NUMERICAL PREDICTION ON CAPSIZING OF A DAMAGED RORO SHIP IN IRREGULAR BEAM WAVES

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ABSTRACT

A numerical model for a damaged RoRo ship in irregular beam seas is presented based on a multiple time scale expansion for taking the interactions between slow and fast motions taken into account. The numerical results are compared with the experimental ones published from University of Strathclyde for the ITTC benchmark testing. The comparison demonstrates that the present numerical model overestimates the roll motion but provides acceptable prediction of the critical wave height for capsizing. It is also remarked the effect of the interactions between slow and fast motions on capsizing can be important.

KEY WORDS: multiple time scale expansion, RoRo ship, damaged stability, capsizing boundary, ITTC benchmark test, survival tests

INTRODUCTION

Disasters of RoRo Passenger ships, in European Waters such as Herald of Free Enterprise and Estonia, resulted in Stockholm Agreement as a regional standard in 1995. This opened a door to assess damage stability of a RoRo ship by means of a physical model experiment. This also forces us to establish a numerical prediction method for minimizing the size of the experiment because the experiment can be expensive and time-consuming.

For this purpose, Turan and Vassalos (1994) proposed a pioneering model of a coupled sway-heave-roll motion for a damaged ship with a strip theory and hydraulic water ingress/ egress model. Then Chang (2000), de Kat (2000), Vassalos and Letizia (1998), Papanikolaou (2000) and many others improved modelling further by considering six-degrees of freedom, hydrodynamic memory effect, three dimensional hydrodynamics and so on. However, guideline for practical modelling has not yet been fully established so far. This is the reason why the ITTC specialist committee for prediction of extreme motions and capsizing conducted a benchmark test of numerical modelling for a damaged ship in 2000-2001. The work described here is a contribution toward this particular benchmark testing from Osaka University and no other contribution from Asia Pacific region exists.

This work focused on a point that behaviours of a damaged ship consists of large-amplitude and slow motion and small-amplitude but fast motion. The authors rationally formulated hydrodynamic modelling of this point and quantitatively evaluate effects of this point.

HYDRODYNAMIC MODELLING

Dynamic behaviours of a damaged ship in waves can be regarded as the sum of large-amplitude and slow motions and small-amplitude but fast motions. Here the slow motions mean sinkage and heel due to water accumulation inside hull and wave drift; the fast motions are harmonic sway, heave and roll motions due to wave excitation. Since a conventional seakeeping theory deal with harmonic motions only, new methodology is expected for ship motions of a damaged ship.

Similar phenomena occurs in a moored ship in waves, that is, a coupled surge-sway-yaw motion having slowly-varying parts and fast-varying parts. Triantafyllou (1982) formulated a consistent theory by a multiple time scale expansion. His methodology was also used for manoeuvring motion in waves, which is also a coupled surge-sway-yaw motion. (Nonaka,1990) In this paper, the authors apply Triantafyllou's method to a coupled sway-heave-roll motion of a damaged ship in waves with the new time scale,

$$\tau = \varepsilon t \qquad (\varepsilon << 1) \qquad (1)$$

other than the normal time scale, t.

Then, the displacements, r, and velocities, $\dot{r}$, can be assumed as follows

$$r(t,\varepsilon) = \varepsilon\gamma_n(t) + \gamma_a(\varepsilon t) \tag{2}$$
$$\dot{r}(t,\varepsilon) = \varepsilon v_n(t) + \varepsilon v_a(\varepsilon t) \tag{3}$$

where the suffices n and a correspond to the fast and slow motions, respectively.

Substituting the above equations to a conventional wave-making boundary value problem (for example, Kan, 1977) and then neglecting higher order terms of ε, the following outcomes are obtained. 1) The water surface condition for the slow motion tends to a rigid wall one; 2) the body surface condition for the fast motion is provided around the slow motion displacements as mean positions. Therefore, the new boundary value problem for a damaged ship can be solved with a conventional manner but with instantaneous sinkage and heel taken into account.

OUTLINE OF PREDICTION METHOD

Based on the pioneering work by Turan and Vassalos (1993), Hasegawa et al. (2000) developed a computer program for calculating dynamic behaviours in regular beam waves. Here a coupled sway-heave-roll motion was dealt by a strip theory but hydrodynamic coefficients were calculated around a hull without sinkage and heel. The water ingress and egress are modelled with Bernoulli's equation with an empirical coefficient, K, (Hasagawa et al., 1999) and the accumulated water inside the hull is assumed as quasi-static.

In the current investigation, this program is upgraded to cover random excitation due to seaways, hydrodynamic coupling due to heel angle between vertical and lateral motions. (Shin, 1982; Fujino and Sakurai, 1982) Roll damping is estimated with Ikeda's semi-empirical formulae (Ikeda, 1984) as well as inertia effect of water ingress and egress. And wave drift is calculated by Maruo's formula and Hsu's concept together with hydrodynamic drag due to large drift angle.(Motora,1982)

Furthermore, based on theoretical conclusions of the previous section, the hydrodynamic forces of the fast motion are calculated with the slow motion taken into account and the hydrodynamic forces at the slow motion are calculated nonlinearly but without free surface effect.

TESTED SHIP AND PUBLISHED EXPERIMENT

The ITTC specialist committee for prediction of extreme motion and capsizing provided a data set of model experiments for benchmark testing of numerical codes for a damaged ship. These experiments were carried out at the Denny Tank by the University of Strathclyde with a 1/40 scaled model of a damaged RoRo ship following the Resolution 14 of SOLAS 95 procedure. As shown in Fig.1, the ship is assumed to have a midship side damage specified by the SOLAS Ⅱ-1/8.4.1 regulation. As a result, two compartments are flooded. Here the permeability of the compartment is 0.95 and that of RoRo space is 1.0. the principal particulars of the ship is shown in Table.1.

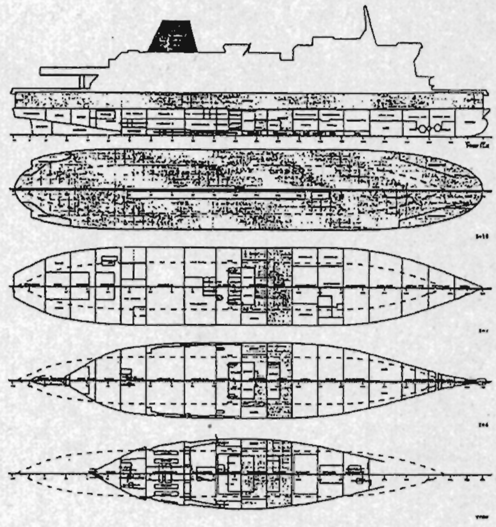

Fig.1 General arrangement

Teble.1 Principal particulars

Items	Full Scale	Model Scale
Length over all	179.00m	4475.0mm
Length between perpendiculars	170.00m	4250.0mm
Breadth	27.80m	695.0mm
Draught	6.25m	156.3mm
Depth	9.00m	225.0mm
Displacement (even keel)	17300ton	270.3kg
Intact KG	12.89m	322mm
Intact Design GM	2.63m	65.8mm

At the tank, roll decay tests and measurements of roll response in regular beam waves carried out for both the intact and damaged conditions. Also, following the Resolution 14 of SOLAS 95 procedure, survival tests were performed in irregular beam waves, which was specified by the JONSWAP spectrum with the wave steepness of 1/25 and the spectral peakness parameter of 3.3. The tests were repeated for five times per one wave-height with different wave realizations. Here the model is initially flooded in calm water and then meets irregular wave trains.

RESULTS AND DISCUSSION

The numerical simulation, based on the forementioned mathematical model, are carried out corresponding to the published model experiments and then the numerical results are compared with the measured ones.

ROLL DECAY TEST

The comparison of roll decay tests in calm water between the model experiments and the numerical simulations for the intact and damaged conditions are shown in Figs. 2-3.In case of the intact condition, the numerical simulation agrees fairly well with the experiment expect for a smaller amplitude region. This means that Ikeda's empirical method for roll damping works well with this RoRo ship. By contrast, in the numerical simulation for the damage condition the roll damping and the natural roll period is underestimated. During this simulated process, the roll amplitude are too small to induce water ingress to the RoRo deck. Because the two flooded compartments under the RoRo deck has watertight structures inside, they may act as flume-type anti-rolling tanks. Based on Barr's formula (Ikeda and Yoshiyama, 1991) the natural periods of the compartments are about 10-13 seconds, which is close to the ship roll period here. Thus, it can be presumed that the roll damping and the natural roll period increased in the experiment by the effect of flooded compartments as anti-rolling tanks.

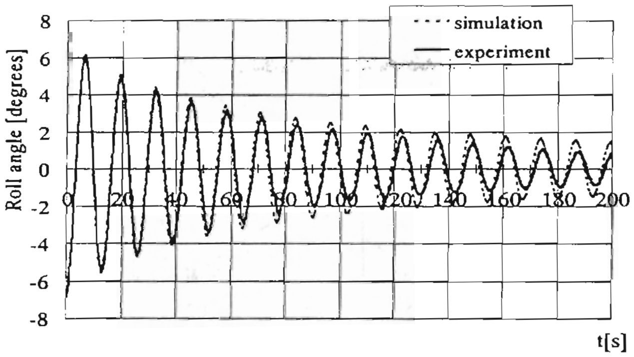

Fig.2 Roll decay test at the intact condition

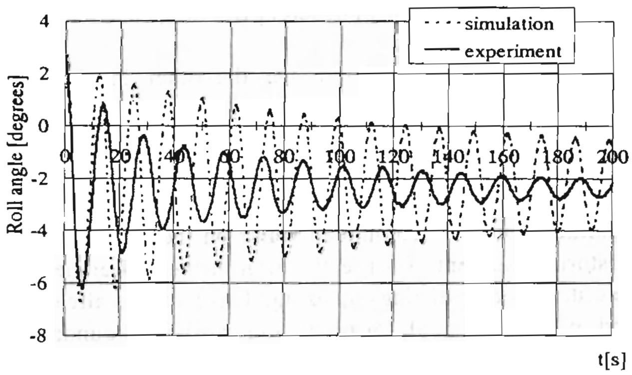

Fig.3 Roll decay test at the damage condition

RAO

The comparison of RAO between the model experiments and the numerical simulations are shown in Figs. 4-5.In case of the intact condition, the agreement between the experiments and the simulations are fairly good. This suggests that the calculation method for wave exciting moment used here is appropriate as well as Ikeda's semi-empirical method.

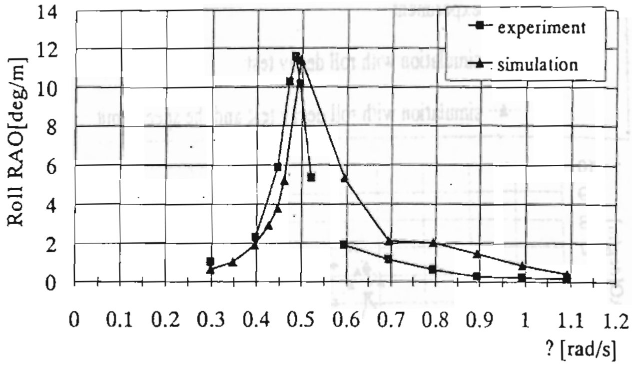

Fig.4 RAO at the intact condition

On the other hand, the simulated values for the damaged condition is much higher than the measured ones. In this simulations accumulated water on the RoRo deck appears and moves transversely bypassing a center casing. This transition of water between the starboard side and port side is also modelled by a hydraulic one but water velocity can be too large because longitudinal water movement is ignored in the simulation. Thus, we attempt to limit the water velocity by passing the center casing, u, with the following formula.

$$u \leq 2/3\sqrt{gh} \tag{4}$$

where h and g means the upstream water depth and gravitational acceleration, respectively. This threshold value is teutatively assumed with the results of dam-break model (Mizoguchi and Tanizawa, 1994) and should be further examined theoretically and experimentally. As a result of this water speed limit, the simulated amplitude becomes much smaller.

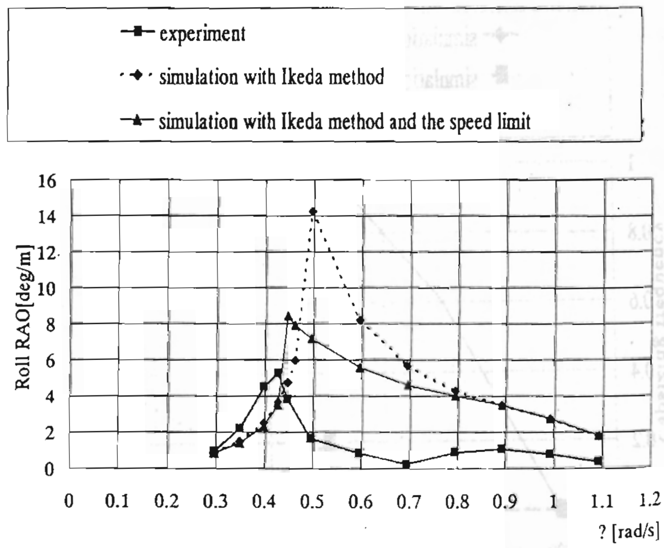

Fig.5 RAO at the damage condition

For taking the anti-rolling effect due to the lower flooded compartments, the measured roll decay test results are used for the simulation in place of Ikeda's semi-empirical method. As shown in Fig.6 this also improves prediction accuracy.

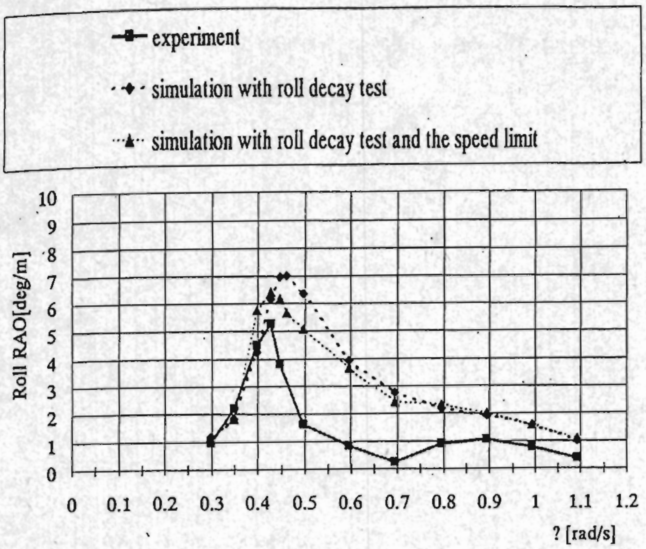

Fig.6 RAO at the damage condition

Since both the water speed limit effect on the RoRo deck and the anti-rolling effect due to the lower flooded compartment work together in real situation, the numerical simulations with these two effects are also added and provide further improvement. However some discrepancy remains at the frequency range coincide with the natural frequency of flooded compartments, detailed experiment or theory for the anti-rolling tank is a future task.

CAPSIZING BOUNDARIES

The survival tests are also simulated and compared with the experiments as shown in Figs.7-8. Here the numerical simulation does not use the roll decay test result and the speed limitation of water on the RoRo deck. Both the

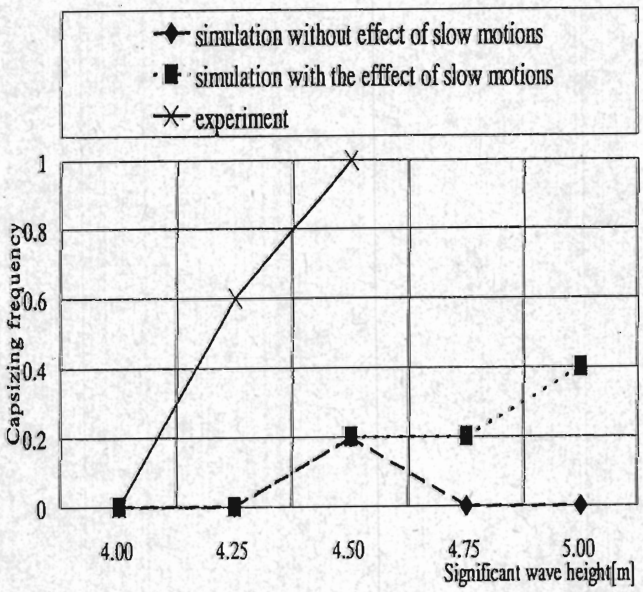

Fig.7 Capsizing boundaries at the damaged condition with and without effect of slow motions on hydrodynamic coefficients

simulations with effect of slow motions on hydrodynamic coefficients of fast motions and that without it are performed. The simulations slightly overestimated the critical wave height of 4.00 metres in the experiment. The capsizing frequency calculated with the model with the effect of slow motions on the hydrodynamic coefficient increases with the wave height, while that without it dose not. No capsizing at higher wave heights in the simulation without the effect of slow motions on the hydrodynamic coefficients appears as a result of the transition from a weather side heel to a lee side heel. Once a ship heels towards the lee side, the damage opening is exposed and further water ingress terminates. Thus this comparison suggests the effect of slow motions on the hydrodynamic coefficients results in more realistic outcomes. The effect of the flooding coefficient, *K*, is also investigated by varying it to 0.7-1.5. As shown in Fig.8, the capsizing frequency depends on this coefficient but the calculated frequencies are lower than the measured one. This suggests further

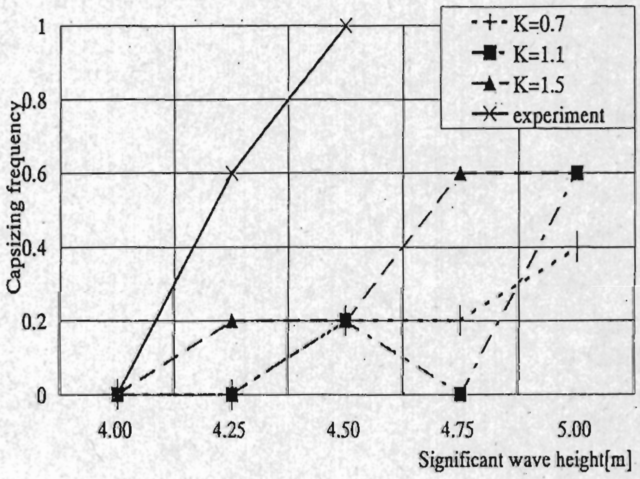

Fig.8 Capsizing boundaries at the damaged condition with different flooding coefficients

elements should be considered. On the other hand, the numerical prediction of the critical wave height is acceptable in spite of disagreement in RAO of the roll angle. This indicates that capsizing of a damaged RoRo ship occurs primarily as a result of loss of static balance between heel moment due to accumulated water on the RoRo deck and restoring moment. Thus, estimation of the roll angle is not so crucial for predicting capsizing. This fact was already utilized by Vassalos et al, for predicting capsizing boundary without any simulation in time domain.

CONCLUSIONS

The following conclusions are based on the results obtained from this study on a damaged RoRo ship:

1) A numerical prediction method is presented based on a multiple time scale expansion for taking the interactions between slow and fast motions into account.
2) The numerical method underestimates roll damping of the damaged ship because the effect of flooded compartments below the RoRo deck as flume-type anti-rolling tanks is ignored.

3) The numerical method overestimates the roll RAO of the damaged ship because the water flow modelling on the RoRo deck is not good enough.
4) The numerical method shows an acceptable prediction of critical wave height for capsizing because the loss of static balance is a primary reason of this capsizing mode.
5) The effect of the interactions between slow and fast motions can be important for realistic capsizing prediction.
6) The effect of the flooding coefficient on capsizing is not small.

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