北見工業大学研究報告
第17巻 第2号 (昭和61年)

Memoirs of the Kitami Institute of Technology
Vol. 17 No. 2 (1986)

Pressure Fluctuations on the Surface of Two Circular Cylinders in Tandem Arrangement*

by Masaru MORIYA** and Hiroshi SAKAMOTO**

(Received September 25, 1985)

Abstract

The fluctuating pressures on the surfaces of two circular cylinders of the same diameter in a tandem arrangement were measured in the subcritical region in order to obtain the distributions of their r. m. s. values of lift and drag coefficient as a function of the spacing between the two cylinders. The spacing ranged from 2.0 to 6.0 diameters. Also, the time historys of the fluctuating lift and drag coefficients could be obtained by a conditional sampling technique. The results strongly suggested that the r. m. s. pressure and the r. m. s. lift force incaeased in a steplike manner at the critical spacing where vortex shedding will just occur from the upstream cylinder. The r. m. s. value of the fluctuating lift coefficient was much larger than that of the drag coefficient for the upstream and downstream cylinders.

1. Introduction

The interference of flow around two circular cylinders has been extensively studied by many investigators. However, there is very little reported to show the surface-pressure fluctuations and fluctuating fluid forces. Authors have already reported the r. m. s. pressure distributions on the surface of cylinders and the spanwise and circumferential pressure correlations between two points[1]. They yielded information about the spanwise coherence of the fluctuating drag and lift forces and properties of r. m. s. fluctuating forces.

In this paper, the properties of the fluctuating pressure on the surface of two circular cylinders in a tandem arrangement are presented in some detail for various different spacings between the cylinders. Measurements are mainly made of fluctuating fluid forces acting on the cylinders, and the fluctuating fluid forces are evaluated using the conditional sampling technique.

2. Experimental apparatus and procedure

The experimental work was carried out in a closed-circuit wind tunnel which has 0.5 m × 0.5 m cross section and a 2.5 m long rectangular test section. Time-mean velocity distributions were measured at several cross sections ahead of the upstream cylinder by means of a Pitot-static tube. Flow two-dimensionality at the test section was well maintained with 6.2 d (d : diameter of the circular cylinder) from the center plane of the wind tunnel and the nonuniformity was

* Presented at the 23th Hokkaido regional meeting of the JSME (September, 1981), Kitami

** Department of Mechanical Engineering, Kitami Institute of Technology.

less than 1%. The free-stream velocity in this experiment was maintained constant at $U_\infty = 20 \pm 0.2$ m/s and the r. m. s. longitudinal velocity fluctuation was about 0.4% of the approch velocity.

The downstream and upstream cylinders tested were machied brass and aluminum respectively with 49 mm diameter, d, with a smooth surface finish. The cylinders were placed at the test section at right angles to the approach flow, and the clearance between the cylinders and the wind tunnel walls was sealed with "0" rings. The flow blockage due to the presence of the cylinder is 9.8% in area. A 0.8 mm diameter pressure tap was located at the center of the span to measure the time-mean pressure on the surface of the cylinder by Betz type manometer with its accuracy of 0.2 mmAq. And time-mean pressure distribution was obtained by rotating the cylinder every 10 defrees from 0 to 180 degrees.

Also the fluctuating pressure on the surface of the cylinder was measured by a semiconductor pressure transducer. The pressure sensing element was installed inside the cylinder with a small cavity between the opening of the tap and the diaphram of the transducer. The pressure transducer responded to pressure fluctuation up to 500 Hz with a gain factor of 1 ± 0.06, the phase lag being negligible. This frequency was well above the frequencies of vortex shedding from the upstream and downstream cylinders.

In order to evaluate the fluctuating forces, first ensemble averaging of the fluctuating pressure on the circumference of the cylinder for each angular position was conducted. Then the ensemble-averaged time variation of pressure along the circumference on the surface of the cylinder was obtained from each phase. The fluctuating forces can be calculated from integration of the ensemble-averaged time variation of pressure along the circumference.

3. Results and Discussion

A defitive sketch of two cylinders in a tandem arrangement is shown in Fig. 1. The diameter of the cylinders is denoted by d and the distance between their centers by l. The angle measured from the front stagnation point is written as θ for the upstream and downstream cylinders. The Reynolds number R $(=U_\infty d/\nu)$ was maintained at 9.0×10^4 throughout the present experiment.

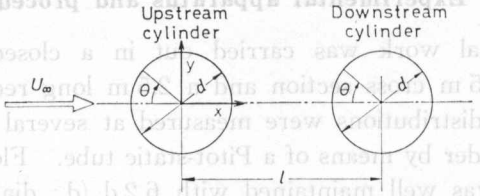

Fig. 1. Two circular cylinders in a tandem arrangement.

3.1 Time-mean pressure, drag and Strouhal number

The time-mean pressure ditributions on the surface of the upstream and

downstream cylinders are presented in Fig. 2 for several nondimentional spacings l/d. These results are seen to agree fairly well with other investigators[1,2].

The time-mean drag coefficients C_D for the upstream and downstream cylinders versus l/d are plotted in Fig. 3 together with those obtained by Arie et al.[1] and Okajima[3] respectively at approximately the same Reynolds number.

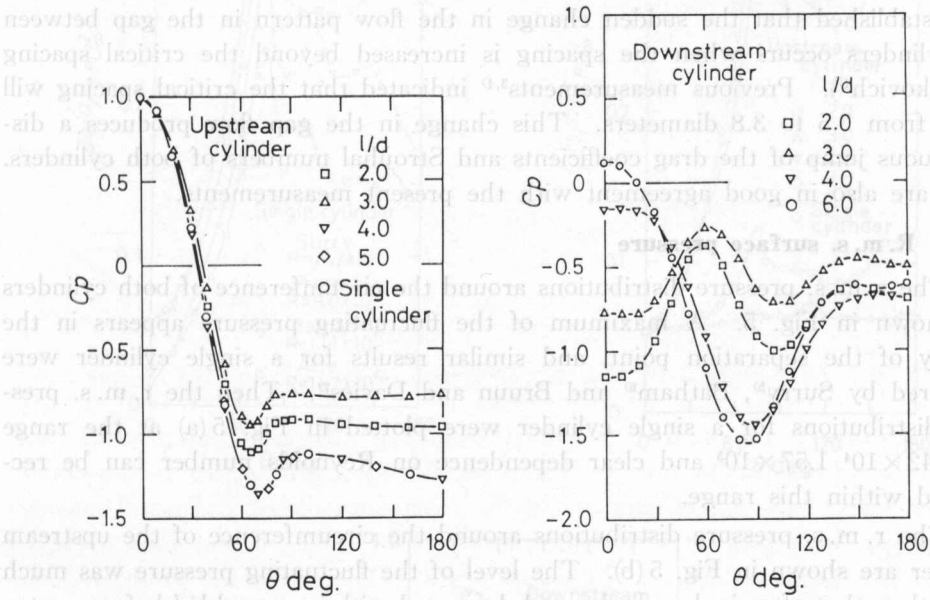

Fig. 2. Time-mean pressure distribution on the surface of (a) upstream and (b) downstream cylinder.

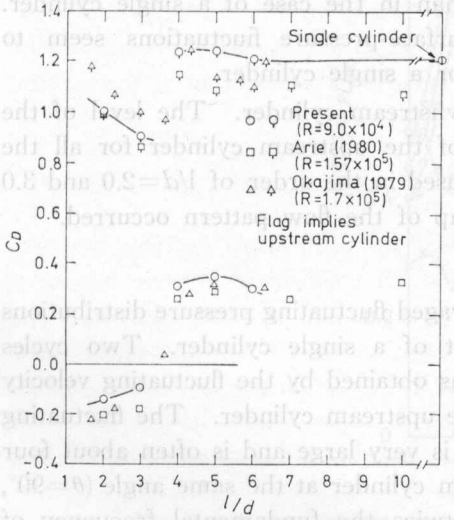

Fig. 3. Time-mean drag coefficient plotted against nondimensional spacing l/d.

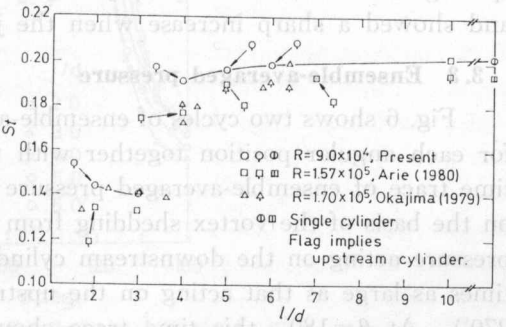

Fig. 4. Strouhal number plotted against nondimensional spacing l/d.

The vortex shedding frequency was determined on the basis of the power spectrum of the surface-pressure fluctuation, i. e. the frequency corresponding to a spectrum peak. The results are shown in Fig. 4 in the form of the Strouhal number S_t versus l/d. The Strouhal number are seen to be almost the same. Also, the results of the present experiment agree with Arie's[1] and Okajima's[3] data taken at Reynolds number $R=1.57\times10^5$ and 1.7×10^5, respectively. It is well established that the sudden change in the flow pattern in the gap between the cylinders occurs when the spacing is increased beyond the critical spacing (Zdravkovich[4]). Previous measurements[3,4] indicated that the critical spacing will range from 3.5 to 3.8 diameters. This change in the gap flow produces a discontinuous jump of the drag coefficients and Strouhal numbers of both cylinders. They are also in good agreement with the present measurements.

3.2 R. m. s. surface pressure

The r. m. s. pressure distributions around the circumference of both cylinders are shown in Fig. 5. A maximum of the fluctuating pressure appears in the vicinity of the separation point, and similar results for a single cylinder were measured by Surry[5], Batham[6] and Bruun and Davies[7]. Then the r. m. s. pressure distributions for a single cylinder were plotted in Fig. 5 (a) at the range $R=4.42\times10^4$ 1.57×10^5 and clear dependence on Reynolds number can be recognised within this range.

The r. m. s. pressure distributions around the circumference of the upstream cylinder are shown in Fig. 5 (b). The level of the fluctuating pressure was much lower than that of a single cylinder and decreased with increased l/d before vortex shedding from the upstream cylinder occurred, i. e. for l/d 3.5. Immediately after the occurrence of the vortex shedding ($l/d=4.0$), however, the r. m. s. pressures sharply increased to a level much higher than in the case of a single cylinder. For spacings greater than $l/d=4.0$, the surface-pressure fiuctuations seem to decrease monotonically to approach those for a single cylinder.

Fig. 5 (c) shows the results for the downstream cylinder. The level of the r. m. s. value was much higher than that of the upstream cylinder for all the spacings tested. The r. m. s. pressure decrsased in the order of $l/d=2.0$ and 3.0 and showed a sharp increase when the jump of the flow pattern occurred.

3.3 Ensemble-averaged pressure

Fig. 6 shows two cycles of ensemble-averaged fluctuating pressure distributions for each angular position together with that of a single cylinder. Two cycles time trace of ensemble-averaged pressure was obtained by the fluctuating velocity on the basis of the vortex shedding from the upstream cylinder. The fluctuating pressure acting on the downstream cylinder is very large and is often about four times as large as that acting on the upstream cylinder at the same angle ($\theta=90°$, 270°). At $\theta=180°$, this time trace shows twice the fundamental frequency of vortex shedding, and also the phase turn over at $\theta=90°$ and 270° for both cylinders.

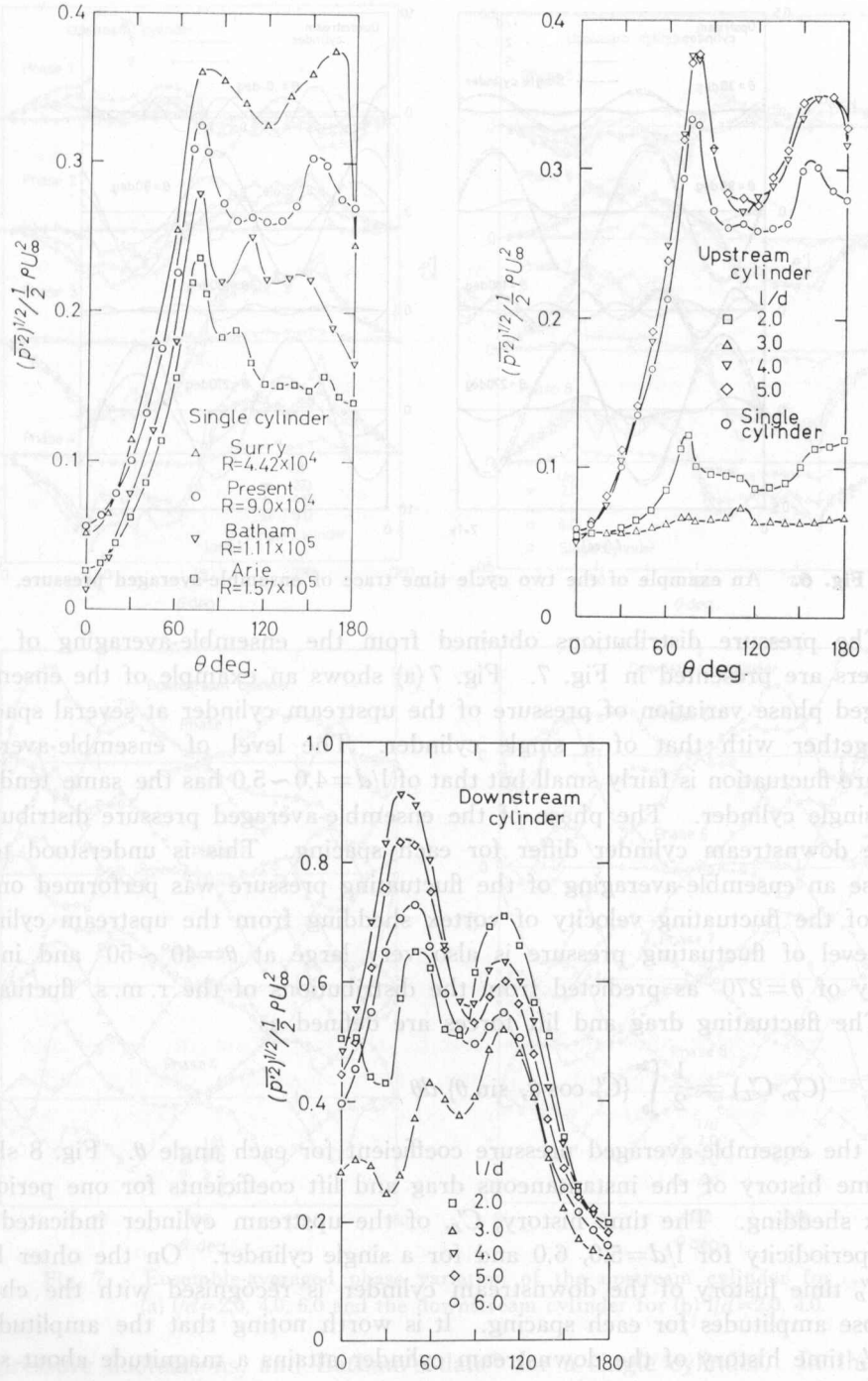

Fig. 5. R. m. s. surface-pressure distribution of (a) single, (b) upstream and (c) downstream cylinder.

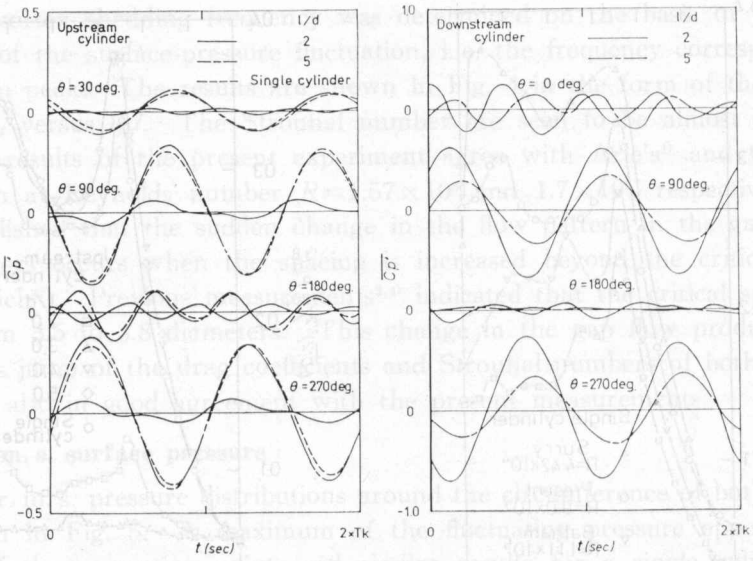

Fig. 6. An example of the two cycle time trace of ensemble-averaged pressure.

The pressure distributions obtained from the ensemble-averaging of both cylinders are presented in Fig. 7. Fig. 7 (a) shows an example of the ensemble-averaged phase variation of pressure of the upstream cylinder at several spacings l/d together with that of a single cylinder. The level of ensemble-averaged pressure fluctuation is fairly small but that of $l/d=4.0\sim5.0$ has the same tendency as a single cylinder. The phase of the ensemble-averaged pressure distributions of the downstream cylinder differ for each spacing. This is understood to be because an ensemble-averaging of the fluctuating pressure was performed on the basis of the fluctuating velocity of vortex shedding from the upstream cylinder. The level of fluctuating pressure is also very large at $\theta=40^\circ\sim50^\circ$ and in the vicinity of $\theta=270^\circ$ as predicted from the distributions of the r. m. s. fluctuation.

The fluctuating drag and lift forces are defined as

$$\{C'_D, C'_L\} = \frac{1}{2}\int_0^{2\pi} \{\bar{C}'_P \cos\theta,\ \sin\theta\}\, d\theta$$

$\bar{C}'_P$ is the ensemble-averaged pressure coefficient for each angle θ. Fig. 8 shows the time history of the instantaneous drag and lift coefficients for one period of vortex shedding. The time history, C'_D, of the upstream cylinder indicated the clear periodicity for $l/d=5.0$, 6.0 and for a single cylinder. On the ohter hand the C'_D time history of the downstream cylinder is recognised with the change of those amplitudes for each spacing. It is worth noting that the amplitude of the C'_L time history of the downstream cylinder attains a magnitude about seven times as large as that of the upstream cylinder.

The r. m. s. drag and lift coefficients evaluated from the time history of C'_D and C'_L are presented in Fig. 9. These experimental measurements are compared with Arie's measurements[1] obtained from the circumferential correlation of sur-

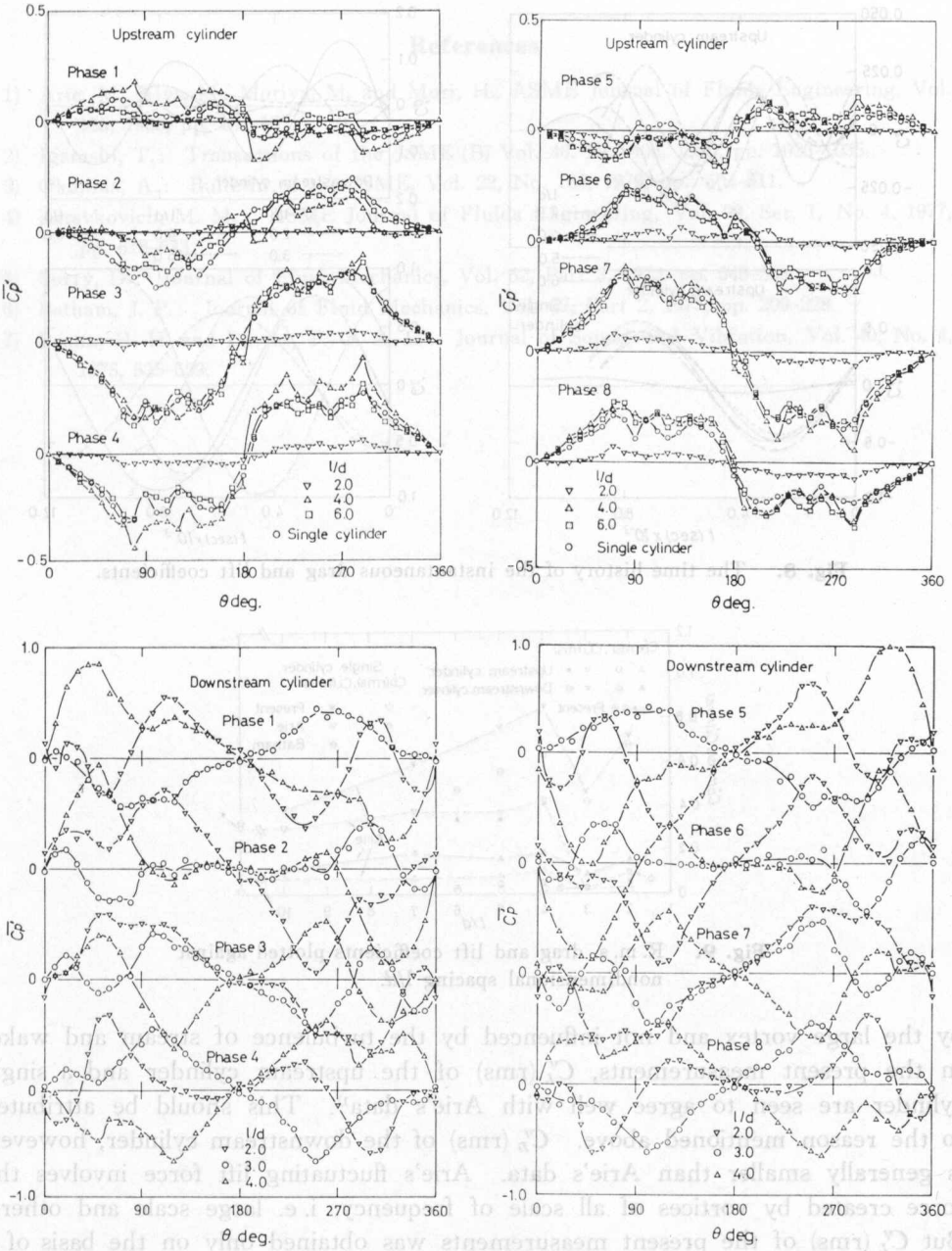

Fig. 7. Ensemble-averaged phase variation of the upstream cylinder for (a) $l/d=2.0$, 4.0, 6.0 and the downstream cylinder for (b) $l/d=2.0$, 4.0.

face-pressure fluctuations, and Batham's data[6] for a single cylinder. In the case of a single cylinder, Batham[6] and Surry[7] found that the fluctuating drag varied with the turbulent stream whereas the fluctuating lift was affected very little by the turbulent stream in comparison with the fluuctuating drag force. This was interpreted to mean that the major part of the fluctuating lift force was generated

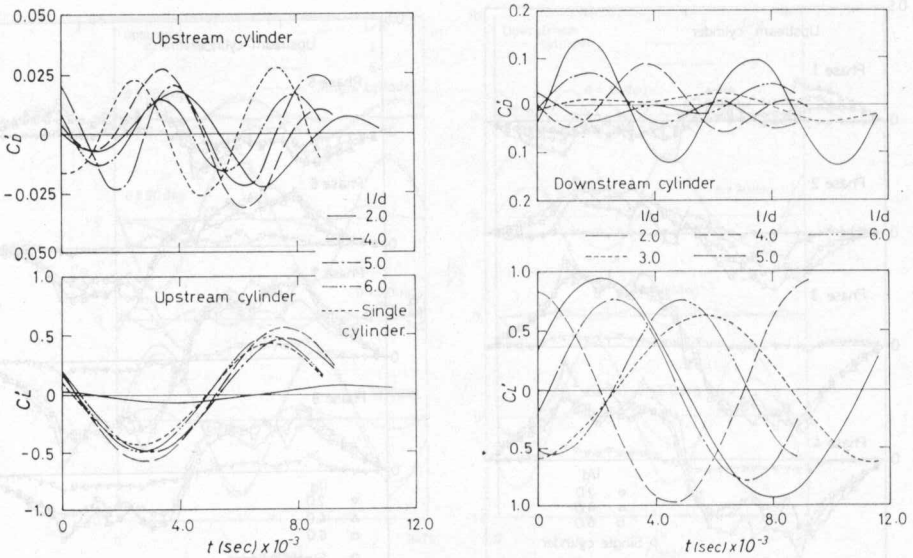

Fig. 8. The time history of the instantaneous drag and lift coefficients.

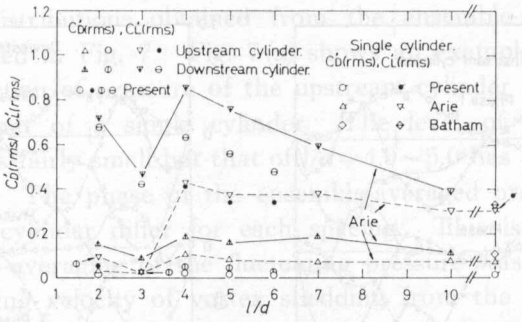

Fig. 9. R. m. s. drag and lift coefficients plotted against nondimensional spacing l/d.

by the large vortex and not influenced by the turbulence of stream and wake. In the present measurements, C'_L (rms) of the upstream cylinder and a single cylinder are seen to agree well with Arie's data[1]. This should be attributed to the reason mentioned above. C'_D (rms) of the downstream cylinder, however, is generally smaller than Arie's data. Arie's fluctuating lift force involves the force created by vortices of all scale of frequency, i. e. large scale and others. But C'_L (rms) of the present measurements was obtained only on the basis of a large scale vortex. Accordingly, it is understandable that the pressure measurements are smaller than Arie's data. Similar comments apply to the C'_D (rms) of the present measurements.

Acknowledgements

The authors express their sincere thanks to Mr. Y. Obata and Mr. K. Abe for their assistance in the contruction of the experimental apparatus.

References

1) Arie, M., Kiya, M., Moriya, M. and Mori, H., ASME Journal of Fluids Engineering, Vol. 105, 1980, pp. 161–167.
2) Igarashi, T.: Transactions of the JSME (B) Vol. 46, No. 406, 1980, pp. 1026–1035.
3) Okajima, A.: Bulletin of the JSME, Vol. 22, No. 166, 1979, pp. 504–511.
4) Zdrsvkovich, M. M.: ASME Journal of Fluids Engineering, Vol. 99, Ser. I, No. 4, 1977, pp. 618–633.
5) Surry, D.: Journal of Fluid Mechanics, Vol. 52, Part 3, 1972, pp. 543–563.
6) Batham, J. P.: Journal of Fluid Mechanics, Vol. 57, Part 2, 1973, pp. 209–228.
7) Bruun, H. H. and Davies, P. O. A. L.: Journal of Sound and Vibration, Vol. 40, No. 4, 1975, 535–559.