Methodology for Calculating Capsizing Probability for a Ship under Dead Ship Condition

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ABSTRACT

Stability under dead ship condition is one of the major scenarios to be dealt with for performance-based intact stability criteria at the IMO. Since the criteria are to be based on a risk analysis, capsizing probability should be calculated. For this purpose, we propose a methodology for calculating capsizing probability under dead ship condition. Firstly, the drifting attitude and velocity is determined by solving an equilibrium equation. Secondly, effective wave slope coefficient is estimated experimentally and theoretically. Thirdly, the capsizing probability is calculated with a piece-wise linear restoring arm. Finally, annual capsizing probability is estimated with wave statistics and operational practice.

KEYWORDS

Dead ship condition; the effective wave slope coefficient; capsizing probability; risk analysis

INTRODUCTION

At the International Maritime Organization (IMO) revision of the Intact Stability Code (IS Code) started in 2002 and, other than that of its prescriptive criteria, performance-based criteria are requested to be developed by 2010. (IMO, 2007) This new criteria should cover three major capsizing scenarios: restoring variation problems such as parametric rolling, stability under dead ship condition and manoeuvring-related problems such as broaching. It was expected to be a probabilistic stability assessment based on physics by utilising first principle tools. This is due 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. Here 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 due to absence of power, a shipmaster cannot do any operational actions. This means that operational factors are not relevant to safety level evaluation. Since some operational actions such as high-speed running in following waves can decrease safety level against capsizing (Umeda and Yamakoshi, 1994), the safety level under dead ship condition can be regarded as that with ideal operational practice.

For this 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. Thus, 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 modern ship-types such as a RoPax ferry. Thus, 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 propose a methodology for calculating capsizing probability of a ship under dead ship condition. First, we estimate drifting velocity and attitude by a local stability analysis. Second, we estimate the effective wave slope and roll damping coefficients with or without model experiment. Third, capsizing probability is calculated with a piece-wise linear approach under the estimated drifting attitude and then risk is also examined. In this paper, we summarise this methodology and present an example of the application of this methodology to a RoPax ferry.

SUBJECT SHIP

For ships having large windage area, the weather criterion or its alternative could be dominant. Among them, a RoPax ferry is selected here as a subject ship. Her principal dimensions, body plan are shown in Table 1 and Fig. 1, respectively, the restoring arm curve is given in Fig. 2.

Table 1: Principal dimension of the car carrier

Length between perpendiculars	170 (m)
Breadth	25.0 (m)
Depth	14.8 (m)
Draught	6.06 (m)
Block coefficient	0.521
Area of bilge keels	61.38 (m^2)
Vertical position of centre of gravity above keel line	10.63 (m)
Metacentric height	1.41 (m)
Down flooding angle	39.5 (degrees)
Natural roll period	17.90 (s)
Lateral projected area	3433.0 (m^2)
Height centre of lateral windage area above water line	9.71 (m)

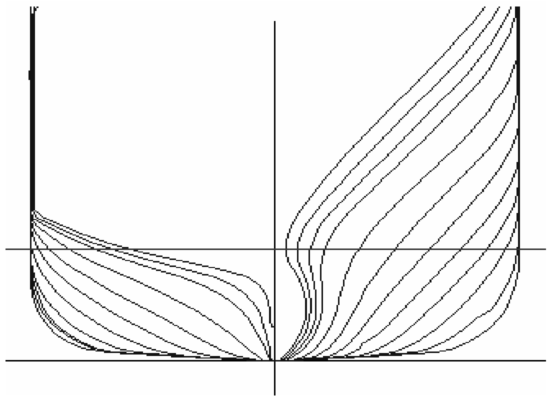

Fig 1: Body plan of the car carrier

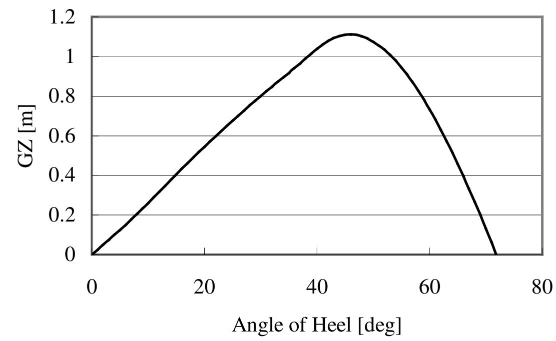

Fig 2: Curve of righting arm of the car carrier

ESTIMATION OF DRIFTING ATTITUDE UNDER DEAD SHIP CONDITION

For estimating drifting velocity and attitude of a ship in regular waves and steady wind, we propose a method for identifying fixed points of a surge-sway-yaw-roll model and for examining its local stability. (Umeda, Koga et al., 2005)

Fixed points can be estimated by solving 4-DOF non-linear equations as shown in the following co-ordinate systems. (Fig 3);

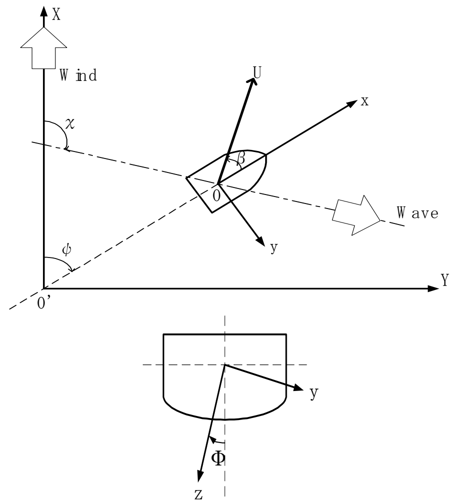

Fig 3: Co-ordinate systems

$$(m+m_x)\dot{u}-(m+m_y)vr = X_H + X_A + X_W \tag{1}$$

$$(m+m_y)\dot{v}+(m+m_x)ur - m_y l_y \ddot{\phi} = Y_H + Y_A + Y_W \tag{2}$$

$$(I_z+J_z)\ddot{\psi} = N_H + N_A + N_W \tag{3}$$

$$(I_x+J_x)\ddot{\phi} - m_y l_y \dot{v} - m_x l_x ur + 2\mu\dot{\phi} + W\overline{GM}\phi = K_H + K_A \tag{4}$$

where,

u, v ; ship speed in x,y-axis

ψ, ϕ ; yaw,roll angle

m ; ship mass

W ; displacement

GM ; metacentric height

m_x, m_y ; added mass in x,y-axis

I_x, I_z ; morment of inertia around x,z-axis

J_x, J_z ; added morment of inertia around x,z-axis

l_x, l_y ; z-direction of centre of m_x, m_y

X, Y ; force in x,y-axis

N, K ; yaw,roll morment

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 (Fujiwara, 2001), and a potential theory for wave-induced drifting forces (Kashiwagi, 2003) are used.

The stability of equilibrium is evaluated by calculating the eigenvalues of the Jacobean matrix in the locally linearised system around equilibrium. The Newton method was used to solve the equations and we assume that wind speed is 26 m/s, wave amplitude is 2.85m and wave length to ship length ratio is 2.94. 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 calculated. 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). The results are shown in Fig 4-7.

These figures indicate that when the relative angle between wind and waves is 0 degrees, 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 condition. And the relative angle is close to 90 deg, the equilibrium becomes unstable in almost head wind and becomes stable in almost following wind.

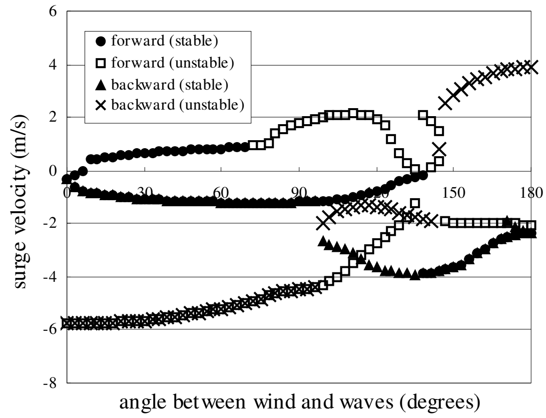

Fig 4: Surge velocity of fixed points as a function of relative angle between wind and waves

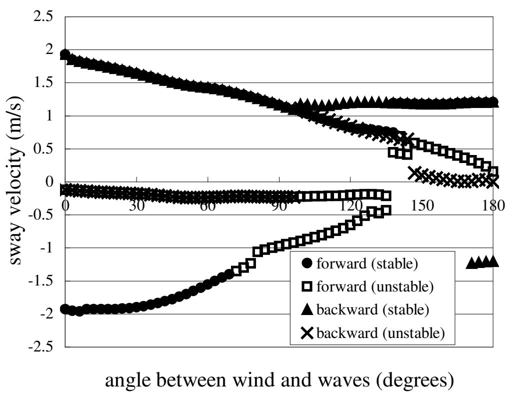

Fig 5: Sway velocity of fixed points as a function of relative angle between wind and waves

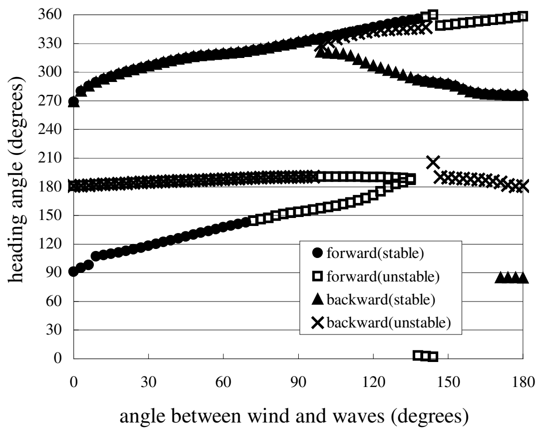

Fig 6: Heading angle of fixed points as a function of relative angle between wind and waves

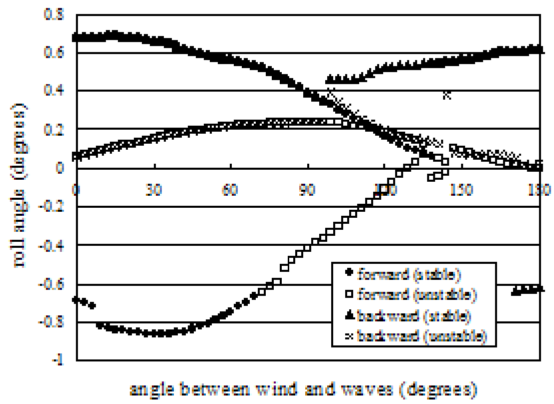

Fig 7: Roll angle of fixed points as a function of relative angle between wind and waves

It is noteworthy here that all fixed points have complex eigenvalues. This suggests that limit cycle around the fixed point may exist when the fixed point is unstable. In addition, an unstable solution with about 0 degrees of yaw angle at 0 degrees of the relative angle between wind and waves may exist but the Newton method here fails to detect it. Further researches for these points are now under way.

ESTIMATION OF EFFECTIVE WAVE SLOPE COEFFICIENT

Since recently, the IMO allows us to estimate the effective wave slope and damping coefficients as well as heeling lever due to beam wind by model experiments with the interim guidelines. The authors applied this model test approach to the RoPax ferry for investigating its feasibility. (Umeda, Ueda et al., 2005) 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.8, 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 9, the difference between the three methods is negligibly small. In conclusion, the interim guidelines can guarantee reasonable accuracy if appropriate constraint is used.

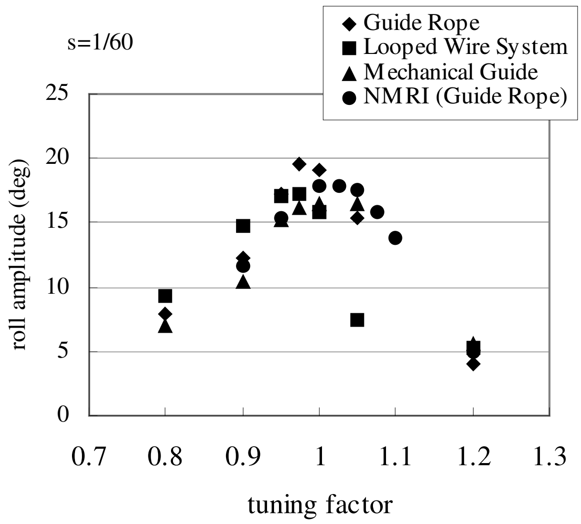

Fig 8: Roll amplitude in regular beam waves with three different constraints as well as the experiment at NMRI (Taguchi et al., 2005).

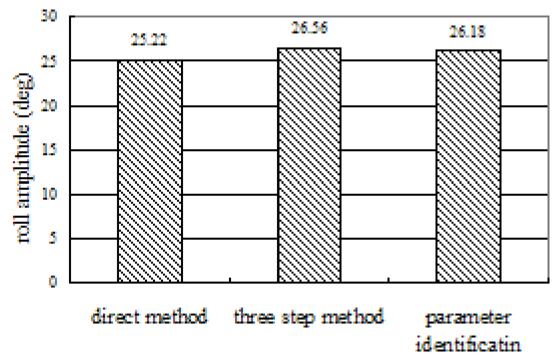

Fig 9: Comparison in estimated roll amplitude of three different estimation methods

The model tests can provide accurate estimation of the coefficients for a given ship but it could be impractical due to cost and time for model testing. Thus, it is desirable to develop an empirical or theoretical method to accurately predict obtained results from the model test. The measured roll damping coefficient from the model tests for the RoPax ferry was 0.0121, while the estimated with the Ikeda's semi-empirical method (Ikeda, 2004) was 0.0134. Thus, Ikeda's method can well predict for roll damping coefficient and it is well known that a strip theory can explain the effective wave slope coefficient. Since a strip theory requires numerical solution of simultaneous equation for determining two dimensional coefficients, however, a further simplified theoretical method is expected to be developed.

For this purpose, the authors (Umeda, Tsukamoto, et al., 2007) investigated several possible simplified versions of theoretical methods and finally proposed to calculate the effective roll coefficient of the rectangular sections only 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 Fig. 10, this simplified method agrees well with the experiment and the strip theory. This is mainly because the diffraction component can almost cancel out the radiation due to sway. It is recommended to use this simplified approach for regulatory purpose.

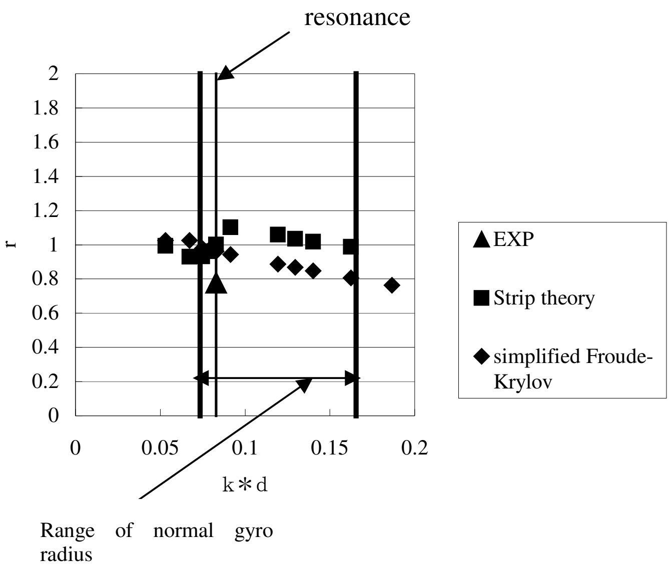

Fig 10: Effective wave slope coefficient, r, of Ro-Pax fery . Here k is the wave number and d is the ship draught.

CAPSIZING PROBABILITY

Capsizing probability in irregular beam wind and waves can be analytically calculated with piece-wise linear restoring moment. This approach was originally developed by Belenky (1993), corrected by Paroka et al. (2006) and verified by Paroka and Umeda (2006a). Here the capsizing probability in a stationary sea state is calculated as the product of the probability exceeding the threshold and the probability of diverging behaviour in the range of negative restoring slope. If necessary, the probability exceeding the down-flooding angle or cargo-shift angle can be taken into account. (Paroka and Umeda, 2006b) Then the annual capsizing probability can be calculated with wave statistics. (Paroka and Umeda, 2006c) Furthermore, the effect of water on deck can be evaluated. (Paroka and Umeda, 2006c) The details of this method is available in these literatures.

In case of dead ship condition, the drifting velocity and attitude should be taken into account. Umeda, Koga et al. (2006) evaluated the effect of drifting velocity by changing the external frequency and the effect of drifting attitude by changing both the windage area and the effective wave slope coefficient.

The results are shown in Fig 11 where the two coexisting stable steady attitudes are investigated. Here the 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 heeling lever due to drift are estimated with the model tests by Taniguchi et al. (2005)

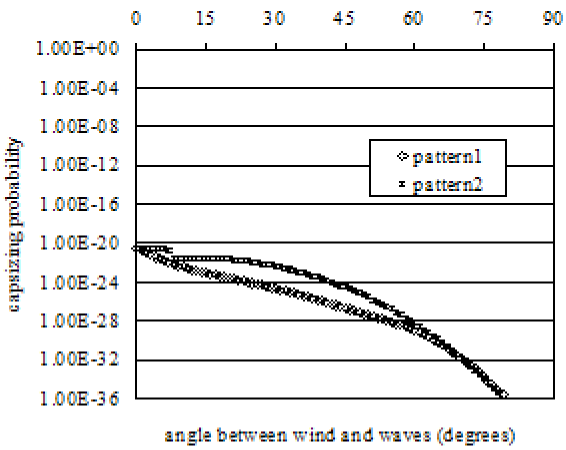

Fig 11: Capsizing probability of the RoPax ferry under the dead ship condition as a function of the relative angle between wind and waves.

From this figure, it is confirmed that the most dangerous condition for this particular ship is beam wind and waves, i.e. χ is 0 degrees. Obviously it depends on underwater and above-water ship geometry.

The authors also investigate the effect of estimation methods of the effective wave slope coefficient on capsizing probabilities for one hour of the duration. As shown in Fig. 12, the simplified estimation method of the effective wave slope coefficient can improve the result with the empirical formula in the current weather criterion and can provide good agreement with the outcomes with the measured coefficient with the interim guidelines or the calculated one with a strip theory. Here the heeling lever due to drift is calculated with the formula in the weather criterion.

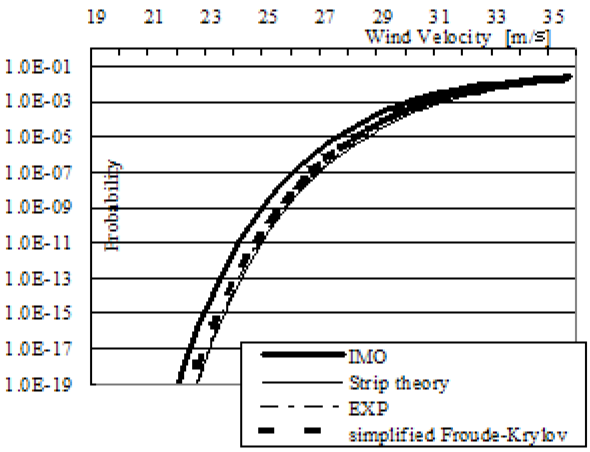

Fig 12: Capsizing probability of the RoPax ferry in stationary beam wind and waves.

RISK ANALYSIS

Finally the authors attempted to evaluate the safety levels of four merchant ships by utilising the above mentioned capsizing probability calculation. (Umeda, Maeda et al., 2007) The annual capsizing probabilities are plotted on a FN diagram as shown in Fig. 13. Here the annual capsizing probabilities, as the ordinate of the FN diagram, are calculated for a car carrier, a container ship, a cruise ship and the RoPax ferry with optimal operational practice, which means a beam wind and waves condition. The operational area for the RoPax ferry is the limited greater coastal area of Japan and those for other three ships are the North Atlantic. The metacentric height and freeboard are adjusted to be each designed condition. The number of people onboard, as the abscissa of the FN diagram, is regarded as the consequence because capsize of intact ship normally does not provide a chance for people onboard to survive. The acceptance criteria of this FN diagram are taken from the IMO document submitted by Japan (2002) in trial and are required further discussion.

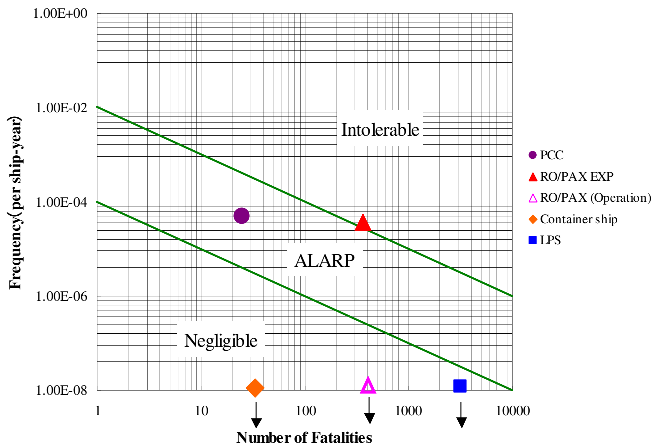

Fig 13: Risk level for ships under designed condition.

This FN diagram suggests that the risk levels against intact capsizing with good operational practice of the containership and the large cruise ship are negligibly small. The risk level of the RoPax ferry exists between the border between the “intolerable” and “ALARP (As Low As Reasonably Practicable)” regions. If we introduce the operational limit, i.e. no operation with 10 m of the significant wave height or over, however, the risk level of the RoPax ferry is moved to the “negligible” region. This operational limitation nearly coincides with actual practice of this ship type. For the RoPax ferry, the heeling lever due to drift are estimated with the model test. The risk level of the car carrier exists in the “ALARP” region so that shift of the down-flooding point upwards should be considered as a cost-effective risk control option.

This methodology proposed in this paper can provide the safety level of these conventional ships. Thus, it is possible that, with this methodology utilizing the same risk levels of conventional ships, stability of unconventional ships can be evaluated.

CONCLUSIONS

The authors proposed a methodology for calculating capsizing probability under dead ship condition. This was extended to risk analysis. The authors believe that this methodology can be utilised as a part of the performance-based intact stability criteria for unconventional vessels.

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