PREDICTION METHODS FOR CAPSIZING UNDER DEAD SHIP CONDITION AND OBTAINED SAFETY LEVEL - FINAL REPORT OF SCAPE COMMITTEE (PART 4) -

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ABSTRACT

Regarding capsizing of ships under dead ship condition, this paper reports experimental, numerical and analytical studies conducted by the SCAPE committee, together with critical review of theoretical progress on this phenomenon. Here capsizing probability under dead ship condition is calculated with a piece-wise linear approach. Effects of statistical correlation between wind and waves are examined. This approach is extended to the cases of water on deck and cargo shift. Further, experimental and theoretical techniques for relevant coefficients are examined. Based on these outcomes, it also proposes a methodology for direct assessment as a candidate for the new generation criteria at the IMO.

KEY WORDS: Dead Ship Condition; Intact Stability Code; Beam Winds and Waves; Capsizing Probability, Piece-Wise Linear Approach, Water on Deck

INTRODUCTION

Stability under dead ship condition is one of three major capsizing scenarios in terms of performance-based criteria, which is requested to be developed for the revision of the Intact Stability Code (IS Code) by 2010 at the International Maritime Organization (IMO). It was expected to be a probabilistic stability assessment based on physics by utilizing first principle tools. This is owing to the fact that probabilistic approach can be linked with a risk analysis and dynamic-based approach enables us to deal with new ship-types without experience.

Therefore, it is important to establish a method for evaluating capsizing probability under dead ship condition because its safety level could be a base for other capsizing scenarios. In case of the dead ship condition, under which the main propulsion plant, boilers and auxiliaries are not in operation owing to absence of power, a shipmaster cannot take any operational countermeasure. This means that operational factors are not relevant to safety level evaluation. Although some operational actions such as high-speed running in following waves can decrease safety level against capsizing, they can be avoided by operators if the safety level under dead ship condition is ensured. In other words, if perfect operation is taken, the safety level during a ship's life-cycle could be comparable to that under dead ship condition.

For the dead ship condition, the weather criterion is currently implemented in the IS Code and provides a semi-empirical criterion for preventing capsizing in beam wind and waves. The dead ship condition, however, does not always mean beam wind and waves. If a ship has a longitudinally asymmetric hull form, ship may drift to leeward with a certain heading angle. Therefore, it is important to estimate the drifting attitude of a ship and to evaluate its effect on capsizing probability. It is also widely known that empirical estimation of effective wave slope coefficient in the weather criterion is often difficult to be applied to new ship-types such as a RoPax ferry, a large passenger ship and so forth. Therefore, the IMO (2006) recently allows us to use model experiments for this purpose although it is not always feasible. A simplified prediction method is still desirable if accurate enough.

Based on the above situation, the authors presented a methodology for calculating capsizing probability of a ship under dead ship condition. In this present methodology, capsizing probability under dead ship condition is calculated by means of piece-wise linear approach.

Through this paper, we summarize this methodology and its application of this methodology to the new generation criteria at the IMO.

First, a prediction method of the annual capsizing probability in beam seas based on a piece-wise linear approach was presented.

Second, the methodology is verified with the Monte Carlo simulation and is extended to the case with cargo shift, down-flooding and water on deck. The effect of several important factors, such as drifting attitude, drifting velocity, hydrodynamic coefficient estimation and statistical correlation between wind and waves are investigated.

Third, safety level in terms of capsizing probability was assessed by means of the present approach for passenger and cargo ships as well as fishing vessels.

HISTORICAL REVIEW

Several methods were developed for estimating capsizing probability in stationary irregular waves. One is the numerical experiment known as the Monte Carlo simulation, in which the expected number of capsizing is estimated by repeating numerical simulation in time domain with different wave realizations (McTaggart and de Kat 2000). If a reliable mathematical model is available, this method seems to be easily applicable. However, since capsizing probability of an existing ship is small, the number of numerical runs could be prohibitively large. In addition, statistical variation of outcomes is not suitable for regulatory purposes. Sheinberg et al. (2006) attempted to improve this approach by focusing on critical local waves. Others are theoretical ones, in which capsizing probability is obtained as the product of the probability of dangerous condition and the conditional probability of capsizing. Some methods utilize stationary linear or non-linear theory for the former and non-linear time-domain simulation of deterministic process for the latter (Umeda et al. 1992; Shen and Huang 2000; Bulian and Francescutto, 2004). Sheng and Huang (2000) use the Markov process for probability density of roll and use the deterministic simulation in the final stage. Bulian and Francescutto (2004) use a simplified stochastic linearization technique, with a Poisson modelling of the capsize event. Their main drawback is an assumption for the final deterministic process. Although some studies (Jiang and Troesch, 2000; Falzarno et al., 2001) for extending the Melnikov approach into random seaways were carried out, no direct relationship with capsizing probability was not provided. Avoiding such a drawback, Belenky (1993) proposed a piece-wise linear approach where both probabilities are analytically calculated by approximating the restoring arm curve with piece-wise linear ones. Because of its fully analytical scheme, the piece-wise linear approach has been utilized for practical purpose as the most promising methodology. An approach that has a series of similarities with the piece-wise linear method, but that is based on a simplified statistical linearization technique, has been developed by Bulian and Francescutto (2004, 2006)

For a ship in irregular beam seas, Belenky derived exact formulae based on a piece-wise linear approach without numerical results. Then he extended his method to the case in both beam winds and waves (Belenky 1994) and provided numerical results with his simplified method (Belenky 1995). Here the formulae relating to the wind effect were not published in detail. Recently, Iskandar et al. (2001) applied Belenky's simplified method to estimated annual capsizing probability of Indonesian Ro-Ro ferry accidents. Others (Umeda et al. 2002; Munif et al. 2004, Francescutto et al., 2004) also applied that to estimate the capsizing probability of fishing vessels and a large passenger ship.

Although Belenky's piece-wise linear method is widely utilized, some unsolved problems remain. Firstly, complete formulae for covering the wind effect have not been published. Secondly, numerical results of the exact formulae have not yet been reported for evaluating the accuracy of the simplified formula. Thirdly, effects of several elements such as wind have not been examined.

Therefore, Paroka et al. (2006) examined these problems with deriving the detailed formulae for the case of beam winds and waves and calculating with both exact and simplified formulae for a car carrier, which has a large windage area.

CAPSIZING PROBABILITY BY MEANS OF THE PIECE-WISE LINEAR APPROACH

The methodology adopted by the SCAPE committee for calculating capsizing probability under dead ship condition is based on the piece-wise linear approach proposed by Belenky(1993). This is partly because it rigorously takes acount of nonlinear restoring moment and its efficient calculation load enables us to obtain annual capsizing probability by integrating many combinations of wave height and wave period in long-term wave statistics. As mentioned above, Belenky's formulation for beam waves (Belenky, 1993) and its extension to beam wind and waves case (Belenky, 1994) had not been complete enough so that Paroka et al. (2006) corrected them. Therefore, in this paper, the upgraded formulation is overviewed.

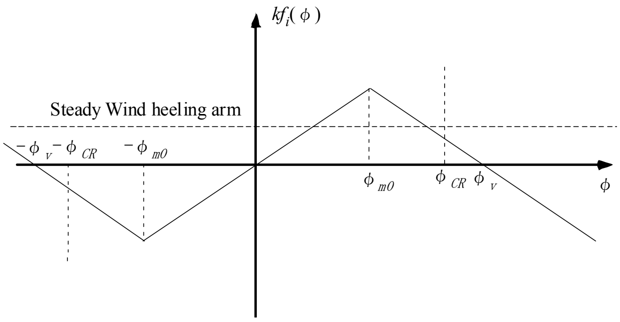

Fig. 1 Piece-wise linear approximation of righting arm.

The capsizing probability here is calculated with the following nonlinear and uncoupled equation of relative or absolute rolling angle of a ship under a stochastic wave excitation and steady wind moment. Usually the ship motion in beam seas is modeled with equations of coupled motions in sway and roll with wave radiation forces and diffraction forces. Watanabe (1938), however, proposed an one-degree of freedom equation of roll angle, ϕ, as follows

$$(I_{xx} + A_{44})\ddot{\phi} + B_{44}\dot{\phi} + WGZ(\phi) = M_{wind}(t) + M_{wave}(t) \qquad (1)$$

where I_{xx} is momentum of inertia of the ship, A_{44} is the hydrodynamic coefficient of added inertia, W is the ship displacement, B_{44} is the hydrodynamic coefficient of roll damping, GZ(ϕ) is the righting arm. $M_{wind}(t)$ is the wind induced moment consisting of the steady and fluctuating wind moment and $M_{wave}(t)$ is the wave exciting moment based on the Froude-Krylov assumption. This is because the roll diffraction moment and roll radiation moment due to sway can cancel out when the wavelength is sufficiently longer than the ship breadth. (Tasai, 1969)

The uncoupled equation of the absolute roll motion (1) can be rewritten by dividing by the virtual moment of inertia as follows:

$$\ddot{\phi} + 2\alpha\dot{\phi} + \omega_0^2 kf_i(\phi) = \omega_0^2 \left(m_{wind}(t) + m_{wave}(t)\right) \quad (2).$$

where $kf_i(\phi)$=GZ(ϕ)/GM, α: roll damping coefficient, ω_0 : the natural roll frequency and $kf_1(\phi)$: the non-dimensional righting arm, $m_{wind}(t)$: the wind induced moment consisting of the steady and fluctuating wind moment and $m_{wave}(t)$: the wave exciting moment based on the Froude-Krylov assumption.

As shown in Fig. 1, the restoring moment coefficient in equation (2) is approximated with continuous piece-wised lines in leeward and windward conditions as follows:

$$kf_i(\phi) = \begin{Bmatrix} kf_0\phi & 0 < \phi < \phi_{m0} \ range1 \\ kf_1(\phi_v - \phi) & \phi_{m0} < \phi \ \ range2 \end{Bmatrix} \quad (3)$$

and

$$kf_i(\phi) = \begin{Bmatrix} kf_0\phi & -\phi_{m0} < \phi < 0 \ range1 \\ kf_1(-\phi_v - \phi) & \phi < -\phi_{m0} \ \ range2 \end{Bmatrix} \quad (4).$$

Here, kf_0 and kf_1 are the slope of the range 1 and range 2, respectively. ϕ_{m0} and $-\phi_{m0}$ are the border between the range 1 and the range 2 in leeward and windward, respectively. Effects of dividing methods of the righting arm curve into piece-wise lines and the case using the relative roll angle can be found in Paroka et al. (2006).

Since Equation (2) is linear within each range, it can be analytically solved without any problems. The border condition, however, should be satisfied. Therefore, capsizing occurs when the roll angle up-croses, ϕ_{m0}, or down-crosses, $-\phi_{m0}$, and then the absolute value of roll angle increases further. Therefore, capsizing probability can be calculated as the product of the outcrosing probability in the range 1 and the conditional probability of divergence of the absolute value of roll angle in the range 2. Belenky (1993) presented the following formula for the probability that a ship capsizes when the duration, T, passes in stationary waves.

$$P(H_{1/3}, T_{01}, W_s, T) = 2P_T(\phi > \phi_{m0}) P_A(A > 0; \phi > \phi_{m0}) \quad (5)$$

Where $H_{1/3}$: the significant wave height, T_{01}: the mean wave period, W_S: the mean wind velocity and T: duration.

Since this formula could exceed 1, Umeda et al. (2004) proposed the following formula.

$$\begin{aligned} P(H_{1/3}, T_{01}, W_s, T) = \\ & P_l P_T(\phi > \phi_{m0} or \phi < -\phi_{m0}) P_A(A > 0; \phi > \phi_{m0}) + \\ & P_w P_T(\phi > \phi_{m0} or \phi < -\phi_{m0}) P_A(A < 0; \phi < -\phi_{m0}) \end{aligned} \quad (6).$$

Here P_l and P_W denote the probability of up-rossing toward leeward and that of down–crossing toward windward. Under the assumption of Poisson process, P_T indicates the probability of at least one up-crossing or down-crossing at the border between the first and second range, ϕ_{m0} or $-\phi_{m0}$. P_A is the probability of diverging behavior of absolute value of the roll angle in the second range including the angle of vanishing stability.

These can be determined as following formulas:

$$P_T(\phi > \phi_{m0} or \phi < -\phi_{m0}) = 1 - exp(-(u_l + u_w)T) \quad (7)$$

$$P_l = \frac{u_l}{u_l + u_W}, \quad P_W = \frac{u_W}{u_l + u_W} \quad (8)$$

$$P_A(A > 0; \phi > \phi_{m0}) = \int_0^{\infty} f(A) dA, \quad P_A(A < 0; \phi < -\phi_{m0}) = \int_{-\infty}^{0} f(A) dA \quad (9)$$

where u_l and u_W denote the expected number of up-crossing and down-crossing, respectively. f(A) denotes the probability density function of the coefficient A,, which is a function of three random variables, namely the initial angular velocity of roll motion, $\dot{\phi}_1$, the initial forced roll, p_1, and the initial forced angular velocity, $\dot{p}_1$, in the second range.

The probability density function of the A coefficient can be determined from a joint probability density function of these three random variables, which can be calculated by using the three-dimensional Gaussian probability density (Price and Bishop, 1974).Then, the probability density function of the coefficient A in leeward can be described as follows:

$$f(A) = \frac{1}{\lambda_2 - \lambda_1} \int_{-\infty}^{\infty} \int_0^{\infty} f\left(\dot{\phi}_1, \dot{p}_1\left(A, \dot{\phi}_1, p_1\right), p_1\right) d\dot{\phi}_1 dp_1 \quad (10)$$

That in windward can be described as follows:

$$f(A) = \frac{1}{\lambda_2 - \lambda_1} \int_{-\infty}^{\infty} \int_{-\infty}^{0} f\left(\dot{\phi}_1, \dot{p}_1\left(A, \dot{\phi}_1, p_1\right), p_1\right) d\dot{\phi}_1 dp_1 \quad (11)$$

where

$$\lambda_{1,2} = -\alpha \pm \sqrt{\omega_0^2 kf_1 + \alpha^2} \quad (12).$$

Furthermore, Belenky (1993) simplified Equations (10) and (11) by using the fact that roll resonance in the second range does not exist because of negative restoring slope. As a result, $f(A)$ can be evaluated with a single integral in place of a double integral.

For evaluating risk of capsizing, it is necessary to calculate annual capsizing probability with sea state statistics of operational water area. The formula of the annual capsizing probability, P_{an}, can be found in Iskandar et al. (2000) as follows:

$$P_{an} = 1 - \left(1 - P^*(T)\right)^{(365\times24\times3600/T)} \tag{13}$$

where

$$P^*(T) = \int_0^\infty\int_0^\infty f(H_{1/3}, T_{01}) \cdot P(H_{1/3}, T_{01}, W_s, T) dH_{1/3} dT_{01} .$$

Here W_s is assumed to be fully correlated with $H_{1/3}$

VERIFICATION AND EXTENSIONS OF PIECE-WISE LINEAR APPROACH

Comparison with the Monte Carlo simulation

For verifying the piece-wise linear approach, Paroka & Umeda (2006b) calculated capsizing probability of a large passenger ship in stationary beam wind and waves and compared it with the Monte Carlo simulation. First, they confirmed that stochastic scattering of the Monte Carlo simulation results is comparable to its confidence interval estimated with the assumption of binomial distribution. Second, it was that the piece-wise linear approach coincides with the Monte Carlo simulation in moderate sea states, such as the mean wind velocity of 28 m/s, within the confidence interval but underestimates it in more severe wind velocity as shown in Fig.2. The results of this underestimation are that the assumption of the Poisson process for outcrossing is not appropriate when the sea state is extremely severe. In addition, it is impossible for the Monte Carlo simulation to accurately quantify the capsizing probability in lower wind velocity because the probability is too small. In conclusion, it is not so easy to verify the piece-wise linear approach but it seems not to be inappropriate to use the piece-wise linear approach for the mean wind velocity of 26 m/s, which the weather criterion deals with, but there is a room for further improvement.

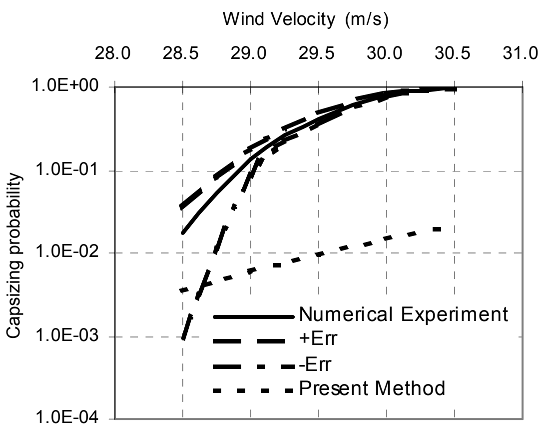

Figure 2. Comparison of capsizing probability of the large passenger ship between the piece-wise linear approach and the error tolerance of Monte Carlo simulation. (Paroka & Umeda, 2006b)

Effect of critical angle for down-flooding or cargo shift

In case of a ship has large angle of vanishing stability, the obtained capsizing probability could be very small but the ship could capsize owing to cargo shift or down flooding when the roll angle is larger than her critical angle. In this case, the calculation method mentioned above cannot be directly applied because angle of vanishing stability cannot be determined.

Therefore,. Paroka & Umeda. (2006a) extend the piece-wise linear seas approach to the case having the critical roll angle. Here the probability of roll angle exceeding the critical value is defined as the probability of roll angle of the second range exceeds the critical value when the roll motion up-crosses or down-crosses the border between the first and the second ranges of the piece-wise linear righting arm curve. This can be written as follows:

$$\begin{aligned} P(H_{1/3}, T_{01}, W_s, T) = \\ P_l P_T(\phi > \phi_{m0} or \phi < -\phi_{m0}) P_{CR}(\phi > \phi_{CR} ; \phi > \phi_{m0}) + \\ P_w P_T(\phi > \phi_{m0} or \phi < -\phi_{m0}) P_{CR}(\phi < -\phi_{CR} ; \phi < -\phi_{m0}) \end{aligned} \tag{14}$$

where P_{CR} is the conditional probability of roll angle exceeds the critical value, ϕ_{CR} .

The conditional probability of roll angle exceeds the critical value is calculated with assuming that effect of exciting moment on the roll motion in the second range is negligibly small. This assumption is based on the fact that resonance is impossible in the second range owing to its negative stiffness. Therefore the roll motion in this range depends only on the initial condition, which is the same as the roll motion at the end of the first range. The solution of the roll motion equation in the second range can be written as follows:

$$\phi_2(t) = A\exp(\lambda_1 t) + B\exp(\lambda_2 t) + (\phi_v - \phi_D) \tag{15}$$

where

$$\lambda_{1,2} = -\alpha \pm \sqrt{-\alpha + \omega_0^2 k f_1} \tag{16}$$

$$\phi_D = \frac{m_0}{\omega_0^2 k f_1} \tag{17}$$

$$A = \frac{1}{(\lambda_1 - \lambda_2)}\left[\dot{\phi}_{02} - \lambda_2\{\phi_{m0} - (\phi_v - \phi_D)\}\right] \tag{18}$$

$$B = \frac{1}{(\lambda_1 - \lambda_2)}\left[\lambda_1\{\phi_{m0} - (\phi_v - \phi_D)\} - \dot{\phi}_{02}\right] \tag{19}$$

Here $\dot{\phi}_{02}$ indicates the initial angular velocity of roll motion in the second range. m_0 indicates the non-dimensional steady wind moment. In order to investigate whether or not the roll angle exceeds the critical value, the following iteration procedure is proposed. Firstly the initial angular velocity of roll motion in the second range with negative A coefficient in the equation (18) is arbitrarily choose. Secondly the time of the angular velocity of roll motion becomes zero is calculated as follows:

$$t_m = \frac{1}{(\lambda_1 - \lambda_2)}\ln\left(-\frac{B\lambda_2}{A\lambda_1}\right) \tag{20}$$

Then the roll angle with the time, t_m , can be calculated by means of the equation (15). If this roll angle is smaller than the critical one, the initial angular velocity is increased and we repeat these processes. When the maximum roll angle has been larger than the critical value, the iteration is stopped and the initial angular velocity is set as the critical angular velocity. The probability of roll angle exceeds the critical value then can be calculated as the same as the probability of the initial angular velocity of roll motion higher than the critical angular velocity. The probability of the initial angular velocity larger than the critical angular velocity can be calculated as follows:

$$P\left(\dot{\phi}_{02} > \dot{\phi}_{CR}\right) = \frac{2}{\sqrt{2\pi D_{\dot{q}}}} \int_{\dot{\phi}_{CR}}^{\infty} \exp\left\{\frac{\dot{\phi}_{02}}{2D_{\dot{q}}}\right\} d\dot{\phi}_{02} \qquad (21)$$

where $\dot{\phi}_{CR}$ indicate the critical value of the angular velocity in the second range. The probability of roll angle exceeding the critical value in a certain exposure time can be calculated by means of the equation (14) with the conditional probability of roll angle exceeds the critical value is replaced by the equation (21).

Numerical results of the car carrier for several critical angles ranging from 55 degrees to 75 degrees are shown in Fig. 3 (Paroka et al., 2006c). The probability of dangerous condition increases when the critical angle decreases. This is because the roll angle can exceed the critical value even if the roll motion in the second range does not diverge. The difference disappears when the unstable heel angle owing to steady wind moment is smaller than the critical value. When the unstable heel angle is smaller than the critical value, the roll angle can exceed the critical value only if the roll motion in the second range diverges.

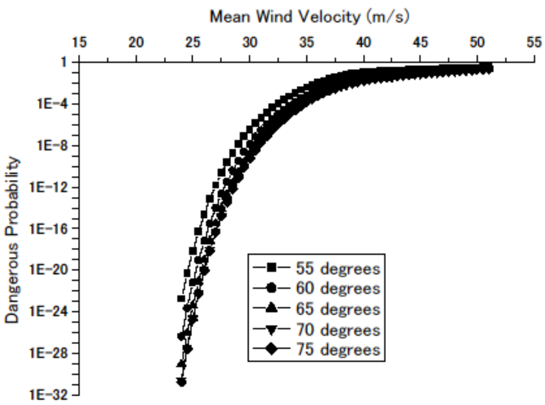

Fig. 3 Dangerous probabilities of the car carrier for different critical roll angles (Paroka & Umeda., 2006a).

Effect of water on deck

For smaller ships such as fishing vessels, the effect of trapped water on deck should be taken into account. This is because these ships have smaller freeboard but higher bulwark comparing with their ship size. As a result, when shipping water occurs, water can be easily trapped by bulwark. Although a certain amount of water can flow out through freeing ports, the balance between ingress and egress can be trapped on deck. The righting arm can decrease because of the water trapped on deck. Many experimental and numerical works about effect of water trapped on deck have been published (e.g. Belenky, 2003) however its effect to capsizing probability has not been investigated.

Paroka & Umeda (2006c) extended the piece-wise linear approach to the case with trapped water on deck. Here the amount of trapped water was estimated with model experiments (Matsuda et al., 2005) by measuring heel and sinkage of the model in irregular beam waves. Water ingresses and egresses through the bulwark top or freeing ports and the balance of these can be determined duringb the experiment. As a result, it was found out that the trapped water on deck could increase the capsizing probability for this ship type as shown in Fig. 4. This is because the trapped water can significantly reduce the mean restoring arm up to the angle of immersion of the bulwark top, which is approximated with piece-wise linear curves as a function of stationary sea state..

As a next step, Paroka & Umeda (2007) incorporated a numerical model for describing water ingress and egress with a hydraulic model into the piece-wise linear approach. As a result, capsizing probability with water on deck can be calculated without a model experiment. Here the dynamic effect of trapped water on deck such as change in added mass, damping coefficient and exciting moment are ignored for simplicity's means.

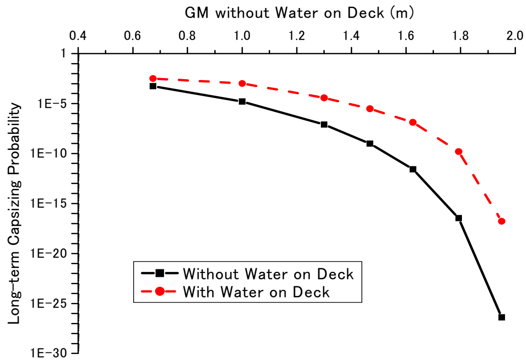

Fig. 4 Long-term capsizing probability with and without water on deck for the purse seiner operating off Kyusyu. (Paroka & Umeda, 2006c)

Effect of drifting attitude and velocity

The dead ship condition does not always mean beam wind and waves. If a ship has a longitudinally asymmetric hull form, ship may drift to leeward with a certain heading angle. Therefore, it is important to estimate the drifting attitude of a ship and to evaluate its effect on capsizing probability.

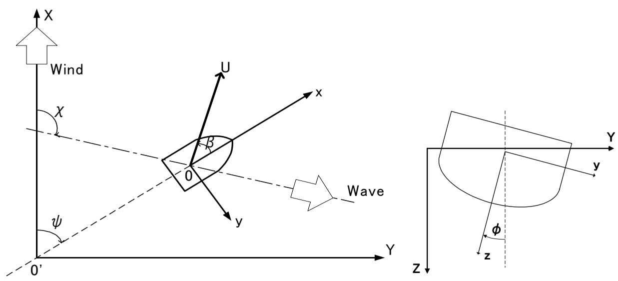

Fig. 5 Co-ordinate systems

For estimating drifting velocity and attitude of a ship in regular waves and steady wind, Umeda et al. (2006b, 2007a) proposed a method for identifying equilibria of a surge-sway-yaw-roll model and for examining its local stability. Equilibria can be estimated by solving 4-DOF non-linear equations in the following co-ordinate systems shown in Fig. 5;

$$(m+m_x)\dot{u}-(m+m_y)vr = X_H + X_A + X_W \tag{22}$$

$$(m+m_y)\dot{v}+(m+m_x)ur - m_y l_y \ddot{\phi} = Y_H + Y_A + Y_W \tag{23}$$

$$(I_z+J_z)\ddot{\psi} = N_H + N_A + N_W \tag{24}$$

$$(I_x+J_x)\ddot{\phi} - m_y l_y \dot{v} - m_x l_x ur + 2\mu\dot{\phi} + W\cdot GM\phi = K_H + K_A \tag{25}$$

where
u,v ; ship speed in x-axis and y-axis,
ψ , ϕ ; yaw and roll angle,
m ; ship mass,
W ; displacement,
GM ; metacentric height,
m_x, m_y; added mass in x-axis and y-axis,
I_x, I_z; moment of inertia around x-axis and z-axis,
J_x, J_z ; added moment of inertia around x-axis and z-axis,
l_x, l_y; vertical position of centre of m_x and m_y
X, Y; external forces in x-axis and y-axis
N, K; yaw and roll moments

Here the subscript H, A and W means hydrodynamic force/moment, wind force/moment and wave-induced drifting force/moment.

In this model, a mathematical model for hydrodynamic forces under low speed manoeuvring motion (Yoshimura, 1988), an empirical method for wind forces (e.g. Fujiwara, 2001), and a potential theory for wave-induced drifting forces (Kashiwagi, 2003) are used.

The Newton method was used to identify equilibria of the equations. As an initial input, the equilibria in the beam wind and waves from starboard and those from port side are calculated. And then, equilibria for different angle between the wind and waves, χ , are traced. The calculation are done in two ways: the first one is that χ changes from 0 degrees to 180 degrees (forward) with the wind direction fixed, and the second is that χ changes from 180 degrees to 0 degrees (backward). Stability of equilibrium is evaluated by calculating the eigenvalues of the Jacobean matrix in the locally linearised system around equilibrium. The example of results is shown in Fig 6.

These figures indicate that when the relative angle between wind and waves is 0 degrees, the ship is drifting leeward in beam wind and wave. Having the relative angle between wind and waves larger from 0 degrees, the heading angle gradually increases from the beam wind.

Ogawa et al.(2006b) examined the present method through the comparison with measured drifting motions. Fig. 7 shows the sway velocity in wind and waves as a function of wind speed. In this calculation, the significant wave height and mean wave period were of the same as in the experiments ($H_{1/3}$ = 9.5 m, T_{01} = 10.4 sec). Only the wind speed was varied in the present calculation. It is found that the computed drift speed is close to the measured drift speed, although the drift speed in beam waves only (wind speed = 0 in Fig. 7) was underestimated. It is confirmed that present method is useful for the quantitative computation of the drift speed under dead ship condition.

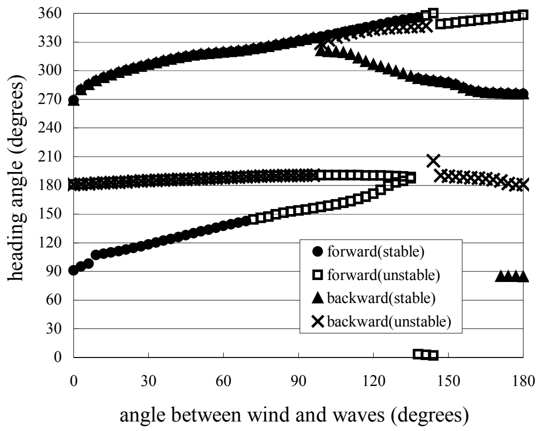

Fig. 6 Heading angle of fixed points as a function of relative angle between wind and waves (wind speed is 26 m/s, wave amplitude is 2.85m and wave length ratio is 2.94). (Umeda et al., 2006b)

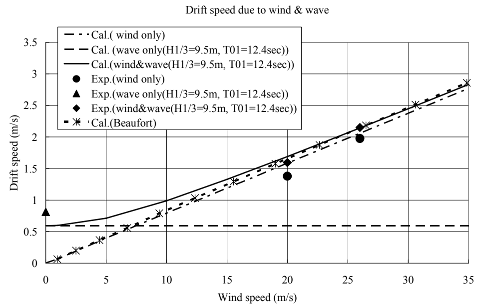

Fig. 7 Relation between the wind speed and the drift speed in wind and waves. (Ogawa et al., 2006b)

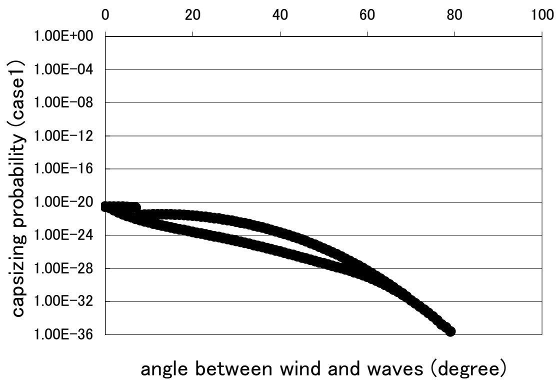

Fig.8 Capsizing probabilities under two coexisting drifting conditions as functions of relative angle between wind and waves. (Umeda et al., 2006b)

An example of capsizing probabilities under two coexisting stable steady drifting states are shown in Fig 8. Umeda et al. (2006b, 2007a) Here the mean wind velocity is 26 m/s and the duration is one hour. The fully developed wind waves under this wind velocity are assumed. In this calculation, the effect of relative angle to wind is modelled as the change in lateral windage area, the effect of relative angle to waves is done as the change in effective wave slope coefficient and the effect of drifting velocity is done as the change in the exciting frequency. In addition, the heeling lever due to drift are estimated with the model tests by Taguchi et al. (2005). It is confirmed that the most dangerous condition for this subject ship under dead ship condition is one in beam wind and waves, i.e. χ is 0 degrees. It is clarified that drifting motion obviously depends on underwater and above-water ship geometry.

Effect of hydrodynamic coefficient estimation

It is also widely known that empirical estimation of effective wave slope coefficient in the weather criterion is often difficult to be applied to modern ship-types such as a large passenger ship, a RoPax ferry and so forth. Based on this background, the IMO allows us to estimate the effective wave slope and damping coefficients as well as heeling lever owing to beam wind by model experiments with the interim guidelines (2006).

Taguchi et al. (2005) and Ishida et al. (2006) carried out almost full set of model tests for a RoPax ferry and verified the interim guidelines as the alternative assessment of the weather criterion. It was clarified that the evaluation of weather criterion considerably differs that with the combination of tests. Umeda et al. (2006a) applied this model test approach to the Ro-Pax ferry for further investigating its feasibility. Based on the interim guidelines, the model experiments were executed with three different constraints: a guide rope method, a looped wire system and a mechanical guide method. The guide rope method means that the model was controlled by guide ropes. The looped wire system means that, by utilizing a looped wire attached to a towing carriage, the yaw motion of the model is fixed but the sway, heave and roll motions are allowed. The mechanical guide is the combination of a sub-carriage, a heaving rod and gimbals. Among them, as shown in Fig.9, the looped wire system is less accurate because natural roll period and damping was slightly changed owing to a looped wire. In case the yaw angle increases with larger wave steepness, the guide rope method has inherent difficulty for keeping a beam wave condition. The guideline allows the three different methods for determining the roll angle from the experiment: the direct method, the three step method and the parameter identification. As shown in Fig 10, the difference between the three methods is negligibly small. In conclusion, the interim guidelines can guarantee reasonable accuracy if appropriate constraint is used.

When we calculate capsizing probability with the piece-wise linear approach, the same difficulty exists. This is because fluid-dynamic coefficients such as effective wave slope coefficient should be separately estimated in advance. Therefore it is desirable to execute model experiments following the IMO interim guidelines. Utilizing model tests, however, could be not always practical owing to cost and time. Therefore, it is desirable to develop an empirical or a theoretical method to accurately predict obtained results from the model test.

It is well known that a strip theory can explain the effective wave slope coefficient in general. (Mizuno, 1973) Since a strip theory requires numerical solution of simultaneous equation for determining two dimensional flows, however, a further simplified method is expected to be developed. For this purpose, Sato et al. (2007) carried out a series of model tests by means of two dimensional models covering large breadth to draft ratios. They confirmed that measured effective wave slope coefficient could be much smaller than that from a strip theory in case of very large breadth to draft ratios. This fact coincides with the experiments by Ikeda et al. (1992) for a small high-speed craft.

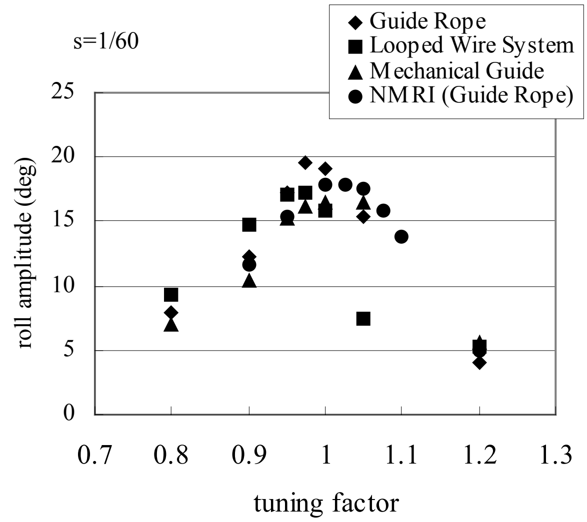

Fig. 9 Roll amplitude of the RoPax ferry in regular beam waves measured with different constraining methods (Umeda et al., 2006a).

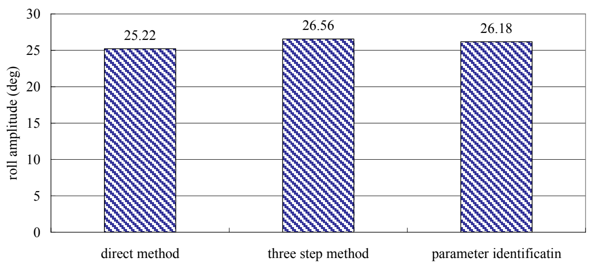

Fig. 10 Comparison of estimated roll amplitude by means of three different estimation methods. (Umeda et al., 2006a)

Umeda & Tsukamoto (2007c) investigated several possible simplified versions of theoretical methods and finally proposed a formula to calculate the effective wave slope coefficient of the equivalent rectangular sections with the Froude-Krylov component on its own. Here the local breath and area of the rectangular section should be the same as those of original transverse ship sections. As shown in Table 1, this simplified formula agrees well with the experiment and a strip theory for existing ships having large windage areas probably because the diffraction component can almost cancel out the radiation owing to sway and the local breadth and area are responsible for restoring moment. Furthermore, they indicate that difference in the effective wave slope coefficient between the present formula and experiments results in only small effects on the estimation of the one-hour capsizing probability in stationary beam wind and waves as shown in Fig.11. Therefore, it is recommended to use this simplified formula for a regulatory purpose.

Table.1 Comparison of effective wave slope coefficients under resonant condition. Here IMO means the formula in the IMO weather criterion and FK indicates the Froude-Krylov prediction. (Umeda & Tsukamoto, 2007c)

	PCC	Ro-PAX	container ship
IMO	1.289	1.120	0.914
Strip theory	0.889	1.000	0.752
EXP	0.937	0.777	0.970
FK(rectangle)	0.950	0.421	1.457
FK(Lewis form)	0.928	0.904	0.833
FK(present)	0.988	0.961	1.074
FK+Diffraction	0.431	0.421	1.741

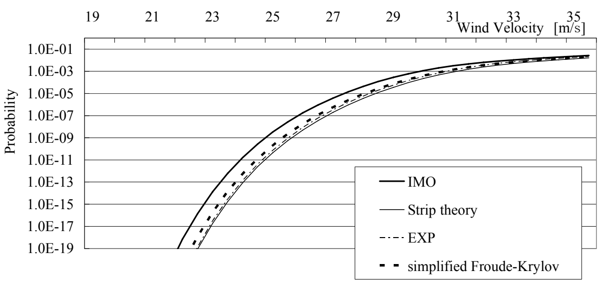

Fig.11 The effect of the effective wave slope coefficient estimation on the one-hour capsizing probability of the RoPax ferry in stationary beam wind and waves. (Umeda et al., 2007a)

Effect of correlation between wind and waves

For the provision of the criteria based on performance-based approaches, the capsizing probability should be assessed preferably with long-term sea state statistics. Ogawa et al. (2006a,2007) constructed a scatter diagram of wave height, wave period and wind speed by means of the wind and wave database developed from hindcast calculation of wind-wave interactions and examined the effect of the correlation of winds with waves on the long-term capsizing probability. Table 2 shows examples of the scatter diagram of wave height, wave period and wind speed for a water area near Minami Daito Islands in the Northern Pacific. It is found that the probability of large wave height and long wave period increases as the wind speed increases.

The long-term probability of capsizing of a ship within N years can be described as follows:

$$P_N = 1-\left(1-P^*(T)\right)^{(N\times 365\times 24\times 3600)/T} \tag{26}$$

where

$$P^*(T)=\int_0^\infty\int_0^\infty\int_0^\infty f(H_{1/3},T_{01},W_s)\cdot P(H_{1/3},T_{01},W_s,T)dH_{1/3}dT_{01}dW_s \tag{27}$$

Ogawa et al. (2006a) calculated the annual capsizing probability of the RO-PAX ferry. Fig. 12 shows her righting arm (GZ) curves. The limiting KG of this ship is governed by the weather criterion so that it was used as a loading condition for the safety assessment. The approximated line of the righting arm curve, of which GM, the area under the GZ curve and the angle of vanishing stability are not changed, is also shown in Fig. 12.

Fig. 13 shows the capsizing probabilities within one year as a function of wind speed. In addition to the capsizing probability by means of the present method, two kinds of capsizing probability are calculated by means of two other wave scatter diagrams. One is the wave scatter diagram normalized for each mean wind velocity (Normalized) and the other is the wave scatter diagram without correlation of wind (No correlation). The wave scatter diagram without correlation with wind was conducted by summing up the present scatter diagram of wave height, wave period and wind speed. Then the capsizing probabilities using two kinds of diagrams is defined as follows:

(Normalized)

$$P^*(T,W_s)=\int_0^\infty\int_0^\infty f_N(H_{1/3},T_{01};W_s)\cdot P(H_{1/3},T_{01},W_s,T)dH_{1/3}dT_{01} \tag{28}$$

(No correlation)

$$P^*(T,W_s)=\int_0^\infty\int_0^\infty f_{NC}(H_{1/3},T_{01})\cdot P(H_{1/3},T_{01},W_s,T)dH_{1/3}dT_{01} \tag{29}$$

where $f_N(H_{1/3}, T_{01}; Ws)$ denotes the normalized wave scatter diagram and $f_{NC}(H_{1/3}, T_{01})$ denotes the wave scatter diagram without correlation with wind. For comparison sake, the short-term probability in the constant wind and waves is also shown in Fig. 13.

It is found that capsizing probability of the RO-PAX ferry complying with the weather criterion is adequately small if the statistical correlation between wind and waves is taken into account. This probability does not depend on the mean wind velocity because the occurrence probability of wind is taken into account in the calculation. The capsizing probability with the normalized scatter diagram is larger than the present method when the mean wind velocity is larger 16 m/s. This indicates that occurrence probability of such strong wind is not so large in this water area during a year. The capsizing probability with the no correlation scatter diagram is larger than the present method. This is probably because unrealistic combinations of wind and waves are included in the calculation.

The capsizing probability taken from the stationary sea state is larger than the present method because the occurrence probability of such sea state is not large during a year in this water area. On the other hand, the capsizing probability from the stationary sea state of the mean wind velocity of 26 m/s is much smaller than the present method. This suggests that the occurrence probability of sea state should be taken into account when we estimate the annual risk from the short-term capsizing probability.

Table.2 Samples of wave height –period diagram in each wind speed (Autumn, 1994-2003, W_s=2, 20, 40(m/s)). (Ogawa et al., 2006a)

Ws=2(m/s), T(sec.)

Hw(m)	3–	4–	5–	6–	7–	8–	9–	10–	11–	12–	13–	14–	15–
11.25–	0	0	0	0	0	0	0	0	0	0	0	0	0
10.75–	0	0	0	0	0	0	0	0	0	0	0	0	0
10.25–	0	0	0	0	0	0	0	0	0	0	0	0	0
9.75–	0	0	0	0	0	0	0	0	0	0	0	0	0
9.25–	0	0	0	0	0	0	0	0	0	0	0	0	0
8.75–	0	0	0	0	0	0	0	0	0	0	0	0	0
8.25–	0	0	0	0	0	0	0	0	0	0	0	0	0
7.75–	0	0	0	0	0	0	0	0	0	0	0	0	0
7.25–	0	0	0	0	0	0	0	0	0	0	0	0	0
6.75–	0	0	0	0	0	0	0	0	0	0	0	0	0
6.25–	0	0	0	0	0	0	0	0	0	0	0	0	0
5.75–	0	0	0	0	0	0	0	0	0	0	0	0	0
5.25–	0	0	0	0	0	0	0	0	0	0	0	0	0
4.75–	0	0	0	0	0	0	0	0	0	0	0	0	0
4.25–	0	0	0	0	0	0	0	0	0	0	0	0	0
3.75–	0	0	0	0	0	0	0	0	0	0	0	0	0
3.25–	0	0	0	0	0	0	0	0.000297	0.000224	0	0	0	0
2.75–	0	0	0	0	0	0	0.000414	0.000405	0	0	0	0	0
2.25–	0	0	0	0	0.000176	0.000589	0.001021	0.000847	3.91E–06	0	0	0	0
1.75–	0	0	0	0	0.000887	0.001245	0.002002	0.002682	5.05E–05	0	0	0	0
1.25–	0	0	0	1.1E–05	0.001218	0.004456	0.004191	0.001685	0.000424	0	0	0	0
0.75–	0	0	0	0.000378	0.001439	0.001877	0.000579	9.28E–05	1.9E–05	0	0	0	0
0.25–	0	0	0	0.000101	4.15E–05	3.73E–05	3.91E–06	1.86E–07	1.86E–07	0	0	0	0
0–	0	0	0	0	0	0	0	0	0	0	0	0	0

Ws=20(m/s), T(sec.)

Hw(m)	5–	6–	7–	8–	9–	10–	11–	12–	13–	14–	15–	16–
15.25–	0	0	0	0	0	0	0	0	0	0	0	0
14.75–	0	0	0	0	0	0	0	0	0	0	0	0
14.25–	0	0	0	0	0	0	0	0	0	0	0	0
13.75–	0	0	0	0	0	0	0	0	0	0	0	0
13.25–	0	0	0	0	0	0	0	0	0	0	3.73E–07	3.17E–06
12.75–	0	0	0	0	0	0	0	0	0	0	3.35E–06	1.86E–07
12.25–	0	0	0	0	0	0	0	0	0	0	1.12E–06	0
11.75–	0	0	0	0	0	0	0	0	0	0	0	0
11.25–	0	0	0	0	0	0	0	0	0	0	0	0
10.75–	0	0	0	0	0	0	0	0	0	0	0	0
10.25–	0	0	0	0	0	0	0	0	0	0	0	0
9.75–	0	0	0	0	0	0	0	0	7.83E–06	4.84E–06	0	0
9.25–	0	0	0	0	0	0	0	6.71E–06	8.24E–05	0	0	0
8.75–	0	0	0	0	0	0	0	1.58E–05	0.00011	7.45E–07	3.91E–06	0
8.25–	0	0	0	0	0	0	2.61E–06	7.32E–05	6.17E–05	5.78E–06	3.5E–05	0
7.75–	0	0	0	0	0	1.3E–06	1.01E–05	0.000168	4.84E–06	6.15E–06	1.3E–05	0
7.25–	0	0	0	0	0	9.69E–06	4.45E–05	0.000351	0	0	0	0
6.75–	0	0	0	0	2.24E–06	4.49E–05	0.000201	9.82E–05	1.49E–06	0	0	0
6.25–	0	0	0	0	4.47E–06	7.84E–05	0.000212	0.000119	7.27E–06	1.45E–05	0	0
5.75–	0	0	0	0	5.33E–05	0.000301	0.000302	0.000128	4.1E–06	3.82E–05	0	0
5.25–	0	0	0	5.03E–06	0.000106	0.00066	1.29E–05	6.28E–05	8.57E–06	6.15E–06	0	0
4.75–	0	0	0	3.78E–05	9.69E–05	0.000248	0	3.73E–06	1.86E–07	0	0	0
4.25–	0	0	0	5.29E–05	7.81E–05	2.5E–05	0	5.59E–07	4.84E–06	0	0	0
3.75–	0	0	2.96E–05	1.9E–05	3.63E–05	0	0	0	0	0	0	0
3.25–	0	0	1.58E–05	2.83E–05	3.06E–05	0	0	0	0	0	0	0
2.75–	0	0	0	2.24E–06	0	0	0	0	0	0	0	0
2.25–	0	0	0	0	0	0	0	0	0	0	0	0
1.75–	0	0	0	0	0	0	0	0	0	0	0	0

Ws=40(m/s), T(sec.)

Hw(m)	8–	9–	10–	11–	12–	13–	14–	15–	16–	17–
15.25–	0	0	0	0	0	0	1.86E–07	0	0	0
14.75–	0	0	0	0	0	0	1.49E–06	0	9.32E–07	5.59E–07
14.25–	0	0	0	0	0	0	0	0	4.66E–06	0
13.75–	0	0	0	0	0	0	0	0	9.32E–06	0
13.25–	0	0	0	0	0	0	0	0	9.5E–06	0
12.75–	0	0	0	0	0	0	0	5.03E–06	3.17E–06	0
12.25–	0	0	0	0	0	0	0	0	0	0
11.75–	0	0	0	0	0	0	0	0	0	0
11.25–	0	0	0	0	7.45E–07	0	0	0	0	0
10.75–	0	0	0	0	0	0	0	0	0	0
10.25–	0	0	0	0	0	0	0	0	0	0
9.75–	0	0	0	0	0	0	0	0	0	0
9.25–	0	0	0	0	0	0	0	0	0	0
8.75–	0	0	0	0	0	0	0	0	0	0
8.25–	0	0	0	0	0	0	0	0	0	0
7.75–	0	0	0	0	0	0	0	0	0	0
7.25–	0	0	0	0	0	0	0	0	0	0

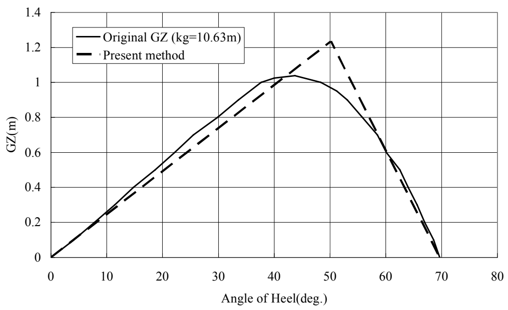

Fig. 12 Righting arm curves of the RO-PAX ferry. (Ogawa et al., 2006a)

The capsizing probability calculation in this paper except for this section assumes that wind is fully correlated wave height based on the WMO's reference data (Umeda et al., 1992). It will be a future task to compare this methodology with the capsizing probability calculated taking account of the statistical correlation between wind and waves. Then the final conclusion whether the statistical correlation should be considered for the performance-based criteria or not will be discussed.

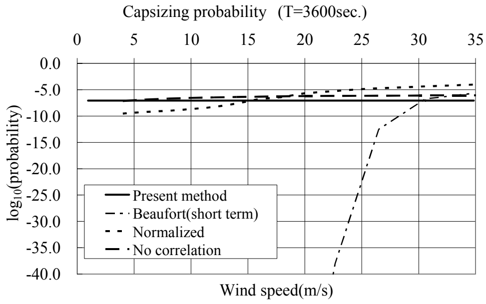

Fig. 13 Capsizing probability in one year of the Ro-PAX ferry under dead ship condition. (Ogawa et al., 2006a)

ASSESSMENT OF SAFETY LEVEL IN TERMS OF THE PIECE-WISE LINEAR APPROACH

Passenger and cargo ships

Umeda et al. (2007a, 2007b) attempted to evaluate the safety levels of four passenger and cargo ships by utilizing the above mentioned capsizing probability calculation. Their principal dimensions of these ships are shown in Table 3. The method for calculating capsizing probability here is the piece-wise linear approach with down-flooding angle taken into account. The mean wind velocity is assumed to be fully correlated with the wave height and the effect of drifting attitude and velocity is ignored. The restoring arm is approximated to keep the metacentric height, the angle of vanishing stability and the maximum restoring arm unchanged.

The calculation results of the annual capsizing probabilities under the designed conditions in the North Atlantic are shown in Fig. 14. Here the annual capsizing probabilities of a LPS (large passenger ship) and a containership under their designed conditions are smaller than 10^{-8} so that the associated risks are assumed to be negligibly small. In particular, the safety against capsizing in beam wind and waves for the containership is sufficient although her designed metacentric height is small. This is because the large freeboard of the containership results in significant increase of the slope of righting arm curve at larger heel angle. On the other hand, larger probabilities are obtained for the Ro-Pax and the PCC (pure car carrier). In particular, the Ro-Pax has large annual capsizing probability, although her number of persons onboard is not small, because her natural roll period is small so that resonant probability increases in ocean waves.

The Ro-Pax ferry investigated here is operated not in the North Atlantic but in Japan's limited greater coastal area, which is water area within about 100 miles from the Japanese coast. (Watanabe and Ogawa, 2000) In addition, her navigation time ranges only from 6 to 12 hours so that she can cancel her voyage if bad weather such as a typhoon is expected. Therefore the calculation of capsizing probabilities of the case in Japan's limited greater coastal area and the case in Japan's limited greater coastal area with operational limitation to avoid the significant wave height greater than 10 meters are executed and compared with the case in the North Atlantic, as shown in Fig. 15. Here the aero- and hydrodynamic coefficients were estimated with experimental data.

The comparison indicates that the effect of water areas is not so large because worst combinations of significant wave height and mean wave period exist also in Japan's limited greater coastal area. This seems to be reasonable because typhoons are included in the wave statistics in Japan's limited greater coastal area.

Table.3 Principal dimensions of ships under designed conditions. Here W: displacement, T_{ϕ}: natural roll period, N: number of persons onboard. (Umeda et al., 2007b).

Items	LPS	Container Ship	PCC	RO/PAX
W (t)	53,010	109,225	27,216	14,983
L_{pp} (m)	242.25	283.8	192.0	170.0
B (m)	36.0	42.8	32.3	25.0
d (m)	8.4	14.0	8.2	6.06
GM (m)	1.58	1.06	1.25	1.41
T□ (s)	23.0	30.3	22.0	17.9
N	4332	33	25	370

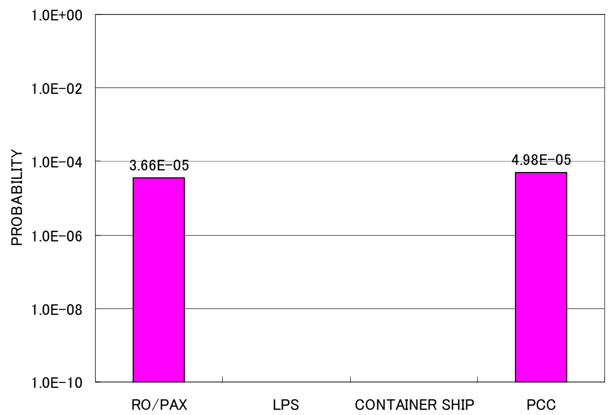

Fig. 14 Annual Capsizing Probability for passenger and cargo ships in the North Atlantic. (Umeda et al., 2007b)

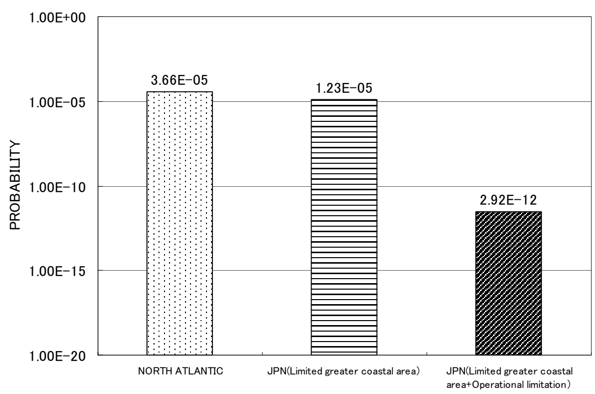

Fig. 15 Effect of operational conditions on annual capsizing probability for the RO/PAX. (Umeda et al., 2007b)

On the other hand, the significant reduction in the capsizing probability is realized by the operational limitation. This explains that the Ro-Pax ferry is safely operated in actual situations with the aid of the operational limitation to avoid bad weather.

Fishing vessels

Table. 4 Principal dimension of the subject ships at full load departure condition. Here F_{BS}: freeboard, T_Z: natural heave period, h_B: height of bulwark and A_f: area of freeing port. (Paroka & Umeda, 2007)

Items	Units	new 135 GT	old 135 GT	80 GT	39 GT
L_{pp}	Meters	38.50	34.50	29.00	23.00
B_S	Meters	8.10	7.60	6.80	5.90
d	Meters	2.851	2.65	2.25	1.77
F_{BS}	Meters	0.485	0.496	0.484	0.396
Δ	Tons	480.98	431.07	276.61	145.70
GM	Meters	1.95	1.65	1.57	1.79
T_{ϕ}	Seconds	5.80	5.87	5.20	3.886
T_z	Seconds	3.413	3.435	3.246	2.218
h_B	Meters	1.50	1.45	1.35	1.30
A_f	$Meters^2$	7.05	4.75	3.40	2.60

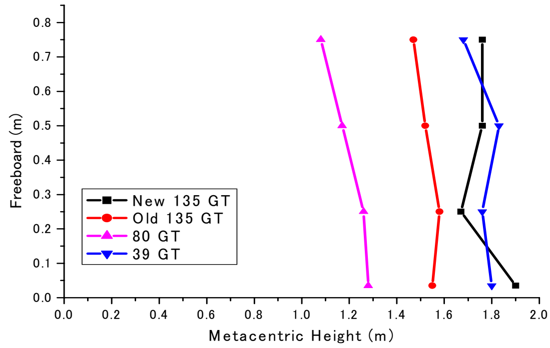

Fig. 16 Marginal lines of purse seiners for the annual capsizing probability of 10^{-6}. (Paroka & Umeda, 2007)

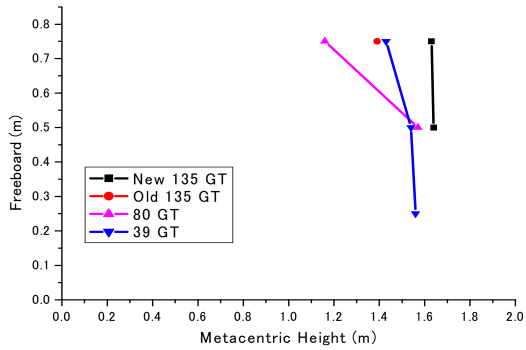

Fig. 17 Marginal lines of purse seiners for the IMO weather criterion for fishing vessels. (Paroka & Umeda, 2007)

Paroka & Umeda (2007) estimated the safety levels of four Japanese purse seiners, whose principal dimensions are listed in Table 4, as one of typical fishing vessels types. By utilizing the piece-wise linear approach with water trapped on deck taken into account, combinations of metacentric height and freeboard realizing the annual capsizing probability is 10^{-6} are identified as shown in Fig. 16. The water areas used here are actual fishing grounds within the Japanese EEZ for these vessels so that wave statistics are obtained from the NMRI database and actual fish catch records (Ma et al., 2004) with assumption that wind velocity is fully correlated with the wave height. This diagram indicates that the designed full departure condition for each vessel has safety level above 10^{-6}. Combinations of metacentric height and freeboard for marginally complying with IMO weather criterion for fishing vessels and the water-on-deck criterion in the recommendation of the Torremolinos Convention are shown in Figs.17-18, respectively. The comparison among these results demonstrates that the weather criterion for fishing vessels on its own is not sufficient for ensuring safety of these fishing vessels because of trapped water on deck but the water-on-deck criterion in the Torremolinos Convention is comparable to the current probability-based calculation.

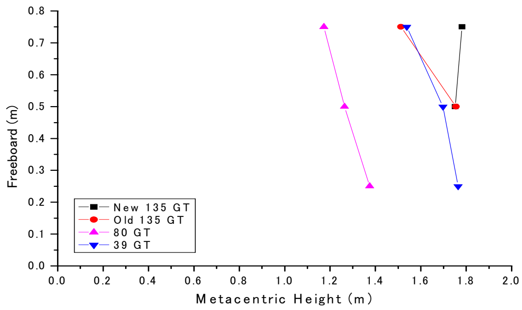

Fig. 18 Marginal lines of purse seiners for the water-on-deck criterion in the IMO Torremolinos Convention. (Paroka & Umeda, 2007)

RECOMMENDATION FOR IMO Performance-BASED CRITERIA

As shown in this paper, it is feasible to calculate annual capsizing probability of a given ship in beam wind and waves by utilizing the piece-wise linear approach presented here. Since a beam wind and wave condition is more dangerous than other drifting attitude, safety level of stability under dead ship condition at least as a relative measure can be estimated with this approach. It is noteworthy here the calculation based on this approach is not time-consuming so that it can be used as a performance-based criterion. In case a simpler approach is also required for a vulnerability criterion, as an existing criterion for stability under dead ship condition the weather criterion can be recommended with refinement with the present achievements such as effective wave slope coefficient and roll damping.

CONCLUSIONS

The activity of the SCAPE committee for stability under dead ship condition provides the following conclusions:

1. A piece-wise linear approach for calculating capsizing probability in beam and waves is presented. The calculated probability coincides with the Mote Carlo simulation results within its confidence interval for the sea state relevant to the weather criterion
2. The calculation method was extended to cover effects of flooding angle or cargo shift angle, water on deck, hydrodynamic coefficient estimation, drifting attitude and velocity and the correlation between wind and waves.
3. By utilizing the above extended methods, safety levels of passenger and cargo ships as well as fishing vessels are calculated as annual capsizing probability, and show that current designs ensures reasonable levels of safety against intact capsizing under good operation practice.

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