tangential velocity component along the path. It is obvious from the figure that net circulation around the lower cylinder is certainly anticlockwise, thus producing a downward (positive) lift force. On the other hand, as the gap flow is directed along the periphery of the upper cylinder for a longer peripheral length, the net circulation around the cylinder is anticlockwise, resulting in a downward (negative) lift force on the upper cylinder.

### 3.2. Fluctuating Fluid Forces

Fluctuating drag coefficient, $C_{DF}$, and fluctuating lift coefficient, $C_{LF}$, distributions for two cylinders are shown in Fig. 3. It can be seen that fluctuating drag and lift are very small at and near $T/D=0.50$. In the figure, apparently, the difference between values of $C_{DF}$ due to the mode 'NW' and mode 'WW' is comparatively larger in the range of $T/D=0.80-1.2$. In this range of $T/D$, the difference in $C_{LF}$ is also large. For $T/D = 1.3-3$, fluctuating fluid forces are considerably greater than that of a single cylinder. This may be due to the predominance of stronger in-phase (wake behind a cylinder is mirror image of the other) vortex shedding from the cylinders.

![Fig. 3. Fluctuating fluid force coefficient distributions: (a) $C_{DF}$, (b) $C_{LF}$, ---, single cylinder.](image)

### 4. CONCLUSIONS

1. The mode 'NW' causes a higher $C_D$, $C_{DF}$, $C_L$, and lower $C_L$, while the mode 'WW' causes a lower $C_D$, $C_{DF}$, $C_L$, and higher $C_L$, on the respective cylinders.

2. The differences in $C_{DF}$ and $C_L$ induced by modes 'NW' and 'WW' are greater in the range of $T/D=0.8-1.2$. $C_{DF}$ and $C_L$ are considerably greater than that of a single cylinder for $T/D=1.3-3$.

3. The action of lift forces on the cylinders is outward (repulsive) for $T/D > 0.2$. However, for $T/D=0.10$, an inward lift force, $C_L = -0.12$, acts on a cylinder that is associated with mode 'NW'.

### 5. REFERENCES
