

On the Drift Speed of Floating Bodies in Waves

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ABSTRACT

In this paper, wave drift speed of a floating body is discussed. Measurements of wave drift speed were conducted on both two-dimensional floating body and three-dimensional floating body. Then, an estimation method of wave drift speed was derived from the analysis of measurement results.

The mechanism of wave drift speed varies with wavelength. In short wave range, wave drift force due to wave scattering pushes the floating body. Therefore, drift speed is decided by the equilibrium of wave drift force and fluid drag and it is proportional to the wave slope. In long wave range, on the other hand, wave drift force hardly acts on the floating body, because wave almost transmits the floating body. Therefore, the drift speed is decided by the wave-current speed and it is proportional to the square of the wave slope. Taking these wave drift mechanisms into consideration, an estimation method of wave drift speed, which covers entire wave range, is proposed.

KEY WORDS : Wave drift speed; Wave drift force; Wave current speed

INTRODUCTION

A joint research project named "On the drifting prevention of disabled ships in rough waves" is conducted by National Maritime Research Institute, the Maritime Safety Agency of Japan, Osaka University, Kyushu University, rope manufactures and a salvage company. In this project, development of towing support system for rescue ships and accuracy improvement of drift course prediction system are expected as final output. The authors are in charge of the latter system. The drift course prediction system was developed by the Maritime Safety Agency of Japan and had been put into practice. Accurate estimation of the drift speed is the key technology for the drift course prediction. In the total drift speed, the ocean current speed and tidal current speed are leading terms and drift speed due to wind and waves are correction terms. In the present system, wind corrections such as surface current speed induced by wind and etc. are fully con-

sidered. However, wave correction is very poor. To improve the accuracy of the prediction, the authors are studying wave induced drift speed of freely floating body in waves. In this paper, drift speed due to waves is simply called as wave drift speed.

There are two famous reports on the drifting of disabled ships. One is OCIMF report (1981) and another is HAZMAT report (1997). In OCIMF report, wave drift force and towing methods of disabled oil tankers were mainly studied by tank experiment. The drift speed was also argued based on real ship measurement in the actual seas. From the measured total drift speed, the ocean current speed and tidal current speed were subtracted to get wind and wave correction terms. However, these terms were studied together as a wind-wave drift factor and separate analysis was not given. In HAZMAT report, formal risk analysis was performed on disabled ships drifting in a certain sea route by simulations based on OCIMF methods. In neither report, wave drift speed was studied separately. Wave drift force was studied by many researches, Maruo(1960), Newman(1967), Nojiri and Murayama(1975), Kudo and Kobayashi(1977,1978). However, the authors could not find papers on wave drift speed itself.

Accordingly, free drifting tests were conducted in two dimensional and three dimensional tank of NMRI and drift mechanism of freely floating body in waves was studied, and estimation methods of wave drift speed were derived. The outline of the study is presented in this paper.

EXPERIMENTS

Measurement of wave drift speed in the two dimensional wave tank

Fig.1 shows the two dimensional wave tank, $Length = 26m$, $Width = 0.5m$ and $Water Depth = 0.5m$, used for the measurement of wave drift speed. This tank has a plunger type absorbing wave maker at one end, a wave breaking slope at the other end, rails and a light carriage on it.

A round rectangular cylinder with Lewis form section was used as a two dimensional floating body. Table 1 shows its principal dimensions. As fig.2 shows, the body was attached to the light

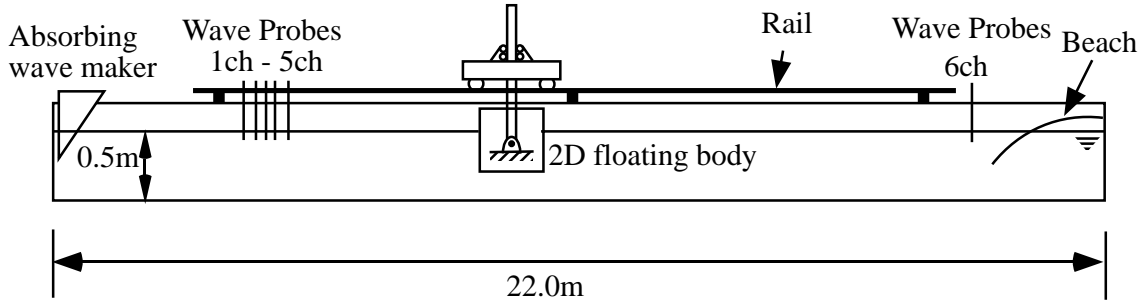


Fig.1: Illustration of two dimensional wave tank

Table 1 Principal dimensions

Breadth	B	0.40	m
Length	L	0.49	m
Draft	d	0.20	m
Displacement	W	39.2	kg
Metacenter height	GM	0.054	m
Lewis Form parameter	H_0	1.00	
Lewis Form parameter	σ	1.00	
Natural Roll Period	T_r	1.32	s

carriage through a gimbal and a heave rod.

The origin of wave drift test was set to the location distant $5m$ from the absorbing wave maker and the length of measurement range was taken $8m$ from the origin. We measured the time to pass each $1m$ section in the range by a stopwatch and obtained average wave drift speed in the sections. The measured wave drift speed was converged to constant value very soon.

We used both regular and irregular waves. For regular wave, nondimensional wave number $kB/2$ was varied from 0.4 to 2.0 and wave height H_w was varied from $2.0cm$ to $7.0cm$. Corresponding wave slope H_w/λ was from 0.010 to 0.064. For irregular wave, ISSC spectrum (Modified Pierson-Moskowitz type two parameter spectrum) was used. Using significant wave height H_V and wave period by visual observation T_V , ISSC spectrum is given as

$$\Phi_{\zeta\zeta}(\omega) = \frac{0.11}{2\pi} H_V^2 T_V \left(\frac{T_V \omega}{2\pi} \right)^{-5} \times \exp \left\{ -0.44 \left(\frac{T_V \omega}{2\pi} \right)^{-4} \right\} . \quad (1)$$

For the experiment, four T_V values, $0.88sec$, $1.02sec$, $1.32sec$ and $1.57sec$ were used. Corresponding nondimensional wave numbers $k_V B/2$ are 1.051, 0.800, 0.532 and 0.419 respectively. In this paper, the wave length and wave number corresponding to T_V are written as λ_V and k_V respectively and mean wave slope is defined by \bar{H}_w/λ_V , where $\bar{H}_w = 0.625H_V$ is mean wave height.

At the beginning of the experiment, we measured drag coefficient of the body in the two dimensional wave tank by towing test. The horizontal force was measured by a load cell installed between the gimbal and the heave rod. The result is shown in fig.3. Horizontal axis is towing speed $V(m/s)$ and vertical axis is drag force $F_D(N)$. The solid line in the figure is a quadratic

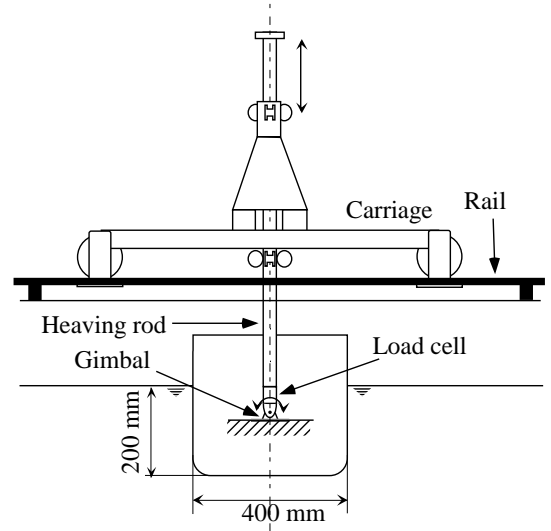


Fig.2: Measuring equipment of 2D floating body motions

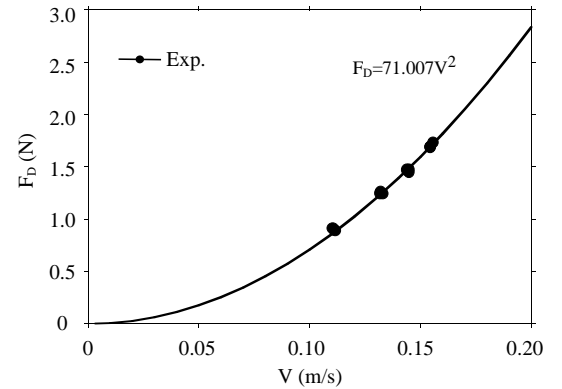


Fig.3: Drag on the 2D body as a function of speed

curve fitted in the sense of least square. From this towing test, drag coefficient of the body is determined as $C_D = 1.449$.

Next, fig.4 shows measured wave drift speed in regular waves of $kB/2 = 0.50, 0.70$ and 2.00 . The horizontal axis is wave

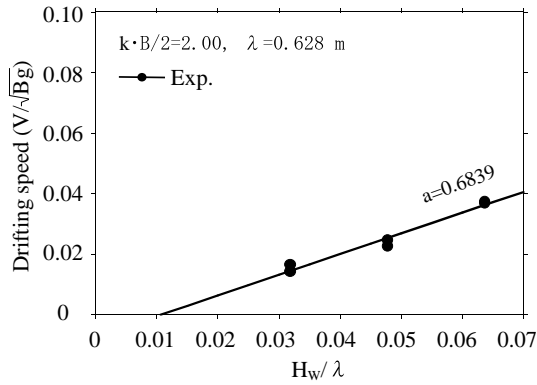
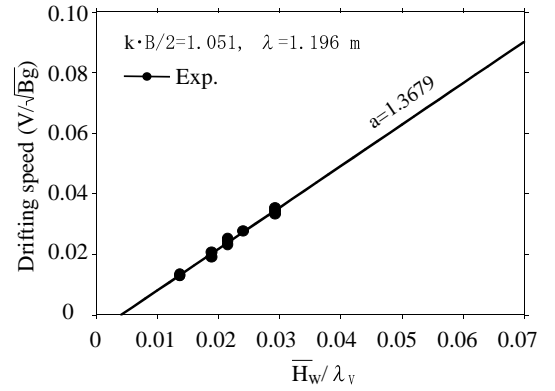
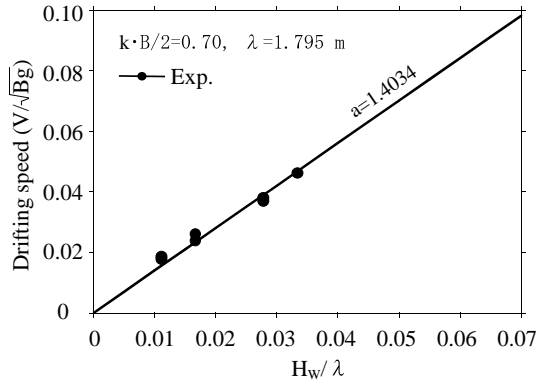
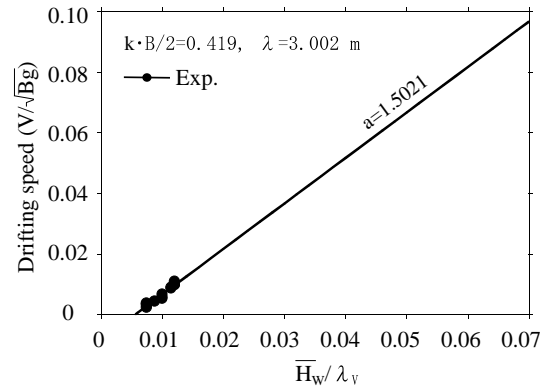
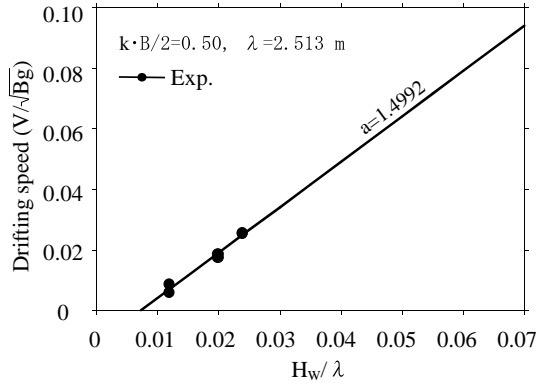


Fig.5: Relation between wave slope and drift speed (2D body in irregular waves)

Fig.4: Relation between wave slope and drift speed (2D body in regular waves)

At the last of this section, friction effect is commented. As fig.4 and fig.5 shows, fitting lines do not pass the origin. This is due to the total friction among the body, measuring equipment and wave tank. By precise measurement, we found total static friction is about 7 grams. The friction effect is comparatively small at nondimensional wave number is about 0.7, where wave drift force has its peak value.

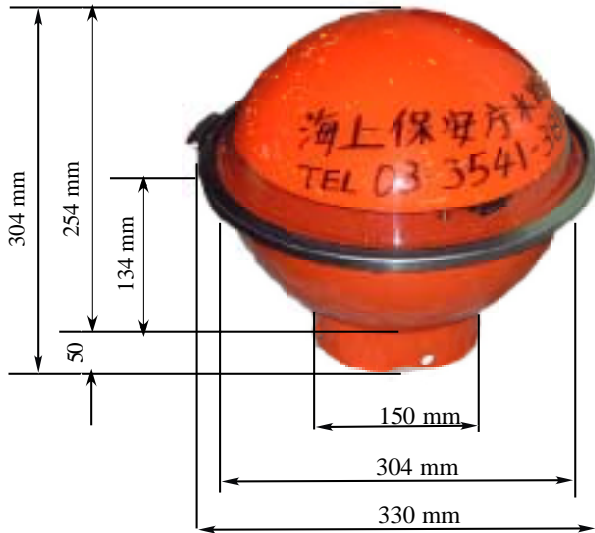
Measurement of wave drift speed in the three dimensional wave tank

We measured wave drift speed of three dimensional body in our small towing tank, $length = 50m$, $Breadth = 8.0m$ and $Depth = 4.5m$. This tank has a flap type wave maker. As the floating body, a spherical buoy is used. This is the genuine buoy used by the Maritime Safety Agency of Japan to measure drift course in the actual seas. Fig.6 shows its picture and principal dimensions. The height of spherical shell is a little shorter than the diameter of equator. At the equator, two half spherical shells are connected by flange. This buoy has cylindrical foot under the shell part. The water line in the fresh water is just below the flange and the draft is $184mm$. The natural period of heave and roll is about $0.7sec$ and $0.6sec$, respectively.

In this experiment, we measured the time to pass each $5m$ section by a stopwatch and obtained average wave drift speed in the sections. The origin of wave drift test was set to the location distant $7.6m$ from the wave maker and the length of measuring

slope and the vertical axis is Froude number V/\sqrt{Bg} , where the body breadth $B = 400mm$ is used as representative body scale. Black dots are measured points and a solid line shows its linear fitting line. The value of the coefficient a is also given in the figure. We can see from the figure that the wave drift speed is almost proportional to wave slope.

Fig.5 shows measured wave drift speed in irregular waves of $k_v B/2 = 0.419$ and 1.051 . The horizontal axis is mean wave slope, the vertical axis is Froude number, dots are measured points and the solid line is its linear fitting line. We can see also from this figure that wave drift speed is almost proportional to mean wave slope even in irregular waves. We conducted several measurements with same spectrum but different time series and confirmed good reproduction of wave drift speed.



Weight = 6.35 kg
 Natural heave period = 0.7 sec
 Natural roll period = 0.6 sec

Fig.6: Spherical buoy used for the measurement

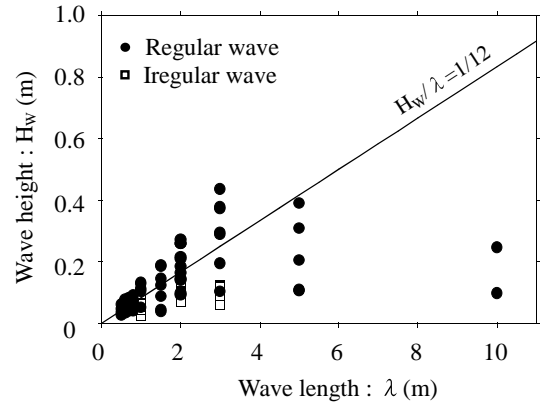


Fig.7: Waves used for the drift speed measurement of the buoy
 (λ_V, \bar{H}_w are used on irregular waves)

range was taken 25m from the origin. Also in three dimensional measurement, the wave drift speed was converged to constant value very soon.

Also in three dimensional experiment, we used regular and irregular waves. Range of wave length we can generate by the flap wave maker of this tank is from 0.5m to 10m. Fig.7 shows the regular waves used for the experiment. The horizontal axis is wave length λ , the vertical axis is wave height H_w and dots in the figure show the combination of λ and H_w . The solid line in the figure shows that wave slope is 1/12 on it. The points over the line, significant wave breaking was observed. In the actual fully developed seas, wave breaking frequently occurs. Therefore, we covered such a large amplitude limits in the measurement. For irregular waves, as explained in the previous section, ISSC spectrum was used. In the experiment, three T_V values, 0.80sec, 1.13sec and 1.39sec, were used. Corresponding nondimensional wave lengths is 1m, 2m and 3m, respectively. The combinations of T_V and mean wave height \bar{H}_w are plotted in fig.7 by white circles.

Fig.8 and fig.9 show measured wave drift speed in regular waves. The horizontal axis is wave slope and the vertical axis is Froude number V/\sqrt{Dg} , where V is wave drift speed and $D = 304mm$ is the diameter of buoy at equator. The solid lines in figures are fitting lines and a is their coefficient. Since the buoy is freely drifting in the tank without any measuring equipment attached on it, the buoy is free from mechanical friction and the all fitting lines pass the origin. The broken lines in the figures show wave-current speed of Stokes wave at free surface.

As fig.8 shows, in short wave range $\lambda = 0.5m \sim 1.5m$, the wave drift speed of the buoy is almost proportional to wave slope and it is faster than the wave-current speed at free surface. Wave-current speed is exponentially decrease with respect to depth. Therefore, in the short wave range, wave-current speed compo-

nent in the total wave drift speed is considered to be much slower than the speed given by the broken line. Taking these experimental fact into account, we can say that the drift motion of the buoy is mainly driven by wave drift force in short wave range.

On the other hand, we can observe in fig.9 that the relation between wave drift speed and wave slope gradually changes from linear to quadratic as wave length becomes longer. At $\lambda = 5.0m$, wave drift speed of the buoy well agrees with wave-current speed of Stokes wave. Since wave drift force is very weak in such a long wave range, we consider the buoy travels with wave-current in long wave range.

As these experimental results show, wave drift mechanism in long wave range is different from that of in short wave range. Therefore, it is necessary to consider both mechanisms to develop theoretical estimation method of wave drift speed. The estimation method is presented in the next section. In this section, experimental results are presented successively.

In fig.8 and fig.9, measured wave drift speed in breaking waves are also plotted. Even in the extremely steep waves such as the wave slope exceeds 1/12, the linear relation between wave drift speed and wave slope was kept and the wave drift speed was found to be not so much affect by wave breaking. Before the experiment, we expected that wave drift speed was much affected by wave breaking. However, from the observation of experiment, we found that wave breaking was local phenomenon and the buoy was not always located at the breaking point. Therefore, effect of wave breaking to wave drift speed of buoy is not so significant.

Next, results in irregular waves are shown in fig.10. The horizontal axis is the mean wave slope and the vertical axis is Froude number. This figure shows that wave drift speed is almost proportional to mean wave slope. For each run of measurement, we used different time signal to generate irregular waves. The measured wave drift speed converged to the almost same value in irregular waves. Reproduction of the results were quite good.

ESTIMATION METHOD OF WAVE DRIFT SPEED

Wave drift speed in short wave range

As shown in the previous section, wave drift speed is proportional to wave slope in short wave range. This relation can be

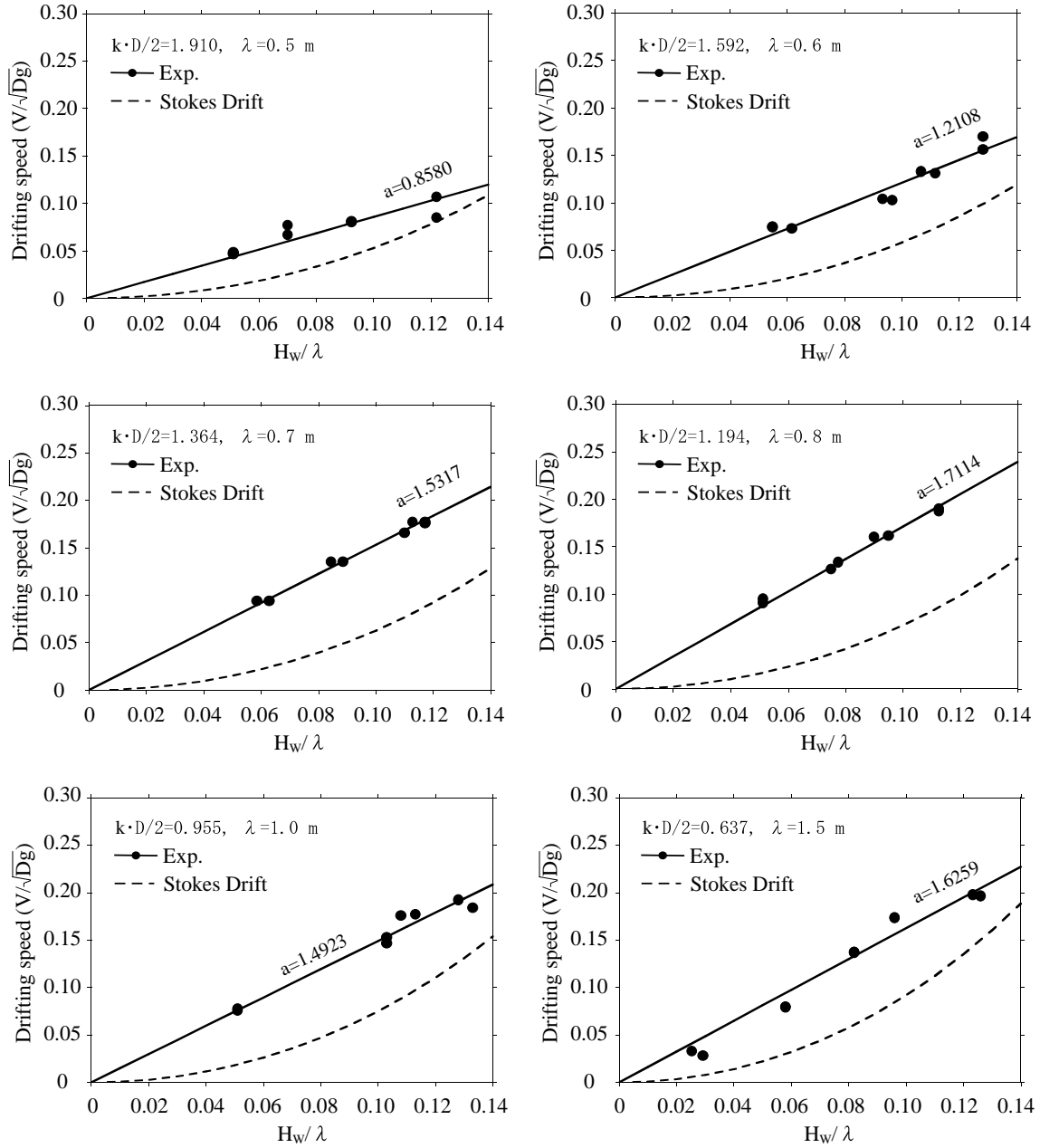


Fig.8: Relation between wave slope and drift speed
(Buoy in regular waves ; $\lambda = 0.5 \sim 1.5$)

derived from the balance between wave drift force and drag force. Wave drift force F_W is proportional to the square of wave height and drag force F_D is proportional to the square of speed.

$$F_W = \frac{1}{8} \rho g D_R C_W H_w^2, \quad (2)$$

$$F_D = \frac{1}{2} \rho A C_D V^2, \quad (3)$$

where A is projection area of the buoy below the free surface, C_D is drag coefficient of the buoy, C_W is nondimensional wave drift force and D_R is the representative body scale. The breadth of the two dimensional body or the diameter of the buoy is used

as D_R . Wave drift speed is obtained from the balance between F_W and F_D as follows.

$$\frac{V}{\sqrt{D_R g}} = \frac{1}{2} \sqrt{\frac{\lambda^2 C_W}{A C_D}} \frac{H_w}{\lambda}. \quad (4)$$

This equation well explains the linear relation between wave slope and wave drift speed. The values of C_D and C_W can be obtained from experiment, database or computation. In this paper, we call the coefficient a

$$a = \frac{1}{2} \sqrt{\frac{\lambda^2 C_W}{A C_D}} \quad (5)$$

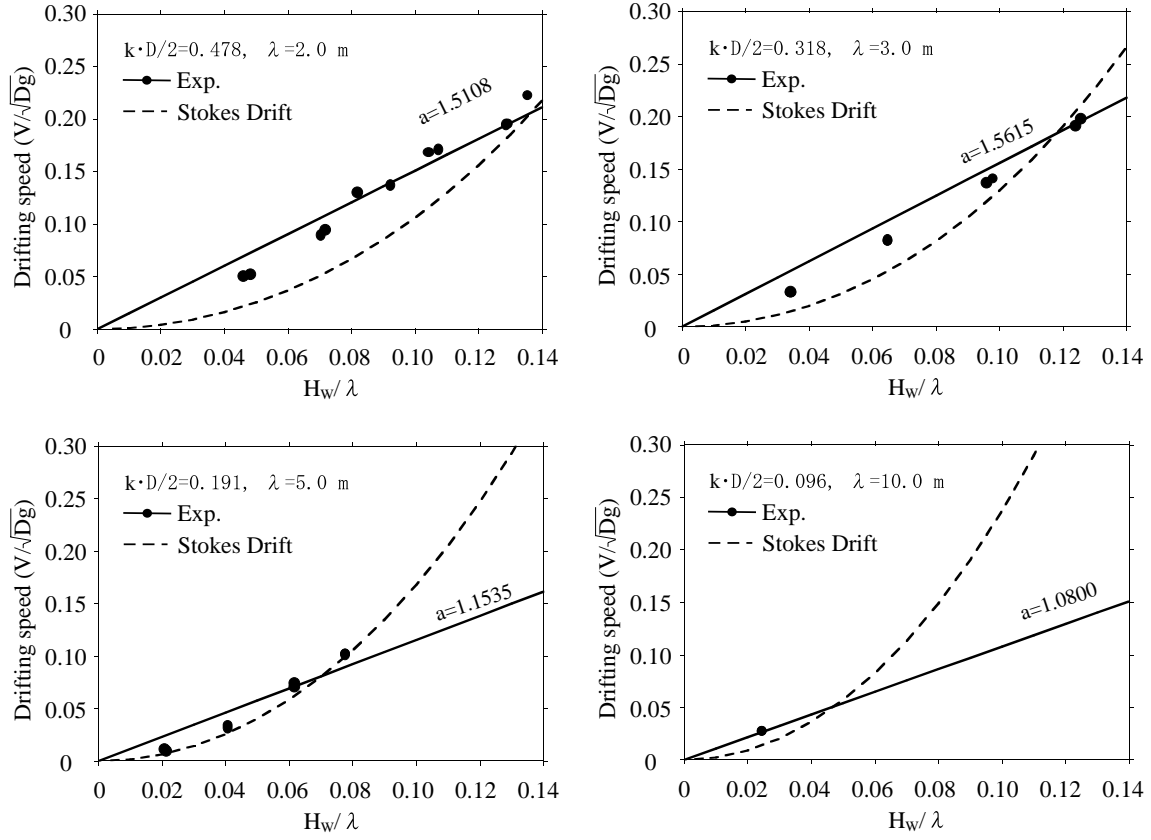


Fig.9: Relation between wave slope and drift speed
(Buoy in regular waves ; $\lambda = 2.0 \sim 10.0$)

as the linear coefficient of wave drift speed.

Fig.11 shows comparison between the estimated value and the measured value of a for the two dimensional body. Black dots are measured value taken from fig.4 and the solid line is estimated value by the above equation. For this estimation, C_W is obtained from numerical simulation by NWT, Tanizawa et al.(1999,2000), and C_D is obtained from the towing test. The agreement between estimated value and the measured value is good.

Next, fig.12 shows the same kind of comparison for three dimensional buoy. Using our database, Hoshino(1997), value of C_D is estimated to be about 0.9 . Value of C_W is obtained from theoretical work of Kudo(1977,1978) for sphere . Black dots are measured value taken from fig.8 and fig.9. As observed in the figure, agreement between estimated value and the measured value is also good.

Wave drift speed in long wave range

Since the incident wave is transmitted without significant scattering by floating body in long wave range, wave drift force acts on the body is very weak. Therefore, the wave drift is driven by wave induced current in long wave range. The wave current speed of Stokes wave U is written as

$$U = c\pi^2\delta^2 e^{2kz} , \quad (6)$$

$$c^2 = \frac{g}{k} \left(1 + \pi^2\delta^2 + \frac{1}{2}\pi^4\delta^4 \right) , \quad (7)$$

where δ is wave slope H_w/λ and c is the phase velocity of Stokes wave, Kinsman(1965). Here, neglecting the higher order terms in c , Froude number of the wave current speed is written as

$$\frac{U}{\sqrt{D_Rg}} = \frac{\pi^2\delta^2 e^{2kz}}{\sqrt{kD_R}} . \quad (8)$$

Assuming that the drift speed of the body can be approximated by the average wave current speed on the projection area of the body, it is given by

$$\frac{V}{\sqrt{D_Rg}} = b\delta^2 , \quad (9)$$

$$b = \frac{\pi^2}{A\sqrt{kD_R}} \int_A e^{2kz} ds . \quad (10)$$

In this paper, we call b as the quadratic coefficient of wave drift speed.

To validate this equation, we applied quadratic regression analysis $a\delta + b\delta^2$ on the measured data shown in fig.9 and determined the value of b . Fig.13 shows the results. The solid line is estimated value of b by above equation and black dots are data obtained by the regression analysis. It can be said the estimated value well agree with measured data in long wave range.

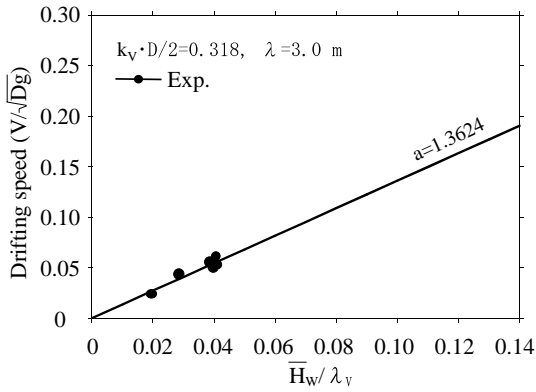
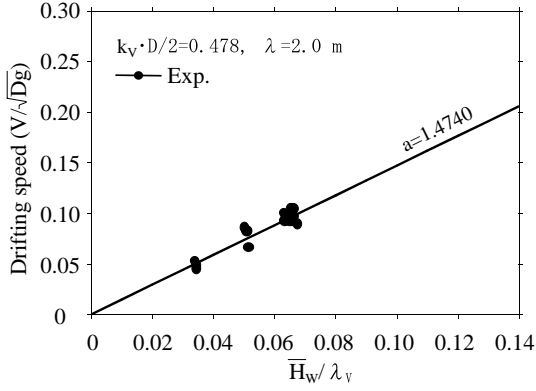
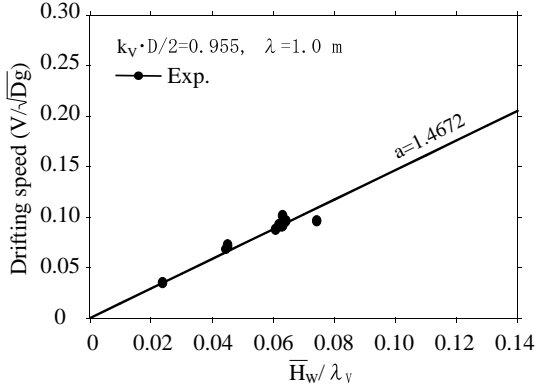


Fig.10: Relation between wave slope and drift speed (Buoy in irregular waves)

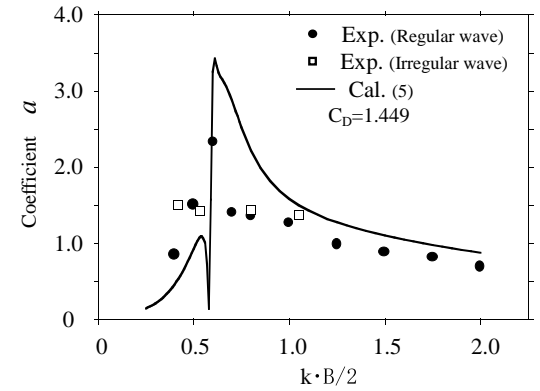
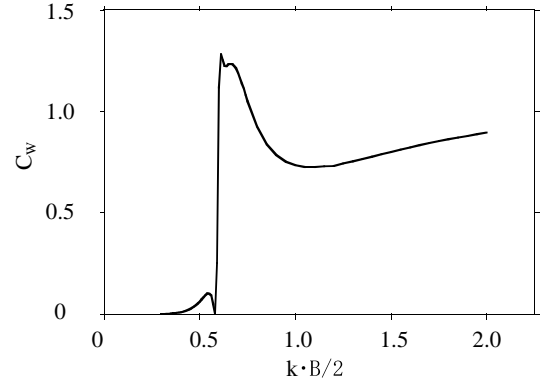


Fig.11: Linear coefficient of wave drift speed of the 2D body

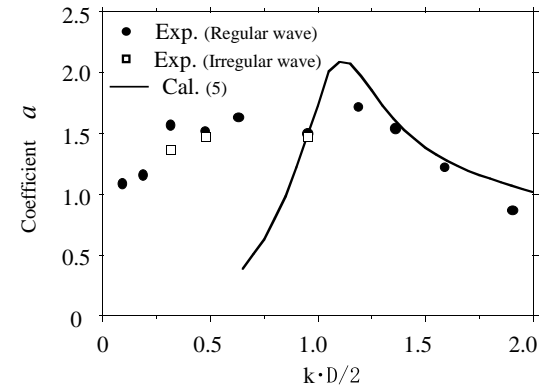


Fig.12: Linear coefficient of wave drift speed of the buoy

Wave drift speed in entire wave range

Considering the results in the previous sections, we expected that wave drift speed in entire wave range is approximated by the sum of the speed in the short wave range and that in long wave range.

$$\frac{V}{\sqrt{D_{Rg}}} = a\delta + b\delta^2 \quad (11)$$

Fig.14 shows the comparison between measured speed and the estimated speed by equation (11). The agreement in the short and the long wave range is reasonable. However, the agreement in the middle wave range is not good as expected. We used the theoretical wave drift force acts on perfect sphere as an approx-

imation of wave drift force on the buoy. The buoy has a flange at the equator and a cylindrical foot. In particular, the flange part went in and out from the free surface in waves and caused non-linear effect. We suppose these things might affect to the wave drift force and make difference near $kD/2$ is $0.5 \sim 1.0$. We need further consideration to develop more accurate estimation method of wave drift speed in entire wave range. Additional experimental with perfect sphere model should be conducted to confirm the hypothesis.

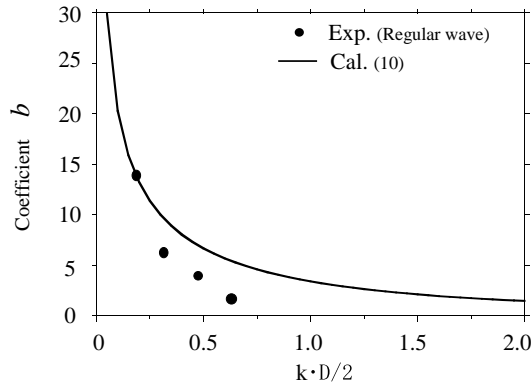


Fig.13: 2nd order coefficient of wave drift speed of the buoy

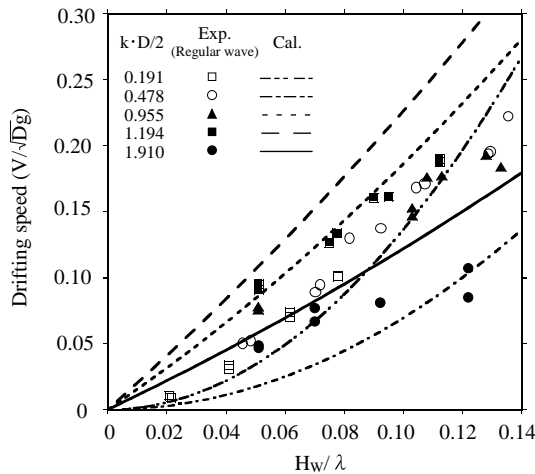


Fig.14: Wave drift speed of the buoy

Wave drift speed in irregular waves

To compare wave drift speed in irregular waves with that of in regular waves, the measured wave drift speed in both regular waves and irregular waves are plotted together in fig.11 and fig.12. White squares show the results in irregular waves. To plot the results, we used \bar{H}_w and k_V as corresponding wave height and wave number of regular wave. As shown in these figures, agreement of wave drift speed in regular waves and irregular waves are good particularly in short wave range. This fact indicates that wave drift speed in irregular waves can be approximated by the that of in regular waves.

CONCLUSION

The following items are main conclusion of this work.

1. In short wave range, wave drift speed induced by wave drift force is dominant. Wave drift speed is determined from the valance between wave drift force and drag force, and it is proportional to the wave slope.
2. Even in the extremely steep waves with breaking, wave drift

speed keeps proportional relation to the wave slope. The effect of wave breaking is not as significant as we expected before the experiment.

3. In long wave range, wave drift speed is dominated by wave-current speed. Wave drift speed is determined by the mean wave-current speed of Stokes wave on the body and it is proportional to the square of wave slope.
4. Wave drift speed in irregular waves are approximated by that of in regular waves by taking \bar{H}_w and k_V as corresponding wave height and wave number of regular waves.

At the last of this paper, a comment on the wave-current speed is supplemented. As far as we discuss about the result of tank experiment, wave drift speed in long wave range is well explained by the wave-current speed of Stokes theory which assumes ideal fluid. The reason of this agreement is little viscous effect in the tank. As Kinsman(1965) argued, wave-current speed of real viscous fluid sometimes much larger than theoretical value of Stokes wave. The validation of the conclusion in the actual seas has not finished, yet.

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