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DETERMINATION OF THE DRAG ON VIBRATING CIRCULAR CYLINDERS

By Sadatoshi TANEDA and Hiroyuki HONJI

Drag coefficients for circular cylinders performing a transverse oscillatory motion in a uniform water flow were measured at the range of Strouhal numbers (non-dimensionalized vibration frequencies) from about 0.02 to 0.5, Reynolds numbers from 47 to 275, and displacement/diameter ratios from 0.4 to 3.8. It was found that the drag coefficient of vibrating cylinders increases monotonically with the Strouhal number and the displacement/diameter ratio. There seems to be no possibility of reducing the drag on circular cylinders by oscillating them laterally.

1. Introduction

It is of hydrodynamical interest to evaluate experimentally the drag on a periodically vibrating circular cylinder placed in a stream of viscous fluid with its axis normal to the flow. In the present investigation drag coefficients for vibrating circular cylinders were measured at intermediate Reynolds numbers ranging from 47 to 275. Although the drag on a cylindrical obstacle at rest in a uniform fluid flow have been investigated from ealier times by Wieselsberger[1)] and others at various Reynolds numbers, the systematic measurement of the drag on a vibrating one has not yet been made in any place. It seems that much yet remains to be done with respect to the non-stationary motion of a body in a fluid flow, and the present work was conducted to take a step toward the problem.

It is well-known that at intermediate Reynolds numbers (nearly $50<R<300$) two-dimensional double vortex wake known as the Kármán vortex street is formed behind a cylindrical obstacle at rest in a uniform viscous flow, and that its shedding frequency has a close relation to the drag acting upon the obstacle. The shedding frequency of the vortices behind non-vibrating cylinders was investigated extensively by Roshko[2)], and the relationship between the Strouhal number and the Reynolds number was experimentally established up to $R=1400$. On the other hand, generation of the Kármán vortex street induces the corresponding periodic vibration of the obstacle placed in the flow. This fluid-induced vibration is a stumbling block from a practical standpoint, and hence has been continually investigated by a number of workers for the purpose of suppressing it. For example, an attempt on suppressing the vibration by the use of modified cylinders with a specially designed suppressor was recently made by Price[3)]. However, the experiment described here was not undertaken to investigate these practical problems.

Recently Koopmann[4] investigated experimentally the influence of periodic vibration of a circular cylinder on its downstream flow patterns near the natural shedding frequencies, and determined the regions over which the cylinder motion controls the shedding frequency of its vortex wake. In his experiment, however, the influence of oscillatory motion on the drag was not examined.

The drag coefficient C_D ($C_D = D/\frac{1}{2}\rho U^2 F$) may depend on such dimensionless variables as the Reynolds number R ($R = Ud/\nu$), the Strouhal number S ($S = Nd/U$) and the displacement/diameter ratio A/d, in the form

$$C_D = f\,(R, S, A/d),$$

where U is the mean velocity of flow, d the cylinder diameter, ν the kinematic viscosity, ρ the water density, F the projected area of the cylinder, and N the vibration frequency. By the Strouhal number is here meant the non-dimensionalized frequency of the periodic cylinder vibration. The measurements were made at Strouhal numbers ranging from 0.02 to 0.5. In this range, the natural shedding frequency of the vortex wake which formed while holding the cylinder stationary in a flow is contained. As the displacement/diameter ratios, values of 3.8, 2.3, 1.4 and 0.4 were employed. And also it was decided to make the measurements at Reynolds numbers of 47, 79, 104, 136, 163, 205 and 275, i.e. from the incipient Kármán range to the transition range.

2. Apparatus and Method

The uniform flows were obtained by moving a small water-filled tank (30 cm × 24 cm × 90 cm) mounted on a carrier at a known uniform velocity from 0.9 cm/s to 3.2 cm/s. The apparatus for measurements of the drag acting on vibrating circular cylinders is illustrated in Figure 1, and also its front view in

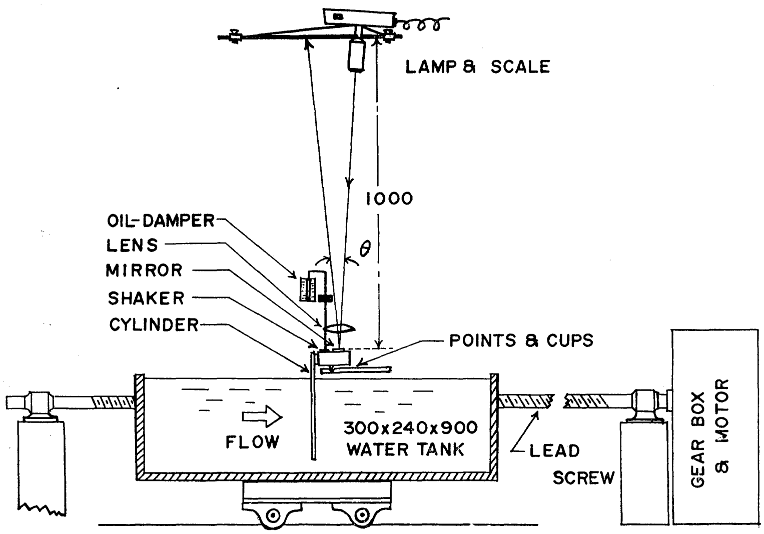

Fig. 1 Apparatus for measuring the drag on vibrating circular cylinders.

Photograph 1. A shaker system with a test cylinder attached to its front side was suspended as a pendulum at two points so as to be free to incline only in a plane parallel to the flow. The cylinder was forced to vibrate sinusoidally in the direction normal to the flow. Small angles of inclination of the pendulum system due to the drag on underwater part of the cylinder were detected with the aid of the lamp and scale method. The shaker system for driving the test cylinder consisted of a small DC drive motor, two dry batteries and several reduction gears. Two kinds of the shaker were made and used ; one for large amplitude tests (the transverse displacement was 1.14 cm) and the other for a small amplitude test (the transverse displacement was 0.21 cm). The system equipped with one of the test cylinders used is shown in Photograph 2.

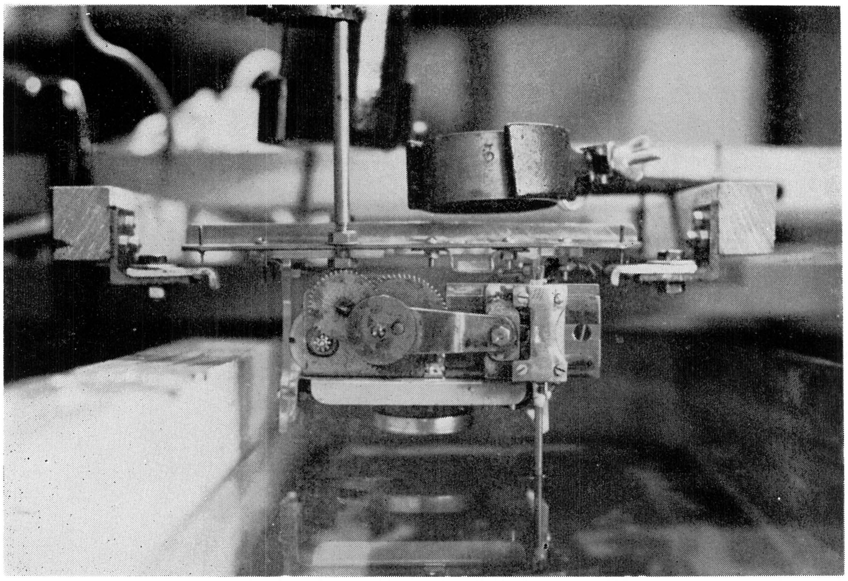

Photo. 1 Front view of experimental apparatus.

In order to avoid the initial shock resulting from starting acceleration, an oil damper was attached to the shaker system. The shaker system was also equipped with an adjustable weight consisting of a small iron block to control the sensitivity of the pendulum system for the drag. All the measurements were began after the flow became stationary. The total mass of the pendulum system composed of the large amplitude shaker, the oil damper, the balance controller and a test cylinder having a diameter of 0.5 cm was 830 g, and that of the small amplitude shaker system 483 g. Three well-polished metal circular cylinders (0.5 cm, 0.3 cm and 0.8 cm in diameter) were used. The displacement amplitude was 1.14 cm or 0.21 cm as previously noted. By combining these values appropriately the displacement/diameter ratios of 3.8, 2.3, 1.4, and 0.4 were employed in the experiment. The spanwise length of the cylinder immersed in the water flow exceeded 20 cm in all cases.

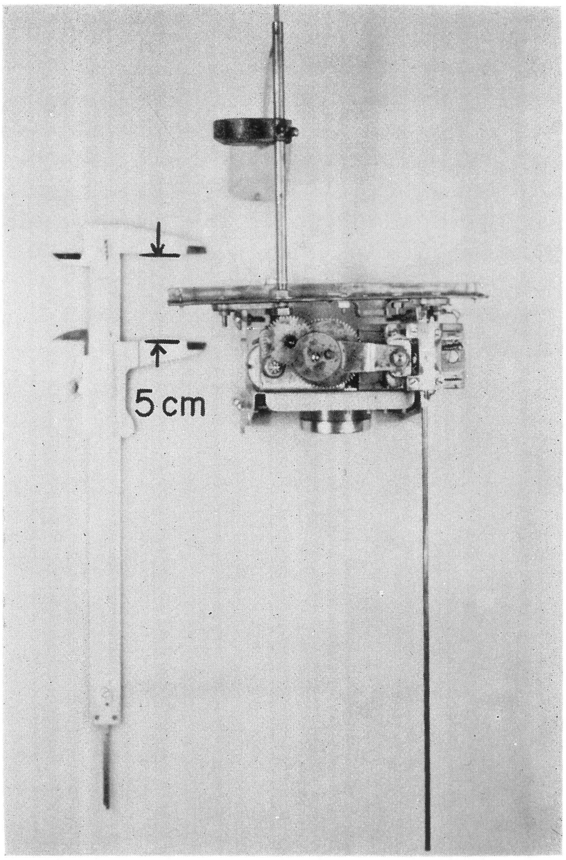

Photo. 2 Shaker equipped with a test cylinder.

A simple optical system well known as the lamp and scale method was used to detect the angle of inclination of the pendulum. A small mirror (0.1 cm × 0.2 cm) was pasted on the upper plate of the shaker system to reflect a reference ray, and immediately before that mirror a convex lens with a focus length of 100 cm was placed. The deviation angle θ in Figure 1 was determined by reading the light-spot displacement on the scale located at the position 100 cm apart from the mirror. Drag coefficients were determined with the known calibration curve. Driving frequencies of the cylinder were measured with a stop-watch by reading the period of every ten (in several cases, five) oscillations.

It should be noted that reciprocating displacement of the center of gravity of the pendulum system due to the rotational motion of one end of a crank rod was inevitable and this caused the corresponding deflection of the reflected light-spot on the scale, which acted as a noise for the measurements especially at the lower frequencies. In such complicated conditions as mentioned above the value at the middle point of the breadth of displacement on the scale was read as the real value for the non-disturbed case.

3. Presentation and Discussion of Results

The Reynolds number and the Strouhal number range over which the measurements were done is shown in Figure 2, where the ordinate indicates the ordinary Strouhal number, i.e. the non-dimensionalized shedding frequency of the vortices behind a stationary circular cylinder, and the abscissa the Reynolds number. A

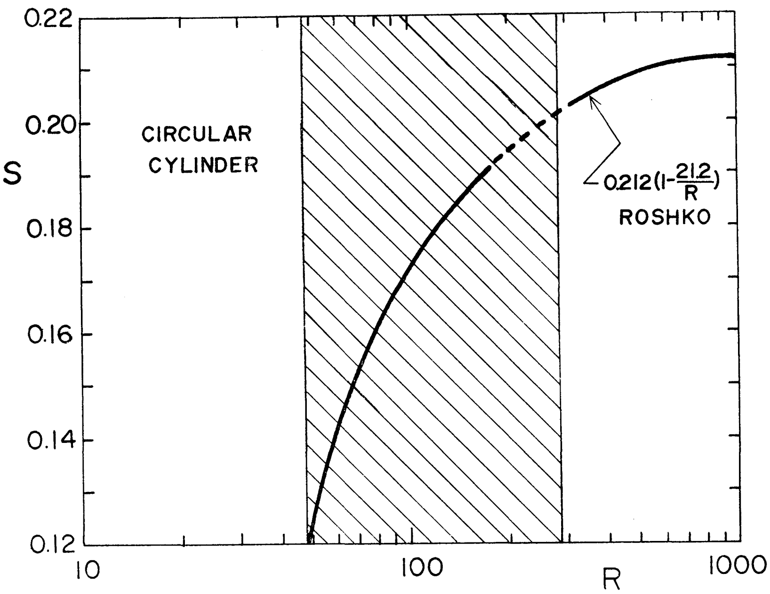

Fig. 2 Diagram of the range (shaded area) examined in the present investigation. (With respect to the Strouhal number, only the main part of the range examined is presented.)

Reynolds number of 47 corresponds approximately to that where the periodic vortex wake starts to develope, and a Reynolds number of 275 to that where the regular vortex street begins to collapse.

Under consideration of the equation $C_D = f(R, S, A/d)$, experimental values are arranged in curves between drag coefficient and Strouhal number and presented in Figures from (3) to (9) for each set of Reynolds numbers, where a horizontal broken line indicates the drag coefficient for a stationary circular cylinder, and a vertical broken line indicates the Strouhal number based on the natural shedding frequency of the vortices behind the corresponding stationary cylinder.

From these experimental results shown in the Figures, the following evidences are found. Most of the drag coefficients for the vibrating cylinders lie above the original value for the non-vibrating stationary cylinder, that is, the drag is increased in general by the vibrational motion of the cylinder. Although of particular interest were the cases when the driving frequency was identical to the natural shedding frequency of the vortices, unusual change is not found in the experimental curve at the corresponding points. There seems to be no possibility of reducing the drag on circular cylinders by oscillating them laterally.

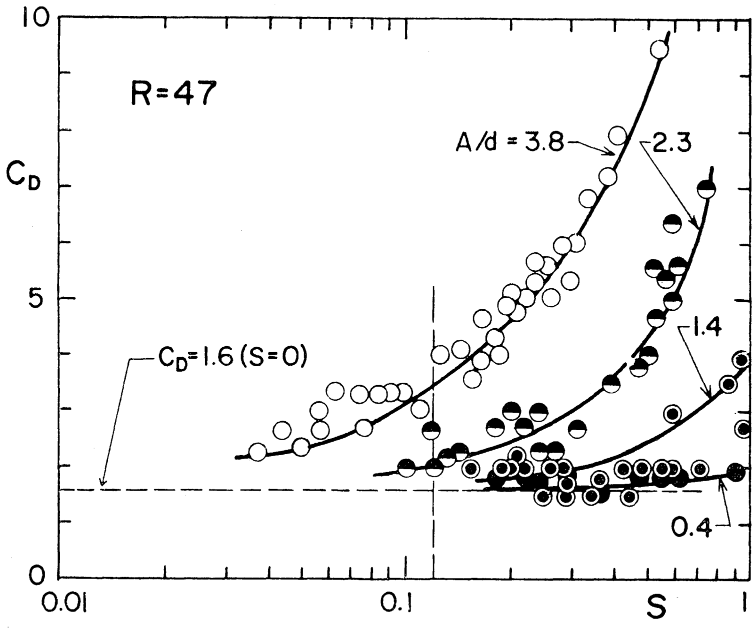

Fig. 3 Drag coefficient plotted against Strouhal number at R=47.

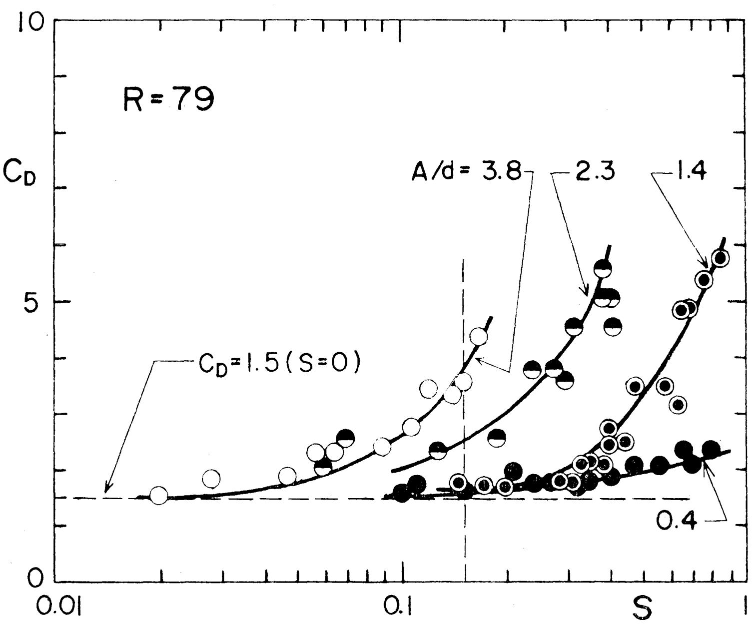

Fig. 4 Drag coefficient plotted against Strouhal number at R=79.

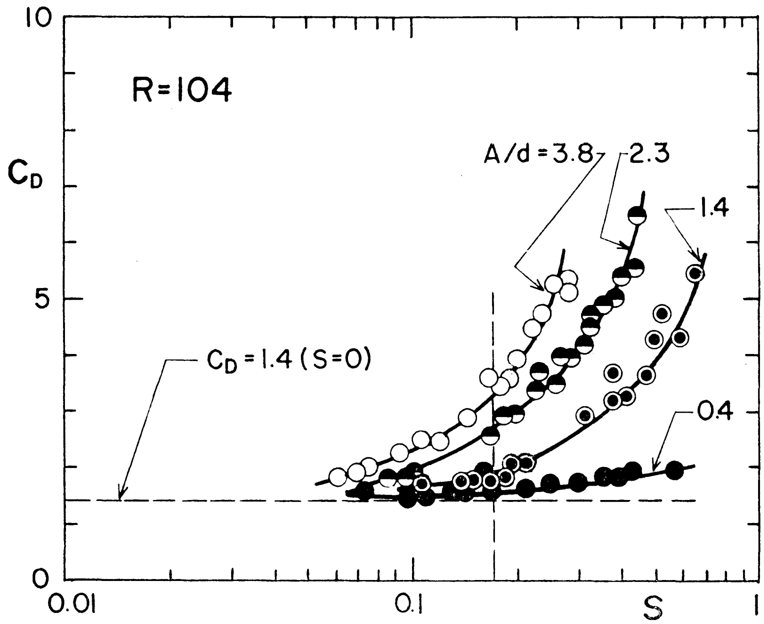

Fig. 5 Drag coefficient plotted against Strouhal number at R=104.

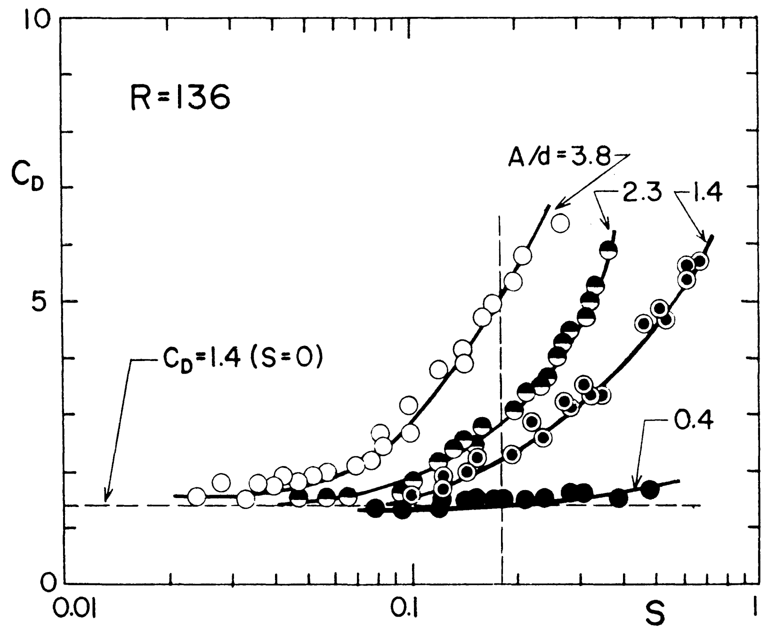

Fig. 6 Drag coefficient plotted against Strouhal number at R=136.

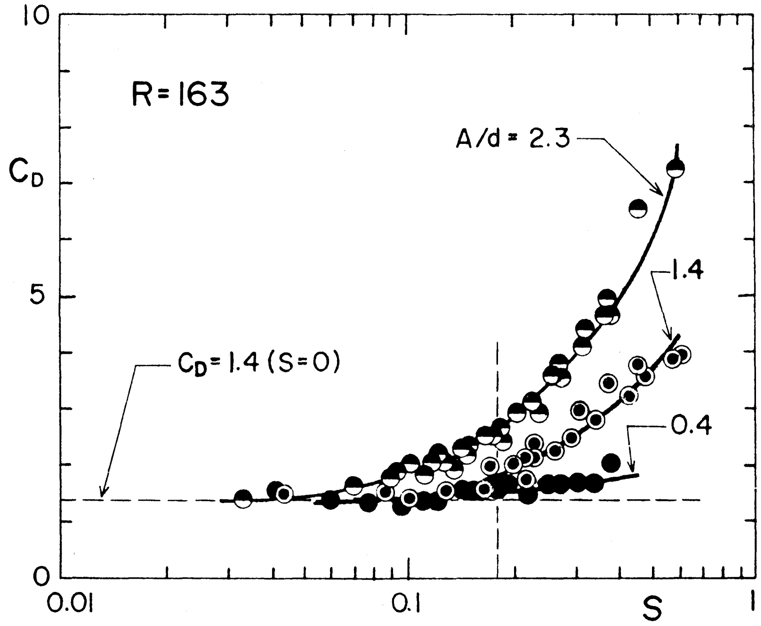

Fig. 7 Drag coefficient plotted against Strouhal number at R=163.

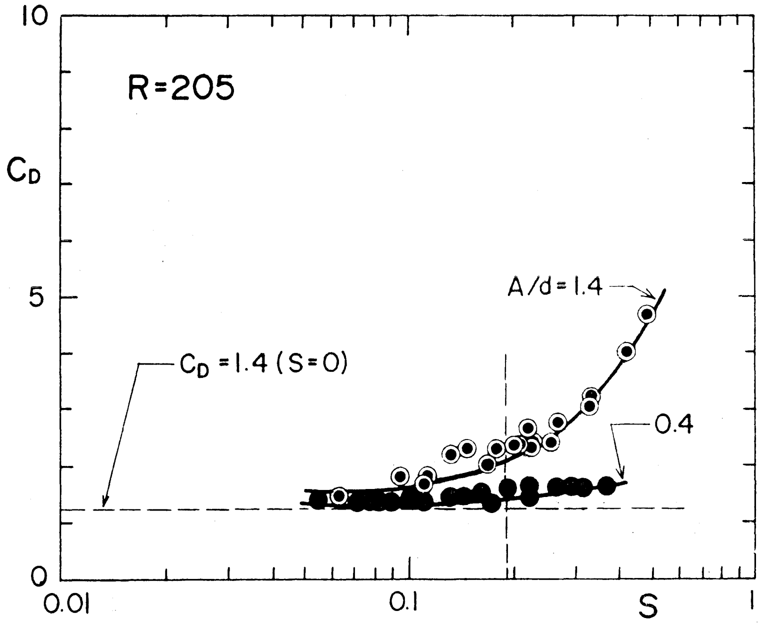

Fig. 8 Drag coefficient plotted against Strouhal number at R=205.

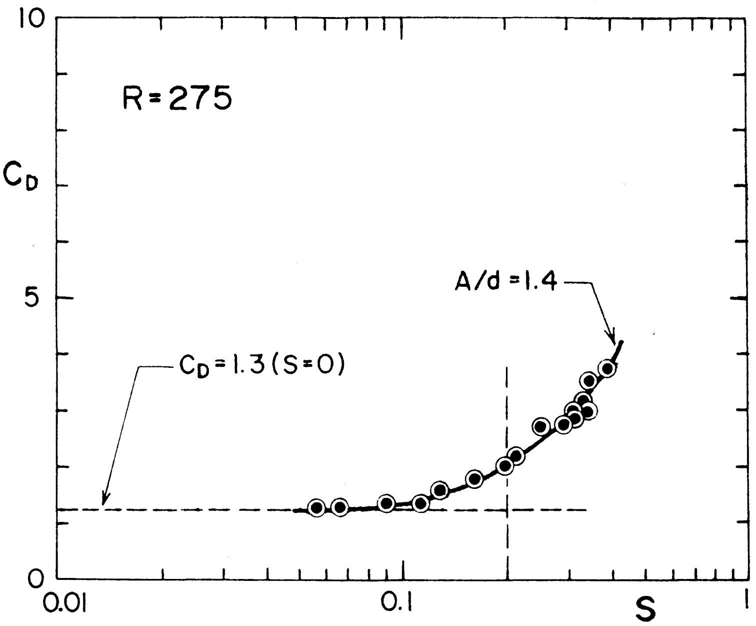

Fig. 9 Drag coefficient plotted against Strouhal number at R=275.

Drag coefficients for several displacement/diameter values are missing in the Figures showing the experimental results. For example, at a Reynolds number of 163 (Figure 7), a curve for the case of displacement/diameter ratio of 3.8 is not given there. Inherent limitations in the technique prevented investigation of the drag at such displacement/diameter ratio.

Koopmann has reported that when a threshold amplitude of about 10 % of the cylinder diameter is reached, a vibrational motion causes a remarkable change of the flow pattern. Since the amplitude in the present experiment exceeds 40 % of the cylinder diameter, it is not confirmed wether there also exists the critical lower limit of the displacement/diameter ratio with respect to the influence of the oscillatory motion on the drag as well as on the flow pattern. However, the fact that the drag coefficient for the displacement/diameter ratio of 0.4 remains almost constant over the Strouhal number range which was examined seems to be consistent with the experimental result of Koopmann.

4. Conclusion

The manner of the Strouhal number dependence of the drag coefficient for vibrating circular cylinders was revealed experimentally. From the results of drag measurements, it was found that the drag on a vibrating cylinder increases monotonically with the vibration frequency and the amplitude.

Although it is well-known that the drag is closely related to the flow pattern, the relationship between the drag and the wake geometry were not examined in the present investigation. Further experiments on the flow pattern behind periodically vibrating cylinders are being carried out by using a somewhat different type of apparatus, and the relationship betwen the flow pattern and the drag will be studied.

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