Fluid Forces on a Cylinder in the Oscillating Flow

By Takashi SAITOU*, Kesayoshi HADANO* and Kenichirou MOTO**

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Abstract

This paper presents the experimental results of the fluid forces acting on a circular cylinder placed in the oscillating flow at Keulegan-Carpenter number up to 38. The drag and inertia coefficients are determined through the use of Fourier average in applying Morison's formula to measured fluid forces. Further, the applicability of this formula is examined. Fluid forces (in-line and transverse forces) were measured simultaneously.

The visualization with aluminum dust shows that vortex shedding from the cylinder is devided into some patterns. Strouhal number in some range of KC number became smaller than that of seady flow because the vortex shedding is restricted by a return flow.

1. Introduction

For fluid forces on a body in the oscillating flow many investigations have been made to elucidate property of wave force acting on vertical piles which are mounted in the ocean of wave motion field. But the accurate values are not given, even to a circular cylinder, which is the simplest shape, because of complicated circumstance. There are two kinds of fluid forces on cylinders in oscillating flow, one is in-line force and the other is transverse force (lift force). In early works, in-line force mainly attracted attention and was measured to estimate both drag and inertia coefficients, and there exist excellent investigations by Keulegan and Capenter. It is reported by Bidde (1) that when a cylinder is placed in wave motion field the ratio of the lift force due to wake vortex to in-line force attains to about 60 percent similarly to the case of cylinder in steady flow. Some investigations following Sawaragi and Nakamura's (2) one examined both the method of estimating the lift force and its appearance due to wake vortex, and the vortex pattern in wake. For example, the investigation by Iwagaki · Ishida (3), by Ishida · Kuwayama (4), and by Sawamoto · Kashii (5) or Ikeda (6). These investigations tried to explain phenomena in respect to the relation between wake vortex and the lift force. However, from the viewpoint of both measurement and its accuracy it is insufficient to determine such as the magnitude of wake vortex. Thus the wake vortex has been understood in terms of the lift force. But in oscillating flow field, the shedded vortexes move according to the reversal flow, then the flow ahead a cylinder is not the same as in the steady uniform flow. It is supposed that wake vortex also affects in-line force. To this point, Noda · Matsumi

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* Department of Civil Engineering

** Graduate Student, Civil Engineering

(7) reported about the scatter of drag and inertia coefficient. They examined closely experimental apparatus, experimental procedure and analysis method, and investigated the influence of wake vortex on drag and inertia forces. Hayashi · Takeuchi (8) tried to grasp the flow pattern around cylinder from the time variation of both drag and inertia coefficients and velocity fluctuation. Further, Sawaki · Kashii (5), Ikeda · Nakamura · Yamamoto (6), Hayashi · Takeuchi (9) found the long period fluctuation of lift force, which is called "groan phenomena", and Ikeda et al. examined the condition of its appearance. Since phenomena are extremely complicated and measurement of vortex shedding with accuracy is difficult, it cannot be said that any appropriate value is given to fluid forces on a circuler cylinder which is the simplest shape.

From the point that the lift force is closely related to vortex patterns in wake when vortex shedded in wake moves on toward a cylinder and strongly affected by a flow pattern around a cylinder, the present study intends to grasp vortex motion at the reversion of main flow and the flow pattern induced by this vortex. In the experiment, variations of in-line and lift forces, and velocity variation were measured simultaneouly. Further, flow visualization was performed by taking pictures of the movement of polystyrene particles or aluminum dust added in the flow as a tracer. From the experiment, frequency property of lift force variation, phase relation of in-line and lift force variations etc. are investigated.

2. Apparatus and Procedure

Oscillating flow was formed in a horizontal tunnel whose cross-section is rectangular (56 cm wide × 100 cm long × 1.0 cm depth), using two vertical circular tanks which are connected to a tunnel and are filled with water to some elevation. Iron weight lifted in one of the two circular tanks is oscillated harmonically in the vertical. (see Fig. 1) The upper plane of a tunnel is made of glass board for the benefit of flow visualization. The cylinder was made of an acrylic resin of a diameter of 50 mm and length 9.2 mm under the depth of the test section.

A simultaneous measurement of in-line and transverse forces on a cylinder was made by means of four strain gauges mounted on a brass-ber which fixed the cylinder as a cantilever in the direction of in-line and transverse. From a calibration using a known weight the forces acting on the cylinder can be determined. The results of a calibration show that the ratio of a deformation of loading direction to that of transverse direction is less than 7 percent. Beside, submerged natural frequency of fluid force measurement system is 54Hz. Value of the velocity was estimated by measuring the variation of water elevation in a 30 cm diameter tube tank without float forced vibration. For a calibration of this method, velocity distribution at the point 5 cm away from one side wall was measured by a pitot tube. The result of velocity distribution in maximum velocity of oscillating flow was shown in Fig–2. In this figure $z/H=1.0$ means on the glass board, $z/H=0.0$ means on the iron plate.

To research a flow pattern around the cylinder, particularly the flow pattern after inversion, polyethylene particles of diameter about 0.1–0.4 mm and aluminum dust were mixed in the flow as a traser, twenty pictures were taken per second by 16 mm camera. In order to find a locus of traser, 3 or 4 pictures were taken per second by turning a disk front of motor-driven camera to cut off the light 4 times per an exposure time. As for experimental conditions, the period of the flow is 3.3–6.7 second, the maximum velocity of the flow is 9.4–39 cm/sec, Keulegan-Carpenter number is 6 – 38.

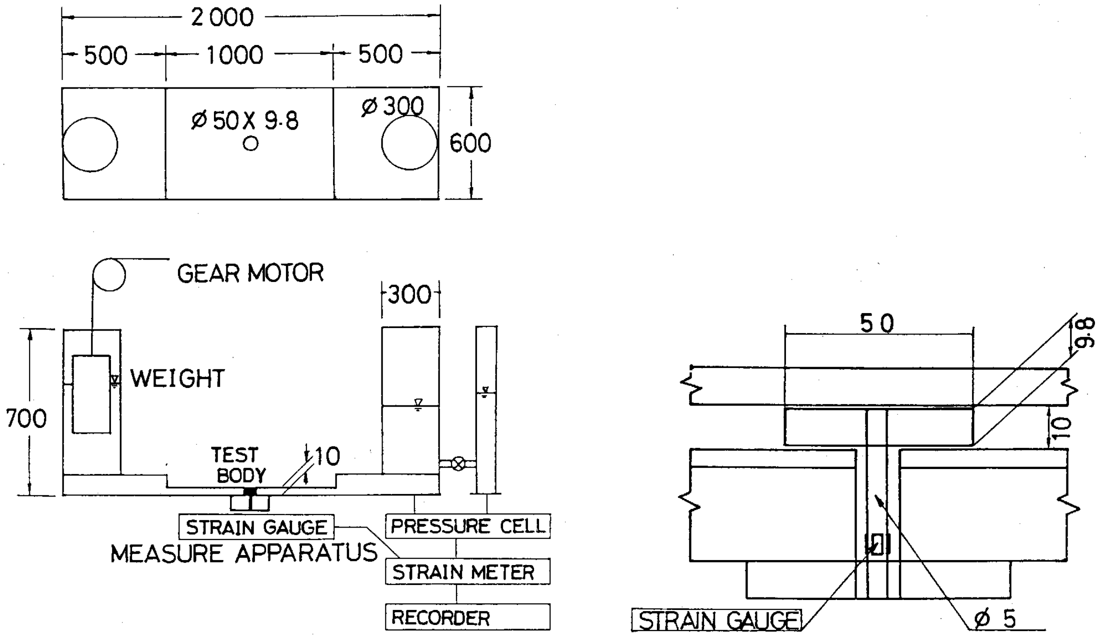

Fig. 1 Experimental apparatus and measurement system of fluid forces.

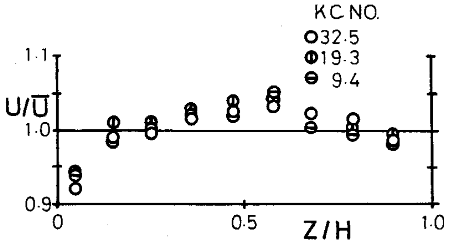

Fig. 2 The velocity distribution in vertical direction.

3. Experimental Results and Discussion

In Fig. 3, observed record of fluctuating in-line and lift forces, as well as spectrum density of lift force are indicated for the case of KC number 12.8, 21.1 and 34.1. The difference between the fluctuation of in-line and lift forces will be examined for cases of the three values of KC number. When KC number is in the range of 10–15, as indicated in Fig. 3(a) fluctuation of the lift force in a cycle of oscillating flow is relatively stable, though the higher frequency component is superposed. This high frequency component seems to have a relation to the array of small vortexes generated in the area between a relatively large scale vortexes and surface of the cylinder.

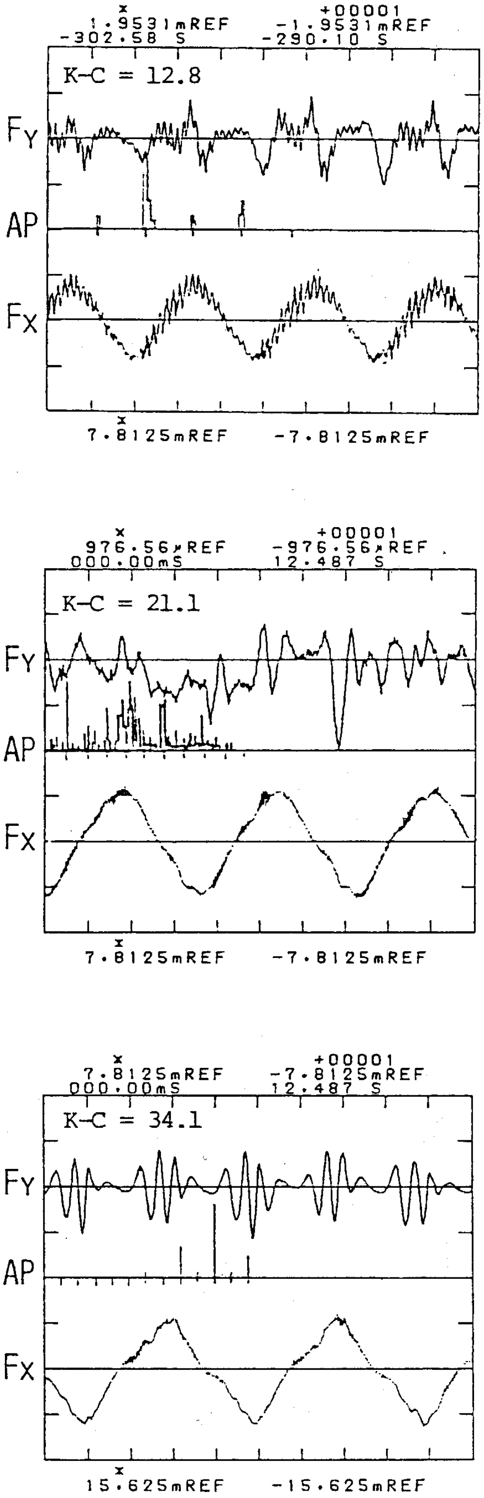

Fig. 3 Fluctuating wave profiles of in-line and lift forces and spectrum of lift force.

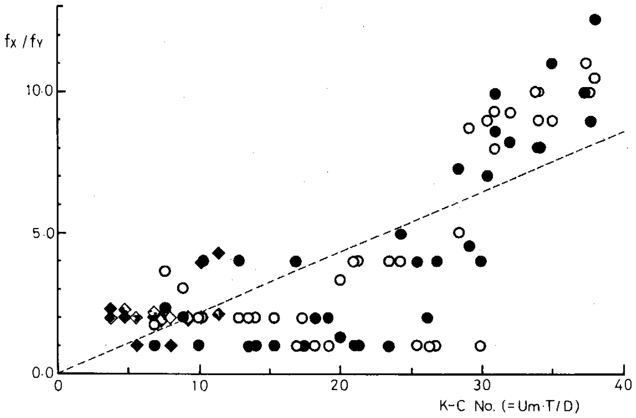

Fig. 4 The dominant frequency of lift force.

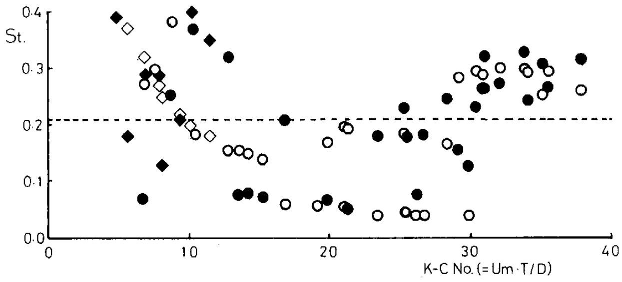

Fig. 5 The relation between KC number and Strouhal number due to the dominant frequency of lift force.

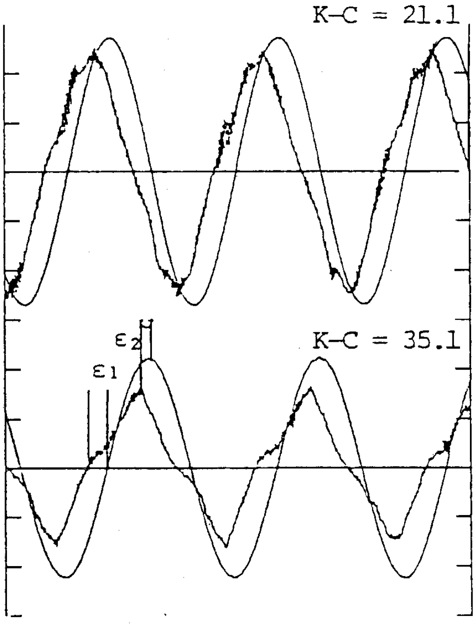

Fig. 6 Fluctuating wave profiles of velocity and in-line force.

When KC number is in the range of 20–25, as shown in Fig. 3(b), the variation of lift force is highly irregular. The dominant frequency widely distributes around four times frequency of the main flow, whereas in the case of KC number smaller than 15 they exist at one, two, three and four times frequency of the main flow.

When KC number exceeds 30, as shown in Fig. 3(c), lift force variation becomes fairly regular. The curve of fluctuating lift force evidently indicates the exsistance of a few dominant frequencies. They are ten, eight and twelve times frequencies of the oscillating main flow.

As for the groan phenomena, Ikeda et al. have pointed out from their experiment with a circular cylinder of diameter 60 cm that the condition for the groan to occur is determined rather by the main velocity condition than by KC number condition. They say that the groan occur when the velocity of the main flow is in the range of 5–15 cm/sec.

In the present experiment the groan occured when the maximum value of the main flow velocity exceeded about 15 cm/sec, though the experimental condition is extremely restricted. But this groan phenomena disappeared when the maximum velocity of the main flow exceeded about 30 cm/sec.

3.1 The Characteristic Frequency of Lift Force

In Fig. 4, the ratio of the dominent frequency of lift force to that of the main flow is plotted against KC number. In this figure, blank circle symbols mean the most dominant frequency and filled circle symbols mean the secondly dominant one.

When KC number is smaller than 18, the component of twice frequency of main flow is most dominant. Component of the same frequency as main flow is clearly less than that of twice a frequency. However, when KC number is in the range of 20–30, frequency component of the first and second dominant are comparable. Though a flow pattern around the cylinder is complicated and unstable, it seems that this is closely associated with appearance of the groan phenomena. Ikeda et al. have shown that the lift force frequency obtained from zero-up cross method is corresponded with that of a pair of vortexes shedding. Fig. 5 shows the plot of $St=Df_y/U_m$ against KC number, where f_y is the dominant frequency of lift force. Dotted line in the figure is Roshko's result which gives the frequency of vortex shedding in the steady flow.

3.2 The Property of Phase for In-line Force

Fig. 6 shows the record of fluctuating velocity and in-line force for KC number of 21.1 and 35.1, where velocity is obtained from variation of water elevation in a circular tank. In both case the phase of in-line force precedes to that of velocity. As the value of KC number becomes smaller, the phase difference of these quantities become larger. Next, normalized phase difference between those of fluctuating velocity and in-line force is plotted against KC number in Fig. 7, where (a) is obtained from the times of maximum changes of both velocity and lift force and (b) is obtained from the times of both maximum velocity and lift force. The dotted line in this figure is

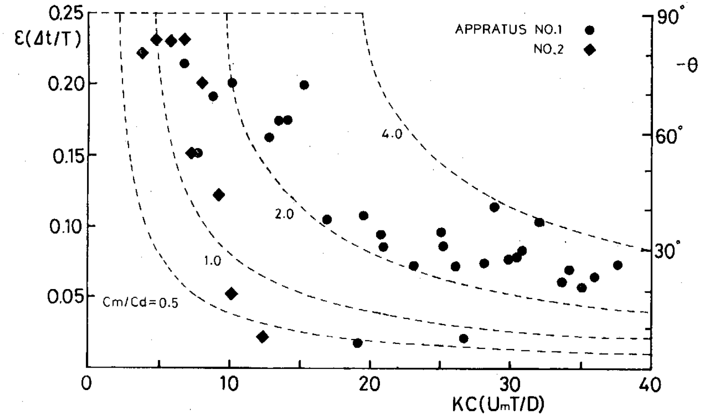

Fig. 7(a) The phase relation of in-line force (at maximum velocity).

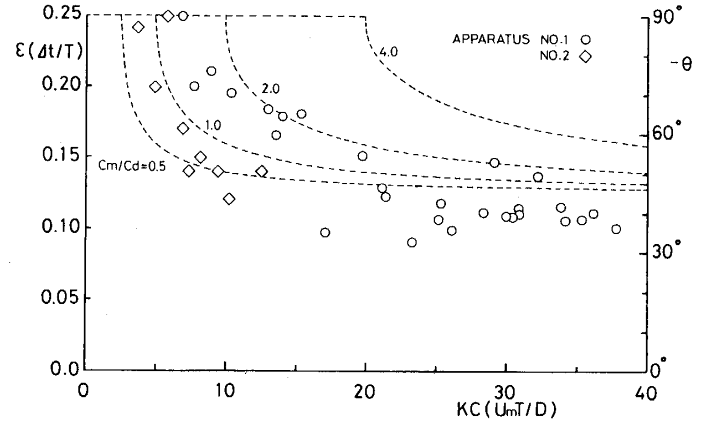

Fig. 7(b) The phase relation of in-line force (at maximum acceleration).

the relation from Morison's formula in the case when the ratio of drag coefficients to inertia one is constant. The real line is the relation which is obtained by substituting Sarpkaya's results for drag and inertia coefficient into Morison's formula. The figure shows that when KC number is smaller than about 15 the essential difference between (a) and (b) isn't recognized. While, when KC number is larger than 30, (b) is larger than (a) by 20 dgrees, that is, the phase difference between in-line force and velocity at reversion of the main flow is larger than that at the maximum velocity.

To understand these situations, flow patterns around the cylinder before and after the reversion of the main flow was visualized. Polyethylene particles were used as a tracer and their locus were traced from several photographs taken by a motor-driven camera. The result of visualization is indecated in Fig. 8.

Though this figure is obtained in the case of large KC number, a pair of vortexes which are located symmetrically or asymmetrically behind the cylinder in the decelerating stage increase their scale just before the reversion, then they shed in the direction of the transverse. As the scale of vortexes become large, a violent flow occurs between the vortexes. The velocity of this flow is comparable with the maximum velocity of the main flow. Then after reversion of the main flow, a pair of vortexes shed in both sides of the cylinder and the flow caused by these vortexes becomes gentle. From the

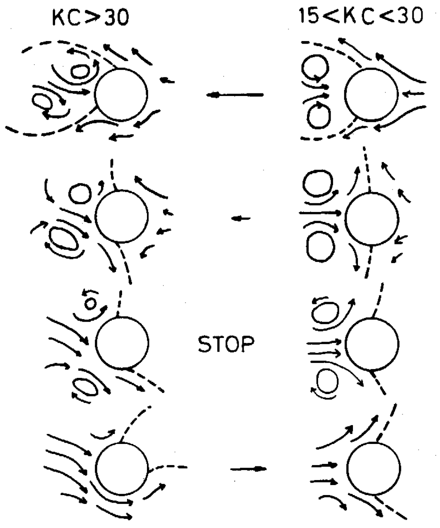

Fig. 8 The flow situations around the cylinder at just before and after the reversion of the main flow.

above result and the fact that the precedence of the in-line force phase to that of main flow at the reversion is larger than that at the maximum values, it is natural to consider that the precedence of the phase of in-line force more depends on the flow caused by a pair of vortexes behind a cylinder just before the reversion of main flow than on the inertia force. If a pair of vortexes behind a cylinder are asymmetric, the flow pattern near the cylinder behave as a superposition of uniform flow and circulation around the cylinder, and the reversed main flow acts on a cylinder meandering due to vortexes.

Conclusions

The summary of this investigation is as follows;

(1) The groan phenomena was recognized in the range of 15–30 cm/s the maximum main flow velocity. In this case, the value of Strouhal number using the dominant frequency of lift force is small and vortex shedding is restricted.

(2) The flow caused by a pair of vortexes which are generated behind a cylinder just before the reversion of main flow takes an important role on the phase difference between variations of in-line force and velocity.

(3) The situation after the reversion of main flow is influenced by the pair of vortexes. However, these results are qualitative and the quantitative estimate by means of various methods shoud be made in the future.

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