Analytical Study of the Effect of Drift Motion on the Capsizing Probability under Dead Ship Condition

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ABSTRACT

The effect of drift motion on the capsizing probability under dead ship condition was examined in this paper. Drift speed in beam wind and waves was estimated by the combination of the manoeuvring model of the slow streaming condition, wind force and wave drift force. It is found that the estimated drift speed explains the drift speed measured by the model tests. The capsizing probability, which takes account of the effect of the drift motion, was evaluated. It is verified quantitatively that the drift motion has effect on the capsizing probability.

Keywords: *dead ship, drift motion owing to wind and waves, large passenger ship, cross flow model, capsizing probability*

1. INTRODUCTION

It is well known that a ship, which is almost longitudinally symmetric, suffers beam wind and waves when all her operational means such as propeller thrust and rudder control are lost. Therefore, it is important to assess the capsizing probability under dead ship condition properly and to provide the minimum requirements for an adequate stability. It is also known that a drift motion has effect on the capsizing probability. However, there is few study on the effect of it on the capsizing probability.

Based on the background, the analytical model for the estimation of the roll motion under dead ship condition is proposed. By means of the present method, the effect of the drift motion on the capsizing probability under dead ship is examined.

Firstly, model tests have been carried out by means of a large passenger ship, which has a large windage area. The test comprised free drifting tests in beam wind and waves. The drift speed and roll motions of the passenger ship were discussed. It is found that wind has much effect on the drift speed. It is verified that roll motion of the large passenger ship in the severe sea state is not significant.

Secondly, the drift speed under dead ship condition was estimated by extending the manoeuvring model of the slow streaming condition, which is developed by Yoshimura (Yoshimura, 1988). Wind forces and wave induced lateral force are integrated with the drag owing to the drift motion in the present model.

In the present method, a lateral resistance, which is associated with the drift speed, was estimated under the assumption that the resistance due to water is mainly generated by the vortex-induced viscous forces. Wind force was estimated by means of the empirical formulas, which were developed by Blendermann and Fujiwara (Blendermann, 1996 and Fujiwara, 2001). With regard to the wave drift motion, the wave-induced steady lateral force was estimated by means of the Kashiwagi's method (Kashiwagi, 1992). The only unknown in this method is the Kochin function, which is equivalent to the ship-generated progressive wave far from the ship. The Kochin function was estimated by means of the Enhanced Unified Theory (Kashiwagi, 1995), which incorporates the 3-D and forward-speed effects on the longitudinal source distribution representing ship disturbance in the far field.

By summarizing these estimated forces, the drift speed under dead ship condition was estimated. Having compared with the experimental data, it is confirmed that present method is useful for the qualitative estimation of the drift speed under dead ship condition.

Finally, the capsizing probability was evaluated by integrating a joint probability density function of Gaussian roll and roll rate in waves over the capsizing domain on the phase plane of the roll motion. Based on these findings, the effect of the drift motion on the capsizing probability under dead ship condition was discussed. It is confirmed that drift speed has effect on the capsizing probability under dead ship condition.

2. THE SUBJECT SHIP

The large passenger ship used in the present study has been designed at MARIN for the use in studies on parametric rolling in head and following seas, the results of which had been published at several international conferences (e.g., Luth, 1998). The principal dimensions of the large passenger ship are shown in Table 1. The profile of the large passenger ship is shown in Figure 1. The hull form is typical for a modern large passenger ship. It is equipped with bilge keels and anti-roll fins.

Concerning loading conditions of this ship, the limiting KG is governed by the weather criterion in the IMO Intact Stability code. Figure 2 shows the righting lever (GZ) curves correspond to five KG values. In the calculation of the GZ curves, non-watertight superstructure and down-flooding openings were neglected. The steady and gust wind heeling levers, defined in the weather criterion, are also shown in Figure 2.

Table 1 Principle dimensions of the large passenger ship

Lpp(m)	240
B(m)	32.2
D(m)	22
d(m)	7.75
Displacement(m3)	36895.58
Cb	0.616
B/d	4.15
Roll period(sec)	24.7
GM(m)	1.85
Logitudinal radius of gyration (κyy/L)	0.25
Transverse radius of gyration (κxx/L)	0.45

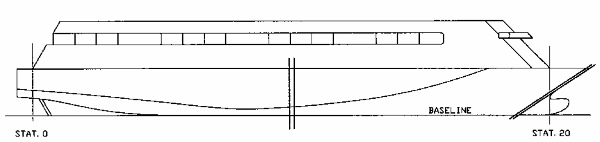

Figure 1 Profile of the large passenger ship

For three of these cases (KG=15 m, 15.6 m and 15.8 m; OG/d=0.935, 1.013 and 1.039), the ship complies with the current weather criterion. In particular, KG = 15.8 m represents the limiting KG case, so the other two KG cases (16 and 16.4 m) would result in failure of the weather criterion.

The present study was carried out for the case of KG=15.8m, which is a critical value against the weather criterion.

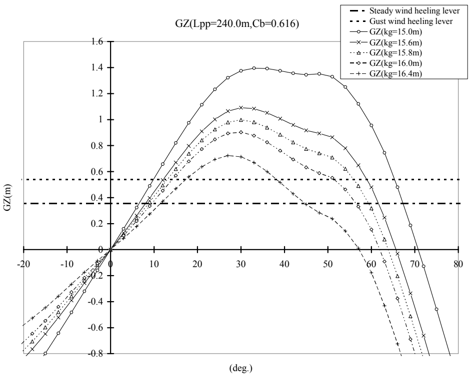

Figure 2 Righting lever (GZ) curve of the large passenger ship

3. EXPERIMENTS IN BEAM WIND AND WAVES

For the examination of the effect of wind and waves on the drift motion, model tests have been carried out at Seakeeping and Manoeuvring Basin of MARIN (dimensions 170m x 40m) in a severe sea states. The test program comprised free drifting tests in beam steady wind only (Wind speed U_T: 20 and 26 m/sec), irregular beam waves only (H_s = 9.5 m, T_{01} = 10.4sec) and in combined beam waves and steady wind. The roll period was measured to be 24.7 sec. by a roll decay test.

Table 2 and 3 show the mean and the standard deviation of measured roll motion and yaw motion respectively. Even in such a severe sea state, the roll motion was very limited. It is clarified that the associated capsize probability would be extremely low for such a sea state. It is found that the standard deviation of yaw motion in beam wind is small. This indicates that ship drifts with the small heading angle and with the steady heading angle generated at the initial stage of the drift motion.

Table 2 Mean and standard deviation of roll in beam wind and waves

U_T (m/sec)	$H_{1/3}$ (m)	T_{01} (sec)	Mean (deg.)	Standard Deviation (deg.)
20	----	----	2.96	0.17
26	----	----	4.90	0.27
----	9.5	10.4	0.40	1.13
20	9.5	10.4	2.89	1.06
26	9.5	10.4	5.22	1.32

Table 3 Mean and standard deviation of yaw in beam wind and waves

U_T (m/sec)	$H_{1/3}$ (m)	T_{01} (sec)	Mean (deg.)	Standard Deviation. (deg.)
20	----	----	14.7	1.59
26	----	----	21.25	0.79
----	9.5	10.4	1.38	9.56
20	9.5	10.4	10.75	1.15
26	9.5	10.4	16.31	1.45

Figure 3 and 4 show the trajectory where the ship drifts in beam wind only (wind speed U_T: 26m/sec) and in beam waves only (H_s = 9.5 m, T_{01} = 10.4sec) respectively. In the present experiments, measurements were begun just in the beam wind and waves. The mean drift speed in beam wind only is 2.0m/sec. The mean drift speed in beam waves only is 0.8 m/sec. It is found that wind has much effect on the drift speed rather than waves.

Figure 5 shows the trajectory where the ship drifts in beam wind and waves. The mean drift speed in beam wind only (Wind speed U_T=26 m/sec) is 2.2m/sec. It is clarified that the ship drifts at close to a beam sea heading angle. It is found that the trajectory in wind and waves looks very similar to the trajectory in beam wind only. It is verified that the wind has a dominant influence on the drift motion.

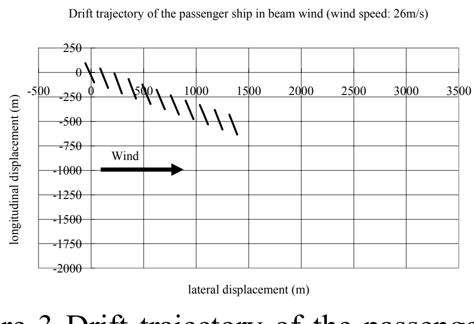

Figure 3 Drift trajectory of the passenger ship in beam wind (wind speed: 26m/s, time interval of trajectory: 70.7 sec)

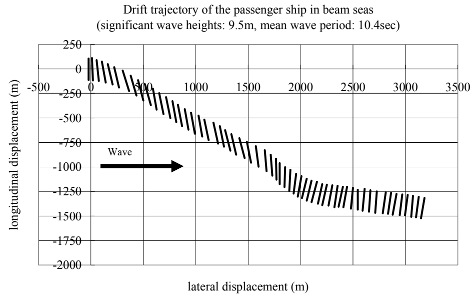

Figure 4 Drift trajectory of the passenger ship

in beam waves (significant wave heights: 9.5m, mean wave period: 10.4sec, time interval of trajectory: 70.7 sec)

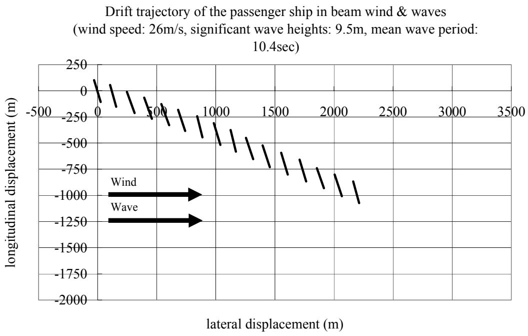

Figure 5 Drift trajectory of the passenger ship in beam wind and waves (wind speed: 26m/s, significant wave heights: 9.5m, mean wave period: 10.4sec, time interval of trajectory: 70.7 sec)

4. ESTIMATION METHOD OF DRIFT SPEED OWING TO WIND AND WAVES

4.1 Equation of Motion

The drift speed under dead ship condition was estimated by extending the cross flow model of the slow streaming condition, which was developed by Yoshimura (Yoshimura, 1988). Wind forces and wave induced lateral force are integrated with drag owing to the drift motion in the present model. The equation of the lateral motion of the drifting ship, which is almost longitudinally symmetric, can be described as follows:

$$(m+m_y)\dot{v}+(m+m_x)ur = Y_H + Y_A + Y_W . \tag{1}$$

Here m denotes ship's mass, m_x denotes longitudinal component of added mass, m_y denotes lateral component of added mass, u denotes the longitudinal component of ship speed, v denotes the lateral component of ship speed, r denotes angular velocity, Y_H denotes the resistance owing to drift motion, Y_A denotes the lateral component of wind force and Y_W denotes the lateral component of wave drift force. However, the equation (1) can be expressed as follows because the results of the experiments show that the angular velocity is negligible.

$$(m+m_y)\dot{v} = Y_H + Y_A + Y_W \tag{2}$$

4.2 Resistance owing to drift motion

In accordance with Yoshimura's cross flow model, the resistance owing to a drift motion can be described as the cross flow drag of the slow streaming condition. In accordance with the similar procedure to the equation (2), the lateral component of the cross flow drag is approximated as follows:

$$Y_H = \frac{\rho}{2} LdV^2 C_{D0} \tag{3}$$

where ρ denotes the density of fluid, L denotes the ship length, d denotes the ship draught, V denotes the ship speed and C_{D0} denotes the cross flow drag coefficient. In this study, C_{D0} was assumed as 0.8.

Strictly, experimental results clarified that the longitudinal velocity of drift motion of the present large passenger ship can not be neglected. It means that not only the equation of the lateral motion but also the equation of the longitudinal motion should be solved.

However, in the present study, only the equation of the lateral motion was solved to estimate the lateral drift speed as the first step of the development of the rational estimation method of drift motions.

4.3 Wind Force

Wind force Y_A can be estimated by means of the experimental formulas by Blendermann (Blendermann, 1996) or Fujiwara (Fujiwara, 2001). In accordance with their methods, the lateral component of wind force is expressed as follows:

$$Y_A = C_{YA} \frac{\rho_A}{2} U_T{}^2 A_L \tag{4}$$

where C_{YA} denotes the aerodynamic drag coefficient, ρ_A denotes the air density, U_T denotes the lateral wind velocity and A_L denotes the lateral projected area. The aerodynamic coefficients by means of the Blendermann's data for the passenger ship and the Fujiwara's empirical equation give almost the same value (0.895 and 0.883). In this study, C_{YA} was assumed as 0.895.

4.4 Wave Drift Force

According to Kashiwagi's theory (Kashiwagi, 1992) which is based on the momentum and energy conservation principles, the wave drift force was calculated. A Cartesian coordinate system was taken as shown in Figure 6. A ship is assumed to advance with a constant speed U and oscillate with a circular frequency ω in deep water. By means of the ship-generated progressive waves at far field, the wave induced sway force is expressed as

$$\begin{aligned}\frac{\overline{Y}}{\rho g \varsigma_w^2} \cong \frac{-1}{4\pi k_0}&\left[-\int_{-\infty}^{k_1} + \int_{k_2}^{k_3} + \int_{k4}^{\infty}\right]\nu \times \\ &\mathrm{Im}\left[C(k)\cdot S^*(k)\right]dk \\ &+\frac{1}{2}\sin\chi\cdot \mathrm{Im}\left[C(k_0\cos\chi)+iS(k_0\cos\chi)\right],\end{aligned} \tag{5}$$

where

$$\left.\begin{aligned}\kappa(k) &= \frac{1}{g}(\omega + kU)^2 = K + 2k\tau + \frac{k^2}{K_0} \\ K &= \frac{\omega^2}{g}, \tau = \frac{U\omega}{g}, K_0 = \frac{g}{U^2}\end{aligned}\right\} \tag{6}$$

$$\begin{aligned}\left.\begin{matrix}k_1\\k_2\end{matrix}\right\} &= \frac{-K_0}{2}\left(1+2\tau \pm \sqrt{1+4\tau}\right) \\ \left.\begin{matrix}k_1\\k_2\end{matrix}\right\} &= \frac{K_0}{2}\left(1-2\tau \mp \sqrt{1+4\tau}\right)\end{aligned} \tag{7}$$

g is the gravitational acceleration, ζ_w is the wave amplitude and k_0 is the wave number of the incoming wave.

Here it should be understood that k_3=k_4 for τ>1/4 and the integration range from k_2 to ∞ in (5) becomes continuous.

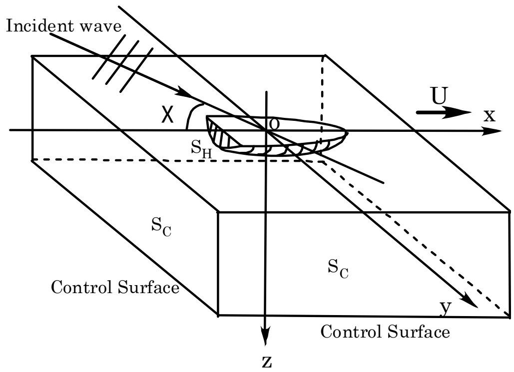

Figure 6 Coordinate system of Kashiwagi's theory

The wave-amplitude functions in (5), $C(k)$ and $S(k)$, are given by the following equations as the superposition of all components of ship-generated waves

$$\begin{aligned}C(k) &= H_{7C}(k) \\ &-\frac{\omega_0\omega}{g}\sum_{j=1,3,5}\frac{X_j}{\zeta_w}\cdot H_j(k)\end{aligned} \tag{8}$$

$$\begin{aligned}S(k) &= H_{7S}(k) \\ &-\frac{\omega_0\omega}{g}\sum_{j=2,4,6}\frac{X_j}{\zeta_w}\cdot H_j(k)\end{aligned} \tag{9}$$

where ω_0 is the circular frequency of the incoming wave, X_j is the complex amplitude of the ship motion of j-th mode and $H_j(k)$ is the Kochin function of the ship-generated progressive waves at far field. In the present method, the Kochin function was calculated by means of the Kashiwagi’s Enhanced Unified Theory (Kashiwagi, 1995).

Figure 7 shows the wave induced steady sway force in beam seas as a function of wave length ratio λ/L (λ:wave length, L:ship length). It is found that the wave induced steady sway force is not affected by the small difference of the heading angle.

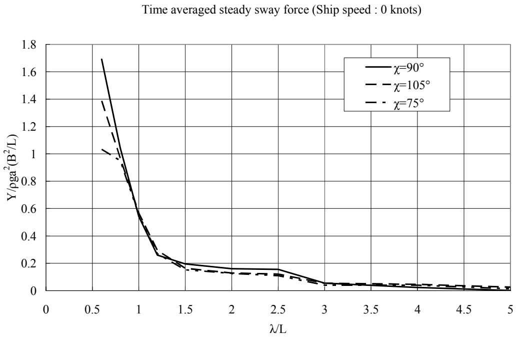

Figure 7 Wave induced steady sway force (Fn=0.0)

By means of the wave spectrum and the response amplitude operator shown in Figure 7, wave drift force in the irregular beam waves is calculated as follows:

$$Y_w = 2\int_{-\pi}^{\pi}\int_{0}^{\infty}\frac{\overline{Y}}{\varsigma_w^2}S_{\zeta\zeta}(\omega)G(\theta)d\omega d\theta. \qquad (10)$$

where $S_{\zeta\zeta}(\omega)$ denotes the wave spectrum, $G(\theta)$ denotes the angular distribution function and θ denotes the encounter angle of wave.

4.5 Comparison with Measured Drift Speed

By substituting of the equations (3), (4) and (10) into the equation (2), the lateral component of the drift speed was estimated. Figure 8 shows the lateral component of the drift speed in wind and waves as a function of wind speed. In this calculation, the significant wave height and mean wave period were given with the same condition of the present experiments (H_s = 9.5 m, T_{01} = 10.4sec). Only wind speed was varied in the present calculation.

It is found that the estimated drift speed well explains the measured drift speed although the drift speed in the beam waves only (wind speed =0 in Figure 8) is underestimated. It is clarified that the present method, which is the combination of the manoeuvring model of the slow streaming condition, wind force and wave drift force, gives a rational drift speed under dead ship condition.

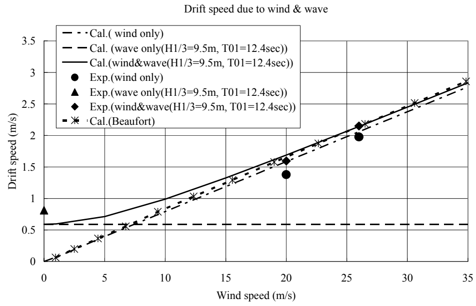

Figure 8 Relation between the wind speed and the drift speed owing to wind and waves.

5. EFFECT OF THE DRIFT MOTION ON THE CAPSIZING PROBABILITY

The capsizing probability is evaluated by integrating a joint probability density function of Gaussian roll and roll rate in waves over the capsizing domain on the phase plane of roll motion (Umeda, 1992). Although roll motion out side the safe region could be non-Gaussian in details, it is clarified that the difference between the present method and the more rigorous one, e.g. the piecewise linear method, could be minor for the present purpose (Belenky, 1995 and Iskandar et al., 2001).

In the present study, the wind velocity U_T is assumed to change with time around the average velocity with Davenport Spectrum. It is assumed that the wind generates long crested waves with the significant wave height $H_{1/3}$ and the mean wave period T_{01} given in Table 4. The ITTC spectrum is used for fully developed waves.

Firstly, the mean encounter frequency was calculated by means of the drift speed in accordance with the present method. Figure 9 shows the mean encounter frequency of the present large passenger ship with and without a drift motion. It is found that the encounter frequency with drift motions is closer to her natural roll frequency. It is clarified that the drift motion has effect on the encounter frequency.

Table 4 Sea states of the Beaufort chart

Beaufort	UT(m/sec)	H1/3(m)	T01(sec)
1	0.95	0.1	1.2
2	2.50	0.2	1.7
3	4.45	0.6	3.0
4	6.75	1.0	3.9
5	9.40	2.0	5.5
6	12.35	3.0	6.7
7	15.55	4.0	7.7
8	19.00	5.5	9.1
9	22.65	7.0	10.2
10	26.50	9.0	11.6
11	30.60	11.5	13.1
12	34.85	14.0	14.1

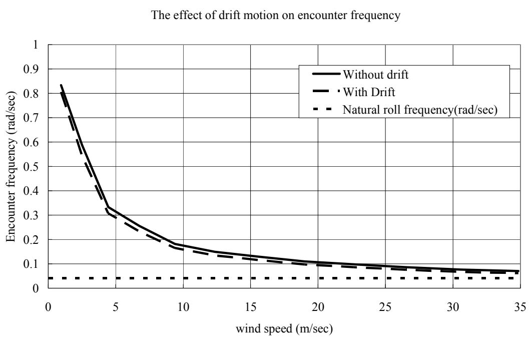

Figure 9 Relation between mean encounter frequency and the wind speed of the large passenger ship (without/with drift motion).

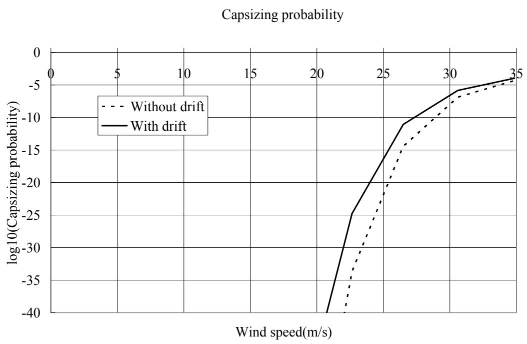

Figure 10 Capsizing probability of the large passenger ship (without/with the drift motion).

Figure 10 shows the capsizing probability of the present large passenger ship. The encounter wave spectrum transformed by the drift speed was used for the estimation of the capsizing probability. It is found that the capsizing probability of the present large passenger ship with drift motion is higher than that without drift motions owing to the difference of the encounter wave frequency. It is confirmed that the drift speed has effect on the capsizing probability under dead ship condition although the degree of the effect depends on the natural roll period.

6. CONCLUSIONS

In this study, model tests have been carried out by means of a large passenger ship in beam wind and waves. The effect of the drift motion on the capsizing probability under dead ship condition was discussed. It is concluded as follows

(1) The wind has much effect on the drift motion under dead ship condition.

(2) The present method, which is the combination of the manoeuvring model of the slow streaming condition, wind force and wave drift force, can estimate the drift speed under dead ship condition qualitatively.

(3) The capsizing probability of the present large passenger ship is affected by the drift motion owing to the difference of the encounter wave frequency.

7. ACKNOWLEDMENTS

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