

CHAPTER 68

UNSTEADY FLOW AROUND A VERTICAL CIRCULAR CYLINDER IN A WAVE

Kenjirou Hayashi*
and
Toshiyuki Shigemura**

ABSTRACT

The unsteady characteristics of flow around a vertical circular cylinder in a typical wave, under which the lift force acting on it is very stable and has a frequency which is twice that of the incident wave, have been investigated experimentally. The relationship between the fluctuating flow velocities near the boundary layer separation points and the lift force acting on a sectional part of the cylinder has been understood quantitatively. To clarify the region where the appearance of stable lift force occurs, the long time records of lift forces acting on vertical cylinders in waves are also performed.

1. INTRODUCTION

In order to develop the study of wave forces acting on the offshore structures, it is important to understand the flow around a vertical circular cylinder in waves. The principal phenomenon of this flow is characterized by the formation of vortices which are shed from the surface of a cylinder. However, it is not understood so well as those in steady flow. This may be due to the complexity of flow round a vertical cylinder in waves, because the incident fluid motion varies along the axis of vertical cylinder with possessing a vertical velocity component. A lot of experimental works remain to be made in these area.

When the wave depth parameter d/L (d =depth of mean water level, L =wave length) is small, shallow water wave, the variation of incident flow with depth is small and the amplitude of vertical velocity component is small compare with that of horizontal velocity component. Therefore, the flow around a vertical cylinder is nearly two dimensional and quite similar to those in harmonically oscillating two dimensional flow, plane oscillatory flow. On the other hand, when the wave depth parameter d/L is large, deep water wave, the flow around a vertical cylinder is three dimensional

* Assistant Professor, Dept. of Civil Engineering, National Defense Academy, 1-10-20 Hashirimizu Yokosuka, 239 Japan.

** Professor, Dept. of Civil Engineering, National Defense Academy, M. ASCE.

because the variation of incident flow along the axis of cylinder is large and the amplitude of vertical velocity component is nearly equal to that of horizontal velocity component.

Many studies have been made to understand the process of vortex shedding from a cylinder in these oscillating flow, plane oscillatory flow and wave, since the original work of Keulegan and Carpenter(1958). They observed the vortex formation round a submerged horizontal cylinder placed in harmonically oscillating flow produces in the node of standing waves and found a close relationship between the vortex-shedding frequency and a Keulegan-Carpenter number defined as $KC=U_m.T/D$ in which U_m is the maximum horizontal water particle velocity during a wave period T and D is a diameter of cylinder.

The relationship between the vortex-shedding patterns and KC number has been obtained by the visualization studies of the flow round a cylinder in waves and in plane oscillatory flow, see for example Bidde(1971) and Bearman(1979). Williamson(1985) made simultaneous force measurement and visualization round a cylinder in plane oscillatory flow by oscillating a cylinder in still water and obtained the detailed description of vortex shedding and the relation of the vortex motions to the lift force profiles in each regime of KC number corresponding to each of vortex shedding pattern.

In order to understand quantitatively the characteristics of flow round a cylinder in these oscillatory flow, the measurements of flow velocities round a cylinder and surface wave pressure on the circumference of a cylinder in waves have been made by Isaacson and Maull(1976), Iwagaki and Ishida(1976), Hayashi and Takenouchi(1980, 1985), Bearman et al.(1985) and Grass et al.(1987).

Hayashi and Takenouchi(1980,1985) measured the horizontal velocity around a vertical cylinder in a wave and the surface wave pressure on the circumference of it by using a Laser-Doppler anemometer and a pressure transducer. These measurements were made in a special flow condition under which the total lift force acting on the cylinder is very stable for a long time with having a frequency which is twice that of incident wave and major portion of vortex shedding and formation take place periodically on mainly one side of the cylinder. The vortex shedding pattern observed was quite similar to those generally observed in waves and in plane oscillatory flow in the approximate range of KC between 7 to 15. The characteristics of time variation and the phase average distributions of both the horizontal flow velocities and the surface wave pressures have been obtained.

Grass et al.(1987) also measured the velocity around a cylinder in waves and in plane oscillatory flow. They find the presence of vortex induced velocity enhancement effect occurring in the flow field round a cylinder both in plain oscillatory flow and in surface waves in the approximate

range of KC between 9 to 12. This velocity enhancement effect is also identified in the results of Hayashi and Takenouchi(1980,1985).

The study described herein is an extension of our study described above, Hayashi and Takenouchi(1979, 1985), clarifying the relationship between the flow around a vertical circular in waves and the forces acting on it. The scope of present study is to investigate the relationship between the flow near the boundary layer separation points and the lift force acting on a sectional part of the cylinder in a wave. The flow near a separation point of boundary layer has an important aspect of vortex shedding phenomenon. However, detail experimental information is scarce in the case of oscillatory flow. In order to clarify the region where the appearance of stable lift force occurs, the long time records of lift forces acting on the vertical circular cylinders in waves were also performed.

2. EXPERIMENTS

2.1 Measurement of Flow Velocity and Surface Wave Pressure

The detailed description of the experimental arrangement used in these measurements has been given previously in our study, Hayashi and Takenouchi(1980,1985). The experiments were carried out in the 39.6m long flume of the Department of Civil Engineering at the National Defense Academy. This flume is 0.6m wide and is equipped with a ballistic-pendulum type wave generator. A long beach with a slope of 1:6.7 is installed at the other end of flume to absorb the wave energy.

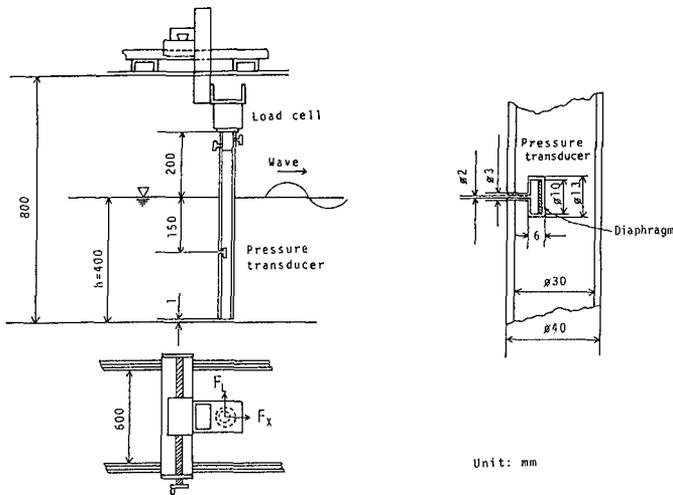


Fig.1 General arrangement of test cylinder

The general arrangement of a test cylinder made of acrylic plastic tube is shown in Fig.1. It was mounted in the flume at a section 24.6m from the paddle of wave generator and 7m from the toe of long beach. For the measurement of the total inline force F_x and total lift force F_y acting on a test cylinder, the upper end of the test cylinder was attached to a load cell(Three Component Strain Gauge Type Load Cell, LMC-3501-1 Nissho Ltd.) which was mounted on a two-dimensional traversing device straddling on the wave flume.

For the measurement of the fluctuating surface wave pressure P on the circumference of the test cylinder at the level of 19cm below the still water level, a diaphragm type pressure transducer(PM10-01, ST Institute Co.) was attached to a pressure tapping placed on a surface of the test cylinder. The test cylinder was attached to the load cell, so arranged that it can be rotated around its axis to bring the pressure tapping to any desired orientation.

The measurements of fluctuating horizontal water particle velocity U , the velocity component in the direction of wave propagation, at the points along a diameter through the cylinder parallel to the wave crest were made by using a laser doppler anemometer(LDA) of a 15mw He-Ne type(Kanomax 27-0900 ser.) and a hot wire anemometer. These velocity measurements were made at the level of 16cm below the still water level. The general view of optical system of LDA working in a forward scatter dual beam mode is shown in Fig.2. In order to eliminate an ambiguity of flow direction when flow reverses under wave motion, the frequency sifter was used in this LDA system.

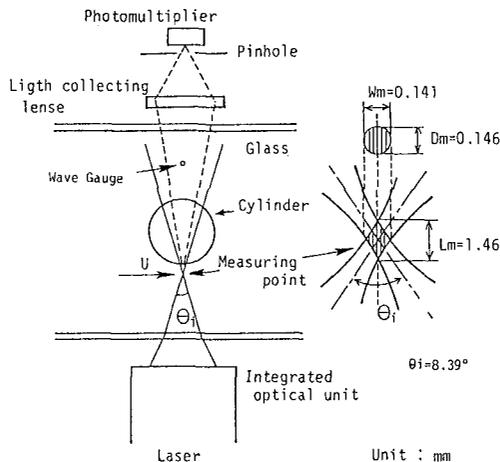


Fig.2 Optical system of laser doppler anemometer

These measurements described above were made in a regular wave; wave period $T=1.6$ sec., wave height $H=10$ cm, wave length $L=2.9$ m, and still water depth $d=40$ cm, which is the same used in our previous work, Hayashi and Takenouchi(1980,1985). The

wave depth parameter d/L is about 0.138. The KC numbers at water surface and at the bottom of flume are 12.5 and 8.2 respectively, i.e. the variation of incident flow with depth is small. The KC number and the Reynolds number at the level of 15cm below the still water level are about 10 and 7700 respectively. The flow pattern around the test cylinder near the level of the measuring points U and P, about 16cm below the still water level, was observed by using a video recorder camera. Aluminum powder was spread in water.

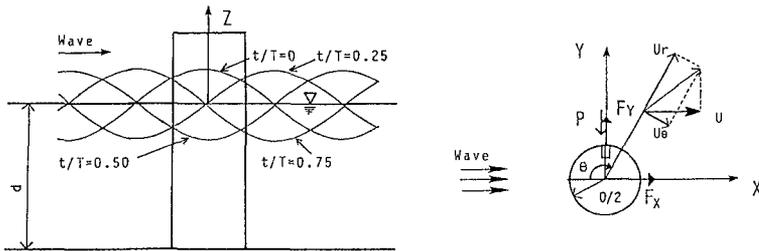


Fig.3 Coordinate system

The coordinate system is shown in Fig.3. The measurement of surface wave pressure P was made at 19cm below the still water level and at 24 angular positions θ by rotating the cylinder at 15 degrees interval around its center axis. The signal of the pressure transducer at each angular point θ was recorded on the magnetic tape recorder simultaneously with the signals of wave gauge and the load cell for a total of about 5 wave periods. Using these data, it is possible to obtain the phase average surface wave pressure distribution circumference of the test cylinder and the phase average sectional inline and transverse forces over 5 wave periods for several wave phase t/T .

The measurements of velocity U were made at the level of 16.5cm below the still water level and at $X=0$ cm by varying Y from -7cm to 8cm. Instead of traversing the measuring points of velocity, the test cylinder was moved in the direction of Y coordinate. The signals from velocity meters were also recorded on the magnetic tape recorder with the signals from the wave gauge, the load cell and the pressure transducer for the total of 5 wave cycles and subsequently analyzed by a signal analyzer. Using this recording method, it is possible to obtain the relationship between the fluctuating velocity U and both the surface pressure P and wave forces F_x and F_y .

2.2 Long Time Measurement of Lift Forces

The long time measurements of lift forces were carried out by using a same facility described above. Two circular cylinders made of acrylic plastic tubes were mounted on a load cell as shown in Fig.1. They were 3cm and 4cm in diameter and 60cm in length. In order to eliminate the end effect, the clearance between the lower end of test cylinders and the bottom of wave flume was kept less than

1mm. Test runs were made at wave period T ranging from 0.8sec. to 2.2sec. At each wave period approximately 4 to 10 wave heights H were generated. The still water depth d was kept at 40cm. The approximate range of rms.KC number and rms.Re number were from 1 to 24 and 200 and 2200. The natural frequency of the test cylinders in still water were 12Hz for $D=3\text{cm}$ and 10Hz for $D=4\text{cm}$ respectively. The analog signals from the load cell and the wave gage were recorded on a magnetic tape recorder over a time interval about 800 wave periods.

3. RESULTS AND DISCUSSION

The record of the time variation of the total lift force F_y obtained from the experiment of flow velocity and wave pressure is shown in Fig.4. As shown in this figure, the time variation of F_y is very stable for a long time.

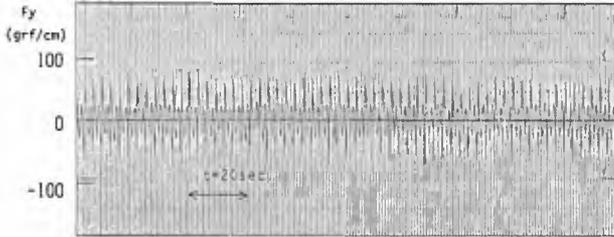


Fig.4 Long time variation of amplitude of lift force

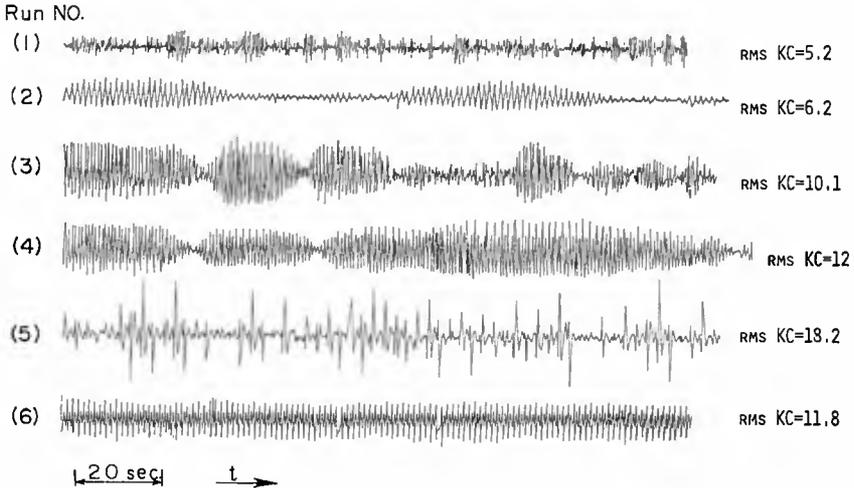


Fig.5 Time variation of lift forces for several rms.kC

The time history of lift force acting on a vertical cylinder in waves has generally irregular characteristics of intermittency and modulation of its amplitude as shown in Fig.5, which is reproduced from a reference, Hayashi and Takenouchi(1979). These irregular characteristics may be due to the sensitivity of lift force to the stream turbulence and poor spanwise correlation of vortex shedding along a cylinder's axis. However, we can recognize the appearance of stable lift force as shown in Fig.4 in this figure, for the case of $\text{rms.KC}=11.8$.

In the case of plane oscillatory flow, it is recognized that the stable lift force appears in the range of KC approximately between 7 to 16 and in this range of KC, the vortex shedding is very stable with taking place on only one side of cylinder, see for example Maull and Milliner(1978), Ikeda and Yamamoto(1981), Williamson(1985) and Grass et al. (1987). The region of stable lift force in waves may be also represented in KC numbers which are related to the case of plane oscillatory flow. However, we should note that there are important differences between the unsteady natures of flow in waves and those in plane oscillatory flow as described previously in introduction.

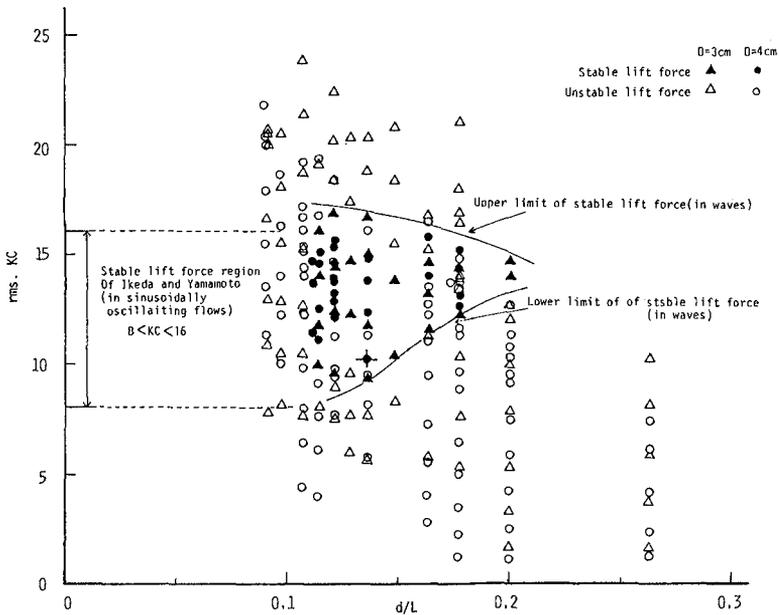


Fig.6 Region of stable lift forces plotted against d/L and rms.KC

The relationship between the configuration of time history of lift forces, which were obtained in the present experiments, and both rms.KC and d/L is shown in Fig.6. In this figure, the black symbols show the appearance of stable lift force. The region of stable lift force for the case of

plane oscillatory flow obtained by Ikeda and Yamamoto(1981) are also shown in this figure. The quantity of present data is not sufficient to define exactly the region of stable lift force acting on a vertical cylinder in waves. This figure shows that the stable lift force occurs in the range of rms.KC between about 9 to 16, for the range of d/L between about 0.1 to 0.2. For the high value of $d/L > 0.2$, the stable lift force does not appear. This may be due to the fact that the vortex shedding is poorly correlated along the axis of the test cylinder, because the variation of incident flow along the cylinder axis increases with the increase of d/L . For the low value of $d/L < 0.1$, the stable lift force also does not appear. This may be due to the increased influence of wave nonlinearity.

While farther dependence of the stable lift forces in waves on Reynolds number is possible as mentioned by Maull and Milliner(1978) and Ikeda and Yamamoto(1981), such dependence is not clear in the present data.

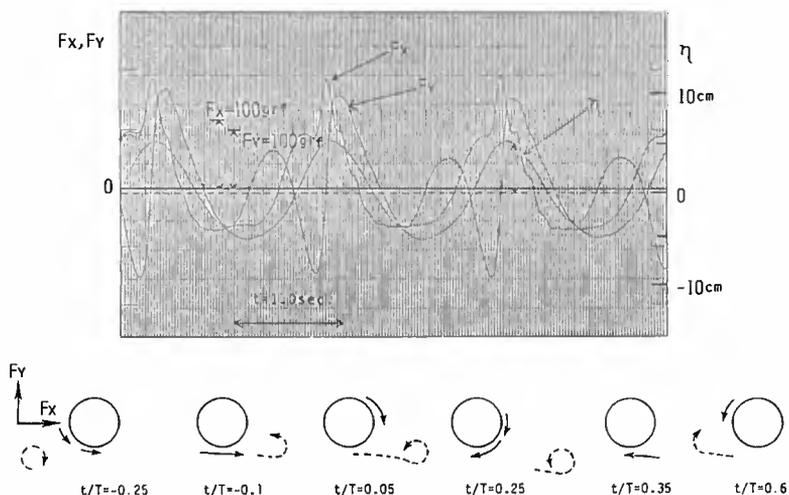


Fig.7 Time variations of lift force F_y , inline force F_x , and free surface elevation η with vortex shedding patterns

In the present experiment of flow velocity U and surface wave pressure P , the time variation of lift force F_y is very stable for a long time as shown in Fig.6. The relationship between this F_y , and inline force F_x and water surface elevation θ with time are shown in Fig.7. The frequency of F_y is two times as much as those of F_x and η .

The process of vortex shedding in a period of incident wave is also shown in Fig.7. These sketches of vortex shedding patterns were estimated from the observation of flow near the level of velocity measurement U and surface wave pressure P , which were made by using a video camera in the present work, and the velocity distributions around a

vertical cylinder in waves which were obtained for several wave phases in our previous study by the author(1980,1985). The major portion of vortex shedding and its activity, which occur during each half cycle, take place periodically on only one side of the cylinder, negative side of Y coordinate. These are quite similar to those generally observed in plane oscillatory flow in the range of KC between about 7 to 13, which has been described in detail by Williamson(1985) and Grass et al.(1987).

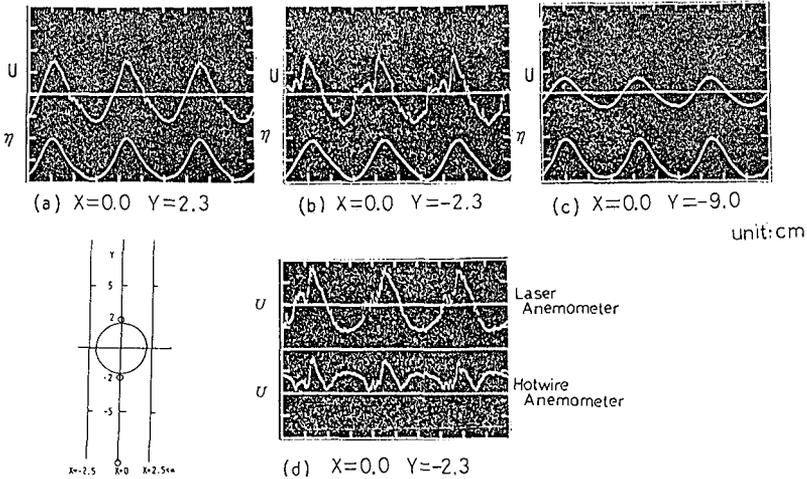


Fig.8 Out put signals of velocities U and water surface elevation η

Time variations of horizontal water particle velocity U at various Y points of $X=0$ cm, which were obtained by using the LDA, are demonstrated in Fig.8 (a),(b) and (c) respectively. To show the phase of incident wave, the time variation of water surface elevation η measured by the wave gauge mounted just beside the test cylinder as shown in Fig.1 is also demonstrated in these figure. The time variation of U demonstrated in Fig.8(c) shows that of incident wave, because the measuring point of U at $Y=-9$ cm is enough far from the test cylinder so that the existence of cylinder is negligible. We can recognize remarkably that the fluctuation of U at $Y=-2.3$ cm is large compared to that of U at $Y=2.3$ cm. This is due to the fact that the major portion of vortex shedding and its activity take place on only one side of the cylinder, $Y<0$, as shown in Fig.7. In order to show the accuracy of the LDA measurement for the fluctuating velocity U , a comparison of velocity signals from the simultaneous measurement using the LDA and the hot wire anemometer which were placed at nearly same position at $X=0$ cm and $Y=-2.3$ cm is demonstrated in Fig.8(d). We can recognize that they almost agree except for very small velocity.

Figure 9 shows the relationship between the phase variations of pressures P at $\theta=90^\circ$ and $\theta=-90^\circ$, the

velocities U at $X=0\text{cm}$, $Y=-2.2\text{cm}$ and -2.2cm , the lift force F_y and free surface elevation η . The velocity U at $Y=2.2\text{cm}$ and the pressure P at $\theta=90^\circ$, and the velocity U at $Y=-2.2\text{cm}$ and the pressure P at $\theta=-90^\circ$ were measured simultaneously respectively. Although a little is known about boundary layer separation from the test cylinder in the present work, the points of $\theta=90^\circ$ and $\theta=-90^\circ$ seem to be near the separation point of it. The influences of the appearance of asymmetric vortex shedding on both phase variations of velocities U and pressures P are clearly recognized.

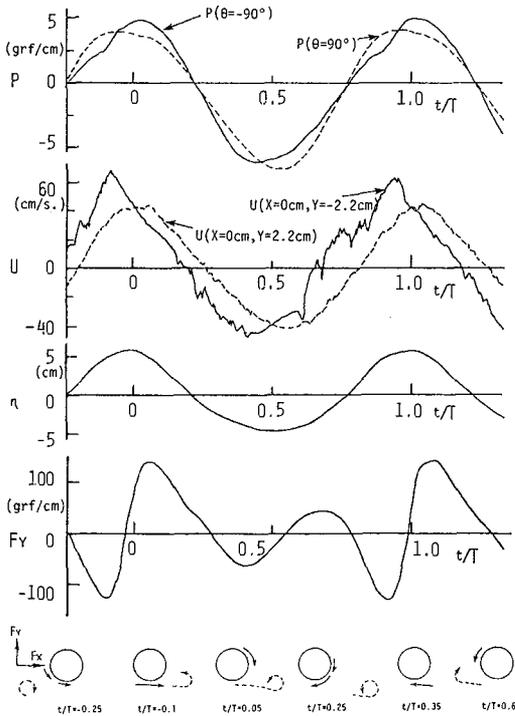


Fig.9 Phase variations of wave pressures P , velocities U and lift force F_y

Figure 10 shows the details of phase variation of the velocities U at the points of $X=0\text{cm}$, $Y=2.2\text{cm}$ and $Y=-2.2\text{cm}$, and the free surface elevation η . These records cover 5 cycles of the incident wave period and identify the origin of cycle. In order to investigate the influence of both the presence of the test cylinder and the vortex sheddings on the velocities U at these points, theoretical curves calculated from Stokes third order wave theory and linear diffraction wave theory are plotted in this figure. The measured velocities U at $Y=2.2\text{cm}$ is predicted quite well by

linear diffraction wave theory, but the velocity U at $Y=-2.2\text{cm}$ deviates markedly from the diffraction theory. We can

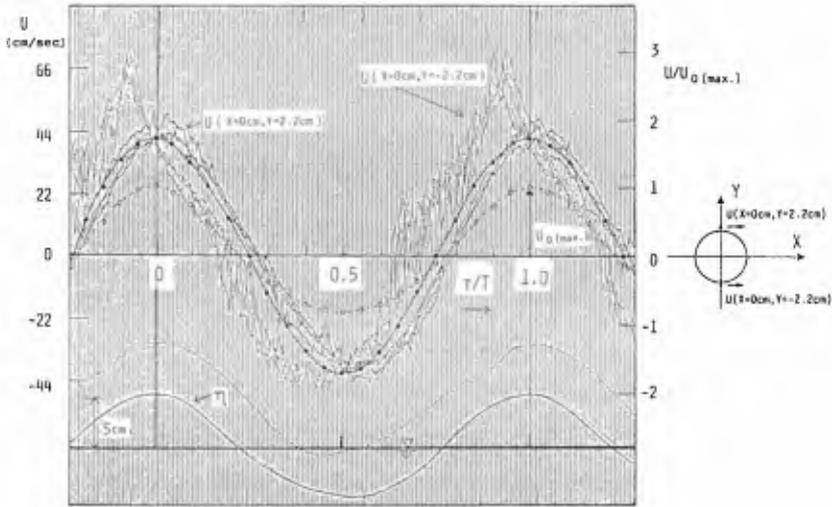


Fig.10 Details of phase variations of velocity U at $X=0\text{cm}$, $Y=-2.2\text{cm}$ and $Y=2.2\text{cm}$
 (—●— Linear diffraction wave theory)
 (- - -○- - - Stokes third order wave theory)

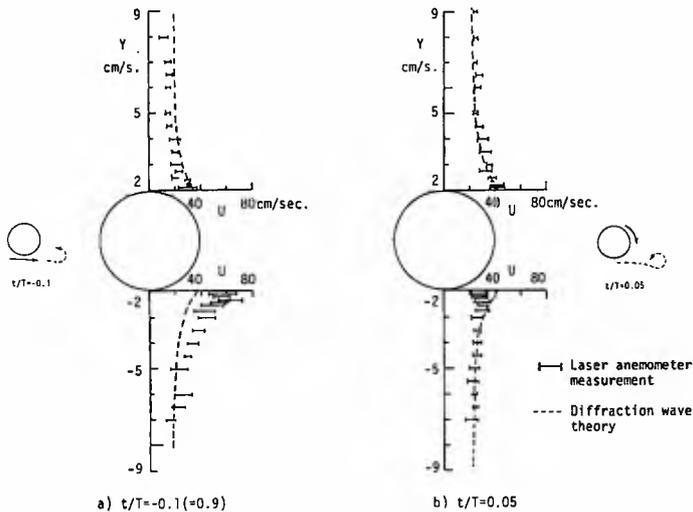


Fig.11 Distributions of wave velocities U around test cylinder at $X=0\text{cm}$ for $t/T=-0.1$ and $t/T=0.05$

recognize that the phase of U at $Y=-2.2\text{cm}$ proceeds faster than that of these wave theories. These may be due to the fact that the major portions of vortex shedding and its activity take place on the negative side of Y coordinate as described in Fig.7.

The distribution of measured horizontal velocity U at $X=0\text{cm}$ plotted at $t/T=-0.1(=0.9)$ and $t/T=0.05$ are shown in Fig.11 (a) and (b). In order to show the influence of the vortex shedding which appears mainly in the negative side of Y coordinate, see Fig.7, the theoretical curve of Linear diffraction wave theory is also plotted in these figures respectively. At $t/T=-0.1$, the crest of wave is approaching to the test cylinder and the peak value of F_y acts in the direction of negative Y coordinate as shown in Fig.7. In this case, the incident flow is passing from left to right with increasing the horizontal velocity U . The measured velocity U exceeds the value of Linear diffraction wave theory in the range of $-5\text{cm}<Y<-2\text{cm}$. This phenomenon, which is called the velocity enhancement by Grass et al.(1987), may be due to the existence of vortices which are shed and formed in the negative side of X coordinate during a last half wave cycle and then converted back over the negative side of Y coordinate. On the other hand, the measured velocity U near the test cylinder in the positive side of Y decreases as compared with the theoretical value. This phenomenon may be due to the existence of a counterclockwise circulation round the test cylinder. At $t/T=0.05$, the crest of wave has just passed through the cylinder and the incident flow is passing from left to right with decreasing the horizontal velocity. At this phase, the peak value of F_y appears in the direction of positive Y coordinate. The measured velocity U decreases in the range of $-3\text{cm}<Y<-2\text{cm}$ and increases just near the cylinder in the part of positive Y coordinate as compared with theoretical value. This phenomenon may be due to the existence of a clockwise circulation round the cylinder, which have been induced by the vortex sheddings from the surface of the test cylinder around $\theta=-90^\circ$.

In order to obtain a quantitative relationship between the flow around the cylinder and the lift force acting on it, following analysis was carried out. The lift force ΔF_{yc} acting on a vertical cylinder in waves may be estimated by Eq.(1), which is an approximation of Laggally's theorem and is equal to the Kuta and Jukovsky theorem as explained by Sawamoto et al.(1980).

$$\Delta F_{yc} = -\rho \Gamma U_0 \quad (1)$$

where ρ is fluid density, Γ is the total circulation around a cylinder induced by vortex sheddings, and U_0 is the incident horizontal velocity (=free stream velocity). If we suppose that the circulation Γ is evaluated by Eq.(2),

$$\Gamma = (U_1 - U_2) \cdot \pi \cdot D / 2 \quad (2)$$

the lift force ΔF_{yc} can be re-written as follow,

$$\Delta F_{yc} = -\rho \cdot (U_1 - U_2) \cdot \pi \cdot D \cdot U_0 / 2 \quad (3)$$

where U_1 and U_2 are the velocities at diametrically opposite surface points on the central cross-section of a cylinder.

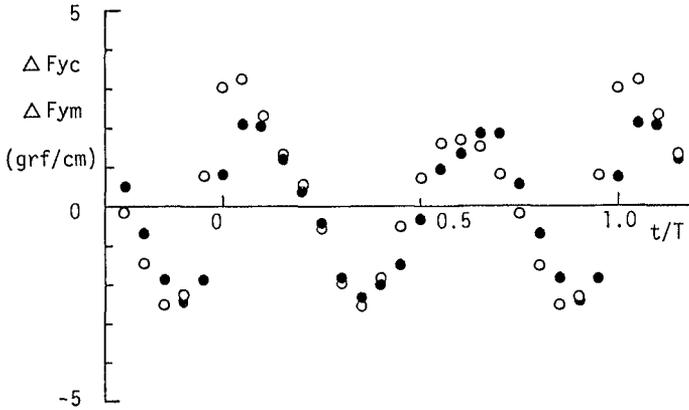


Fig.12 Phase variations of lift forces
(● ΔF_{yc} , ○ ΔF_{ym})

Figure 12 shows the phase variation of ΔF_{yc} which was calculated by substituting the measured velocities u at $X=0\text{cm}$, $Y=-2.2\text{cm}$ and $Y=2.2\text{cm}$ into Eq.(3). The phase variation of the measurement lift force ΔF_{ym} , which is computed by integrating the measured surface pressure distribution around a test cylinder for several wave phases t/T , is also plotted in this figure. It is quite interesting that the calculation value of ΔF_{yc} evaluates quite well the phase variation of the measured lift force ΔF_{ym} in spite of very rough assumption is used in the calculation of ΔF_{yc} .

4. CONCLUSIONS

In this study, the unsteady characteristics of flow around a vertical cylinder in a wave have been obtained quantitatively by measuring the flow velocities U and the surface wave pressure P . The influence of the asymmetric vortex sheddings, which were obtained by a visualization of flow around the cylinder using video camera, to the velocities U and the surface wave pressures P have been obtained. The relationship between the flow velocities U near the boundary layer separation points on the cylinder surface and the lift force acting on a sectional part of it have been studied quantitatively by using a Kuta and Jukovsky theorem.

The dependence of a stable lift forces in waves on rms.KC number and wave depth parameter d/L is confirmed. However, farther depends of it on Reynolds number is not clear in the range of Reynolds number used in the present experiment.

ACKNOWLEDGMENT

We gratefully acknowledge the several valuable advises given by professor J.R. Chaplin(of The City University in London).

REFERENCES

- Bearman, P.W. and Graham, J.M.R. and Singh, S., 1979, Forces on Cylinders in Harmonically Oscillatory Flow, in Mechanics of Wave Induced Forces on Cylinders(ed. T.L. Shaw).
- Bearman, P.W., Chaplin, J.R., Graham, J.M.R., Kostense, J.K., Hall, P.F., and Klopman, G., 1985, The loading on a cylinder in post-critical flow beneath periodic and random waves., Proc., 4th. Int. Conf. on the Behaviors of Offshore Structures, Delft, pp. 213-225.
- Bidde, D.B., 1971, Laboratory study of lift forces on circular piles, Journal of the Waterways, Harbors and Coastal Engineering Division, ASCE., Vol. 97, No. WW4, pp. 595-614.
- Grass, A.J., Simons R.R. and Cavanagh, N.J., 1987, Vortex-induced velocity enhancement in the wave-flow field around cylinders, Proceedings of the 6th. International Offshore Mechanics and Arctic Engineering Symposium - Volume 1I, pp. 155-164.
- Hayashi, K. and Takenouchi, T., 1979, The fundamental study of flow field around a vertical cylindrical pile subjected to waves, Proceedings, 20th. Japanese Conference on Coastal Engineering, Japan Society of Civil Engineers, pp. 406-410 (In Japanese).
- Hayashi, K. and Takenouchi, T., 1985, Characteristics of flow around a vertical circular cylinder in a wave, Coastal Engineering in Japan, Vol.28, pp. 207-222.
- Ikeda, S. and Yamamoto, Y., Lift forces on cylinders in oscillatory flows, Report of Dept. of Foundation Engineering and Construction Engineering, Saitama University, Vol.10, pp. 1-15.
- Iwagaki, Y. and Ishida, H., 1976, Flow separation, wake vortices and pressure distribution around a circular cylinder under oscillatory flows, Proc. 15th Coastal Engineering Conference, Honolulu, pp. 2341-2356.
- Isaacson, M. de St. Q. and Maull, D.J., 1976, Transverse forces on vertical cylinder in waves, Journal of the Waterways, Harbor and Coastal Engineering Division, ASCE., Vol.102, WW1, pp.49-60.
- Keulegan, G.H. and Carpenter, L.H., 1958, Forces on cylinders and plates in an oscillating fluid, Journal of Research of the National Bureau of Standards, Vol. 60,

No.5, pp. 423-440.

Mau11, D.J. and Milliner, M.G., 1978, Sinusoidal flow past a circular cylinder, Coastal Engineering, Vol.2, pp. 149-168.

Sawamoto, M., Kikuchi, K., Ohba, M. and Kashiwai, J., 1980, Force on a circular cylinder in an oscillatory flow, Coastal Engineering in Japan, Vol.23, pp. 147-158.

Williamson, C.H.K., 1985, Sinusoidal flow relatives to circular cylinders, Journal of Fluid Mechanics, Vol.155, pp. 141-174.