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Hydrodynamic Forces Acting on a Horizontal Circular Cylinder with an Inclined Angle to the Wave Crest in Regular Waves

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ABSTRACT

Hydrodynamic forces acting on an inclined circular cylinder oscillating sinusoidally in still water and a horizontal circular cylinder submerged deeply with an inclined angle to the wave crests in regular waves were experimentally investigated in low *Kc* number condition (*Kc*<5). In the case of the sinusoidally oscillating cylinder, the drag and lift force are negligible, and the inertia coefficients are in good agreement with the potential value. In the case of the horizontal cylinder with an inclined angle to the wave crests, the reduction of the inertia coefficient decreases with the increasing of the inclined angle.

INTRODUCTION

In shallow-water waves, the flow around a horizontally submerged cylinder is generally idealized as plane oscillatory flow as a vertical cylinder in waves. Hydrodynamic forces on a vertical cylinder in waves or a right-angled cylinder to plane oscillatory flow have been investigated by many researchers, and characteristics of the hydrodynamic coefficients of those cylinders seem to have been clarified in detail.

Hydrodynamic forces acting on an inclined cylinder have been studied by several researchers. The results, however, do not always agree. Sarpkaya (1982) experimentally investigated the hydrodynamic forces on inclined smooth and rough circular cylinders in plane oscillatory flow, and pointed out that the hydrodynamic coefficients significantly depend on the inclined angle. Particularly the inertia coefficients of the cylinders increase with the increasing of the inclined angle, and those tend to much larger values than the potential value as the *Kc* number closes to zero. He did not show the reason why the measured values are much larger than the potential value at such a low *Kc* number region where no vortex shedding is believed to occur. Cotter and Chakrabarti (1984) measured wave forces on a submerged test section that was a part of a circular cylinder inclined with respect to vertical in regular waves. The results of the experiments demonstrated that the inertia coefficient takes about the same value as the potential value at a very low *Kc* number, and the dependence of the inclination on the inertia coefficients appears at a *Kc* higher than 5. Williams (1986) calculated diffraction forces on a surface-piercing circular cylinder inclined to the seabed by using the integral equation method in the potential theory, and pointed out that the inertia force on the inclined cylinder is larger than that of the vertical cylinder. He concluded that the results obtained by Sarpkaya (1982) are reasonable, though there is no free surface or diffraction effect in the results of Sarpkaya's experiments.

As mentioned above, the fundamental data for predicting the effect of inclination of a circular cylinder in plane oscillatory flow confuse us. Therefore, in the first part of this paper, hydrodynamic forces acting on an inclined circular cylinder that is sinusoidally oscillated are measured to confirm whether the inertia coefficient of the inclined cylinder takes the same value as the potential value at a very low *Kc* number.

In deep-water condition, the orbits of water particle are almost circular in regular waves. Due to the orbital flow effect, wave forces on a horizontal cylinder in deep-water waves are different from those in shallow-water waves. It was first found by Chaplin (1984a, 1984b) that inertia force on a horizontal circular cylinder in regular waves with its axis parallel to the wave crests dramatically decreases with increasing *Kc* number due to the occurrence of circulating flow around the cylinder at very low *Kc* numbers (1<*Kc*<3). In plane oscillatory flow, however, there is no reduction of the inertia force in such a low *Kc* number as shown by Sarpkaya (1986). Following Chaplin's work, the authors (1988, 1989, 1990a) investigated the wave forces on the horizontal cylinder in regular and irregular waves experimentally and theoretically, and pointed out that the reduction of the inertia force is caused by separated vortices from the cylinder that are in much greater scale than those in plane oscillatory flow at the corresponding *Kc* number. The authors (1990b) also showed that the inertia force on the horizontal circular cylinder moving at a constant speed in regular waves significantly depends on the steady motion.

In the second part of this paper are described investigations of the effect of inclination on wave forces acting on a circular cylinder horizontally submerged in a deep-water wave.

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Experiments and Analysis

The force measurements have been carried out in a towing tank (70 m × 3 m × 1.6 m) at the University of Osaka Prefecture. The tank is equipped with a flap-type wave maker at one end.

In order to clarify the effect of inclination on wave forces acting on a horizontal cylinder in shallow-water waves, hydrodynamic forces acting on inclined circular cylinders forced to oscillate sinusoidally by a forced oscillation mechanism were measured. In the present experiments, the period of the oscillation T is 1.4 s only. Three smooth cylinders at inclined angles of 15°, 30° and 45° were used in the experiments. The cylinder whose diameter D is 0.0603 m was submerged horizontally and deeply enough to avoid the free surface effect in still water as shown in

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KEY WORDS: Hydrodynamic force, circular cylinder, inclined angle, low Kc number, circulating flow, viscous effect.