On Estimation of Ship Rolling Motion with Flooded Water on Vehicle Deck

Toshifumi Fujiwara and Tomihiro Haraguchi
Ship Dynamics Division, National Maritime Research Institute
Tokyo, Japan

ABSTRACT

The Ro-Ro passenger ship 'Estonia' sank in 1994 because of large amount of flooding water on vehicle deck. To prevent such kinds of disasters, safety of damaged Ro-Ro passenger ships has been discussed in IMO (International Maritime Organization). This paper investigates validity of a time domain simulation method of rolling motion of a Ro-Ro passenger ship with flooded water on vehicle deck expressed by 2-dimensional lump mass concept. Model experiments with different amounts of water on the deck were carried out to confirm effectiveness of the method in regular beam waves. As a result, the simulation method on rolling motion shows reduction of roll response caused by moving water on deck and roll amplitudes obtained from the simulation are good agreement with experimental ones. The present method shows possibility of assessing the safety of Ro-Ro passenger ships with damaged holes and flooding water on deck.

KEY WORDS: Damage Stability; Flooded Water; Ro-Ro Passenger Ship; Rolling Motion; Estimation Method; Model Experiments

INTRODUCTION

After the disaster of the Ro-Ro passenger ship 'Estonia' in 1994, safety of damaged Ro-Ro passenger ships in severe sea condition has been examined in IMO. Since a Ro-Ro passenger ship has large flat vehicle decks, the condition, which large amount water came into from damaged holes exists on the deck, may cause the ship to capsize. Then it is necessary to consider the influence of the water to keep safety on stability of such kinds of ships.

Many experimental researches on Ro-Ro passenger ships with flooding water have been conducted until now (Ishida, 1996; Hamano, 1997; Haraguchi, 1998; Vassalos, 2000 etc.). It is, however, difficult to capture all dangerous conditions of the ship with flooding water under a limit of sample ships and experimental conditions. Although calculation methods on motion of ships have been presented to predict capsize of the ships (Papanikolaou, 2000; Zaraphonitis, 1997; Hasegawa, 2000), there are many points which are uncertain on application range of them at this stage.

In order to estimate ship motion with flooding water entered into from damaged holes exactly, it is necessary to understand two phase, that is, one is to estimate amount of ingress of water from damaged holes (1), the other is to estimate the ship motion considered dynamic influence of water on deck (2). In the researches of the past, detailed examinations are few concerning validity of application limit and the estimation method in itself though a part of excellent agreement between estimation results and experimental results is shown. We think the problem to estimate the ship motion with flooding water exactly is not identified in the calculation including the both conditions of (1) and (2).

In this paper, we consider the calculation method of rolling motion with flooded water on deck from the viewpoint of (2). The damage holes do not exist on the vehicle deck in this situation. The 2-dimensional lump mass concept for the flooded water proposed by Ishida et al. (1996) and Murashige et al. (1997), which is applied to a box-shaped ship, is used in the calculation. The rolling motion that has high danger of capsizing rather than the other modes of ship motion is only considered in the paper.

MATHEMATICAL MODEL OF SHIP MOTION WITH FLOODED WATER

A ship with flooded water, which has no forward speed, is in beam waves, which is assumed in the condition of damage stability requirements of SOLAS. The equation of two degree of freedom affected from the flooded water is used in the calculation. It is assumed that the coupling motion of rolling and flooded water is dominant in the motion, and the effect of sway and heave motion could be neglected from the equations.

The coordinate system is defined in the Fig.1. The flooded water with width; b_w, depth; d_w exists on the vehicle deck when the ship is in upright, and ship breadth; B, draft; d_s and height of a free board; f_r are defined as shown in the figure.

The surface of the flooded water is flat with slope χ on the basis of the vehicle deck. The flooded water exists in one vehicle deck without

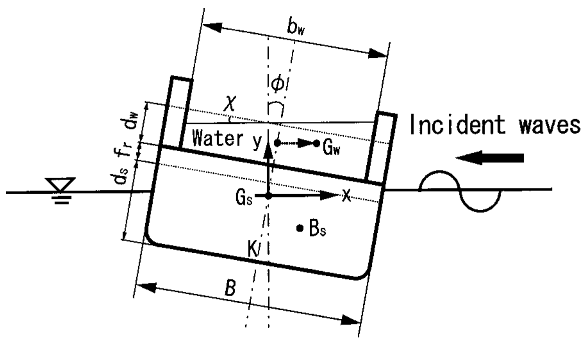

Fig.1 Coordinate system on a Ro-Ro passenger ship with flooded water on deck

partitions such as a central casing, and the center of gravity position of the water is assumed to be not doing movement of 3-dimensional but 2-dimensional movement on the center part of the hull in direction of width of the ship.

Each position of the center of gravity, buoyancy on the ship and the flooded water is respectively defined as G_s, G_w, and B_s, and each position on coordinates is represented as x_{Gw} etc. (S; ship, w; flooded water).

Kinetic energy K, potential energy P, and dissipation energy D of the ship and the flooded water can be expressed under the condition of inclination φ on heel of the ship, χ on the surface of the water as follows;

$$
\begin{aligned}
K_s &= \frac{1}{2} M k^2 \dot{\phi}^2 \\
K_w &= \frac{1}{2} m (\dot{x}_{Gw}{}^2 + \dot{y}_{Gw}{}^2) \\
P_s &= -(M+m) g y_{Bs} \\
P_w &= m g y_{Gw} \\
D &= \frac{1}{2} \nu_s \dot{\phi}^2 + \frac{1}{2} \nu_w \dot{\chi}^2
\end{aligned} \tag{1}
$$

where M; mass of a ship, m; mass of flooded water, k; radius of gyration, ν_s and ν_w; damping coefficients of a ship and flooded water. The position of the center of gravity (x_{Gw}, y_{Gw}) is expressed by using φ and χ as follows;

(i) $|\chi| < \chi^*$

$$
\begin{aligned}
x_{Gw} &= BM_w (\cos\phi + \frac{1}{2}\tan\chi \sin\phi)\tan\chi + (d_s + f_r + \frac{d_w}{2} - KG_s)\sin\phi \\
y_{Gw} &= BM_w (-\sin\phi + \frac{1}{2}\tan\chi \cos\phi)\tan\chi + (d_s + f_r + \frac{d_w}{2} - KG_s)\cos\phi
\end{aligned} \tag{2}
$$

(ii) $|\chi| > \chi^*$

$$
\begin{aligned}
x_{G_w} &= \mathrm{sgn}(\chi)\frac{b_w}{2}\cos\phi + (d_s + f_r - KG_s)\sin\phi - \mathrm{sgn}(\chi)\frac{2}{3}\sqrt{b_w d_w}\,\frac{\cos(\phi+\chi)}{\sqrt{\sin 2|\chi|}} \\
y_{Gw} &= -\mathrm{sgn}(\chi)\frac{b_w}{2}\sin\phi + (d_s + f_r - KG_s)\cos\phi + \mathrm{sgn}(\chi)\frac{2}{3}\sqrt{b_w d_w}\,\frac{\sin(\phi+\chi)}{\sqrt{\sin 2|\chi|}}
\end{aligned} \tag{3}
$$

where

$$
\tan\chi^* = 2d_w / b_w
$$
$$
BM_w = b_w^2 / 12 d_w
$$

The equations of motion of the ship and the flooded water are derived from the Lagrange equation shown in the next expression.

$$
\begin{aligned}
&\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\phi}}\right) - \frac{\partial L}{\partial \phi} + \frac{\partial D}{\partial \dot{\phi}} = Q \\
&\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\chi}}\right) - \frac{\partial L}{\partial \chi} + \frac{\partial D}{\partial \dot{\chi}} = 0
\end{aligned} \tag{4}
$$

$$
\begin{aligned}
L &= K - P \\
&= K_s + K_w - P_s - P_w
\end{aligned}
$$

where

$$
\begin{aligned}
K_w &= \frac{1}{2} m (\dot{x}_{Gw}{}^2 + \dot{y}_{Gw}{}^2) \\
&= \frac{1}{2} m (C_1 \dot{\phi}^2 + 2C_2 \dot{\phi}\dot{\chi} + C_3 \dot{\chi}^2)
\end{aligned}
$$

Q represents exciting roll moment in beam waves. C_n (n=1~3) is the coefficient depended on φ, χ.

Finally, after substituting the equations (1) for the equations (4) and nonlinear terms considered second order are omitted from them, the equations of rolling motion are expressed like as follows;

$$
(Mk^2 + mC_1)\ddot{\phi} + \nu_s \dot{\phi} + (M+m) g GZ(\phi) + mg \frac{\partial y_{Gw}(\phi,\chi)}{\partial \phi} + mC_2 \ddot{\chi} = Q \tag{5}
$$

$$
mC_3 \ddot{\chi} + \nu_w \dot{\chi} + mg \frac{\partial y_{Gw}(\phi,\chi)}{\partial \chi} + mC_2 \ddot{\phi} = 0 \tag{6}
$$

Rolling inertia moment Mk^2 in equation (5) is calculated by using natural roll period of the ship without flooded water on deck. The damping coefficient ν_s that has nonlinear effect is expressed like next expression.

$$
\begin{aligned}
\nu_s &= B_1 + B_2 |\dot{\phi}| \\
&= \frac{2}{\pi}\frac{WGM}{\omega_n} a + \frac{3}{4}\frac{WGM}{\omega_n^2} b |\dot{\phi}|
\end{aligned} \tag{7}
$$

Coefficients 'a' and 'b' are obtained from the results of free decay tests of the model. ω_n is a natural angular frequency of the ship.

The exciting roll moment Q is calculated by Froude-Krylov force in accordance with the researches of Tasai et al. (1981) when wavelength is very long compared with ship breadth. At this time, the Froude-Krylov force assumed when the ship is staying upright condition in the sea will be used simplify in the calculation.

The coefficient ν_w in equation (6) will be express by quadratic functions as well as the equation (7), and the experiment results with two-dimensional model are used in the equation (Fujiwara, 2002).

The motion of the ship and the flooded water is calculated with the Runge-Kutta method after calculating each term in the equations (5), (6).

Table 1 Principal particulars

	Ship		Model (Scale ratio:1/48.6)	
	Intact	Damaged	Intact	Damaged
Lpp(m)	170.00		3.500	
B(m)	25.00		0.515	
D(m)	9.50		0.196	
W(ton)	15020		0.128	
ds(m)	6.60	8.20	0.136	0.170
trim(m)	0.00	-1.30	0.000	-0.026
GM(m)	1.41	2.80	0.029	0.057
fr(m)	2.90	1.30	0.060	0.027
Ts(sec)	17.90	13.40	2.570	1.930
Note: Full load departure condition Designed deck height				

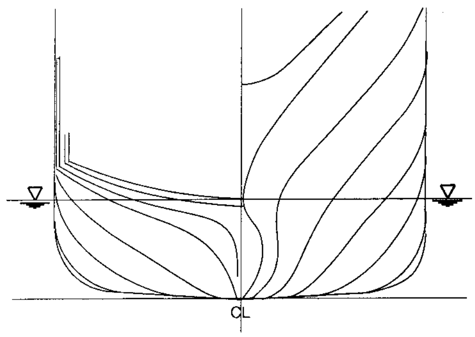

Fig.2 Body plan of the model

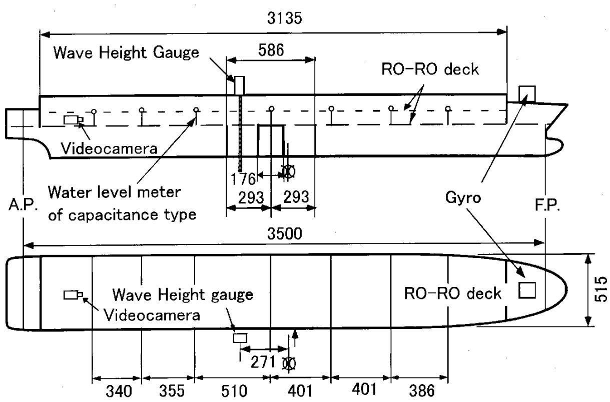

Fig.3 Ro-Ro passenger ship with damaged hole [Unit: mm]

MODEL EXPERIMENTS

To obtain the damping coefficients ν_s and ν_w , free decay tests were carried out, and experiments of rolling motion in beam waves were done by using a Ro-Ro passenger ship model to examine validity of the calculation method shown in the previous. The experiments when the ship has 5%(6kg) and 8%(10kg) flooded water on the deck for displacement (W) of the ship were carried out in our research institute.

Model Ship

The Ro-Ro passenger ship designed on the basis of Japanese one (scale ratio: 1/48.6) was used in the experiments. The principal particulars and the body plan are shown in Table 1, Fig.2. The experimental condition of the model is shown in Fig.3. Neither damage holes nor gateways of water are installed on the deck. There is, however, a damage compartment over 0.176m in length under water line at center part of the hull (midship 2-hold damage scenario) in order to use the evaluation of the safety on damaged Ro-Ro passenger ships in the next stage.

The ship has two floors as the vehicle decks that each height from sea level is 0.027m and 0.122m respectively. In the experiment, water was

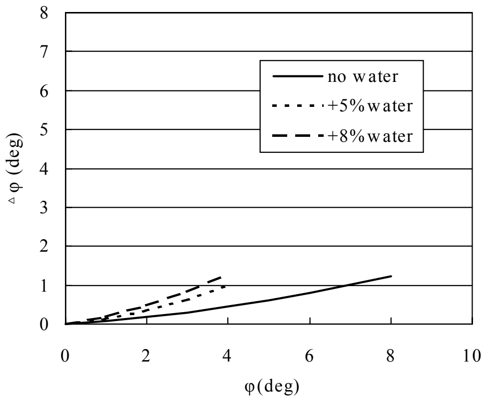

Fig.4 Curves of extinction from free decay tests on experimental conditions

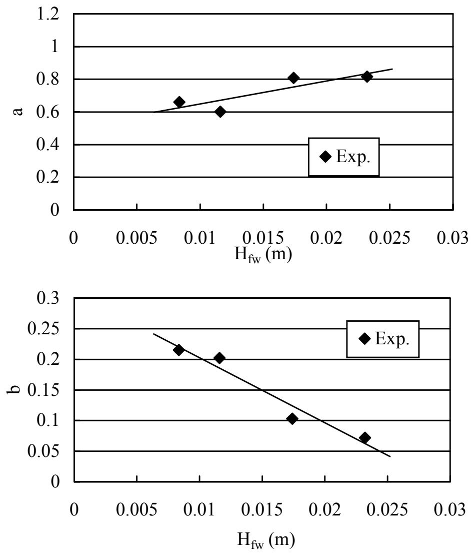

Fig.5 Damping coefficients affected from depth of water on deck

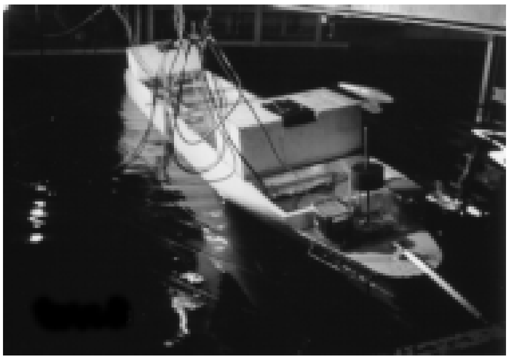

Fig.6 Photo of the experimental condition in the towing tank

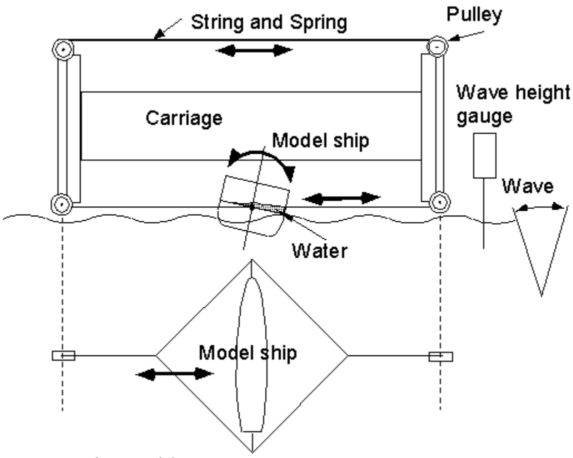

Fig.7 Experimental layout

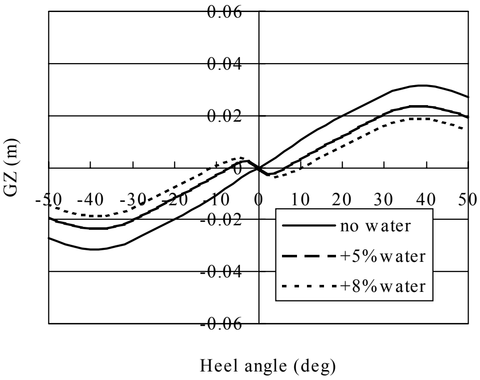

Fig.8 GZ curves of the ship with water on deck

infused into the deck of 0.027m in height. The center of gravity of the model is set to be 0.057m GM in no flooded water condition.

Free decay test of the ship

The extinction curves obtained from the free decay test with and without the flooded water on deck are shown in Fig.4. The damping with the flooded water increases compared with one without the water because of inclination of the ship and effect of the water. In this case, however, we think the damping affected from the water is very small

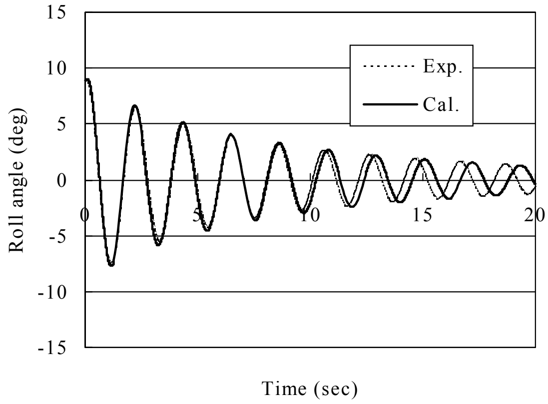

Fig.9 Comparing the experimental result of the ship without water on deck with the calculation result on free decay test

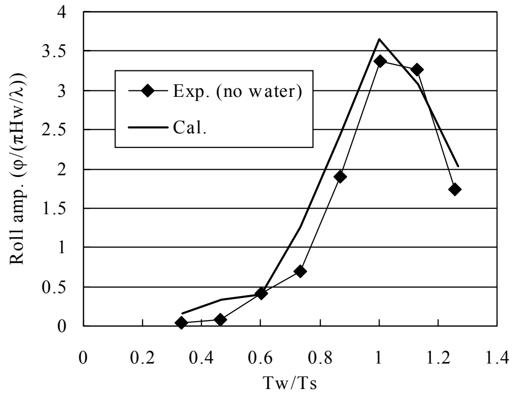

Fig.10 Rolling motion of the ship without water on deck in regular waves

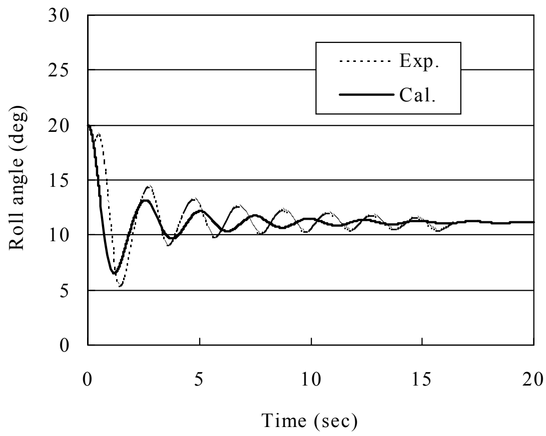

Fig.11 Comparing the experimental result of the ship with water on deck with the calculation result on free decay test

since rolling angle in the tests is very small and the water does not almost move on the deck, and hence the damping coefficient ν_S in the calculation is obtained from the experimental results of free roll tests with flooded water.

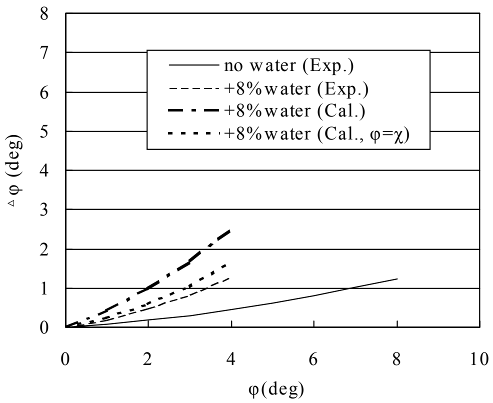

Fig.12 Curves of extinction from free decay tests on the ship with water on deck

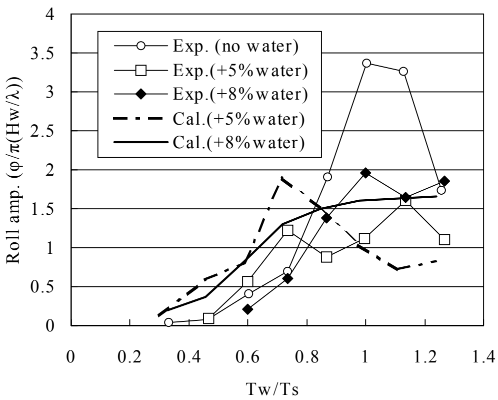

Fig.13 Comparing experimental results with calculation ones on rolling motion of the ship with 5% and 8% water on deck in regular waves (H_w/λ=1/50)

Free decay test of flooded water

The free decay tests on flooded water were carried out with 2-dimensional tank (L×B×H=0.15×0.5×0.45m) to obtain the damping coefficient ν_w. The experimental results depended on height of the flooded water (H_{fw}) are shown in Fig.5.

Experimental condition of measurements on rolling motion in beam waves

The experiments were carried out at the towing tank in our research institute (L×B×D=50×8.0×4.5m). The experimental setting is shown in Fig.6, Fig.7. The ship has no forward speed, and yawing motion is restricted with a string. The ship is able to drift in the direction of lee side under effect of waves.

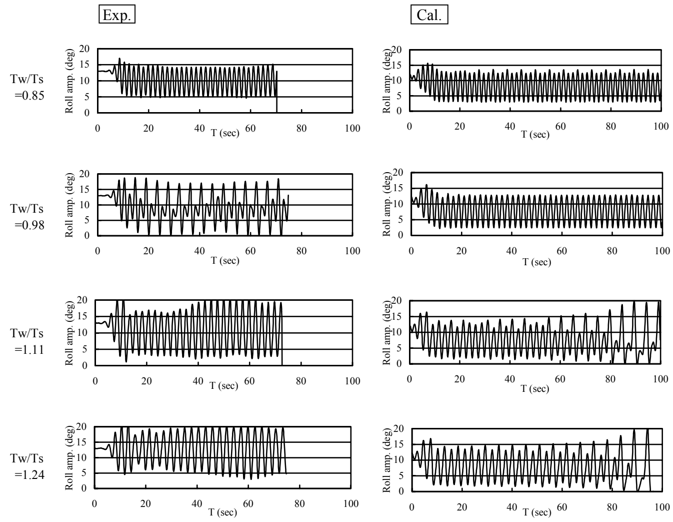

Fig.14 Time history of rolling motion of the ship with 8% water on deck comparing experimental results with calculation ones

The GZ curve of the experimental condition that the ship has flooded water with 5% and 8% on deck is shown in Fig.8. The ship is inclined to the weather or lee side in 8.5 deg (5% water) and in 12 deg (8% water). The wave period is 0.7~2.7 sec (It is worth for 7~19 sec in the real ship.). The slope of incident waves (H_w/λ) is about 1/30~1/50.

CALCULATION RESULTS AND CONSIDERATIONS

Free decay test and rolling motion of the ship without water on deck

The calculation results of free decay test are compared with the experimental ones to confirm effectiveness of the calculation method. The result is shown in Fig.9. As a matter of course, these results coincide with each other since the damping coefficients obtained from the experiments are used in the calculation.

Next, roll amplitudes are compared the calculation results with the experiment ones in regular beam wave when there is no water on the deck as shown in Fig.10. The horizontal axis is ratio of wave period and natural roll period of the ship (T_w/T_s), and the vertical axis is dimensionless value of roll amplitude. The slope of incident waves is 1/57 on the average. The calculation results in beam waves almost agree with the experimental ones.

Free decay test of the ship with flooded water on deck

Fig.11 shows the result of free roll test when the ship has 8% water on deck, and the extinction carves obtained from Fig.11 are shown in Fig.12.

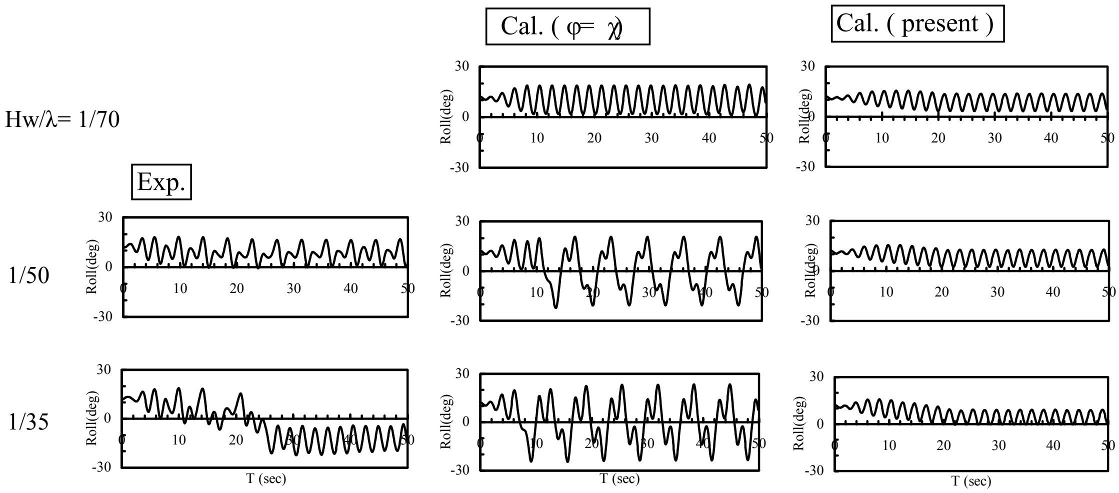

Fig.16 Time history of calculation results on rolling motion in different incident wave slopes

The influence of the flooded water is very large. Roll inertia moment is changed by the effect of the water and natural roll period increases from 2.1 sec to 2.4 sec in the calculation. However, natural roll period of the experiment dose not change in spite of expectation of the effect of the water. Precise solution to the cause could not be obtained.

The damping of calculation results is a little large compared with it of experimental one. The estimation on effect of the flooded water is a little excessive.

Rolling motion in regular beam waves

In case of the flooded water of 5% and 8%, roll amplitudes in regular beam waves are compared the calculation results with the experimental ones. A sin waves having same amplitude of regular waves in the experiments are given in the calculation. The results are shown in Fig.13.

The roll amplitude with the flooded water is considerably small compared with that without the water in the experiments. From this figure, it is understood to be able to estimate the roll amplitude of 5% and 8% water on deck roughly though accuracy of the estimation decreases slightly in short wave length region. The difference between the experiment results and the calculation ones in this region, however, is very small (about 1.0 degree).

The time series (T_w/T_s=0.85~1.24) near synchronization are shown in Fig.14. The nonlinear rolling motion in the experiments is observed at synchronization because of much phase difference in the experiment between rolling and movement of the flooded water.

On the other hand, in the calculation nonlinear motion is observed in 2.4 sec (T_w/T_s =1.1) since the natural roll period changes large as shown in Fig.11.

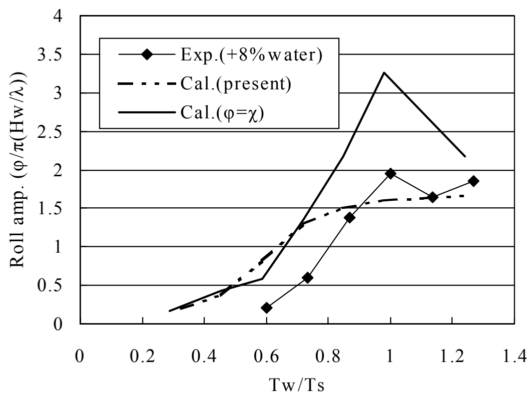

Fig.15 Calculation results of rolling motion in case of $\varphi=\chi$ (H_w/λ=1/50)

Dynamic effect of the flooded water

In case of results shown in Fig.13, 14, H_w/λ is set about 1/50. The movement of the flooded water on the deck is also comparatively small, and large heel transfer from weather side to lee side is not observed in the experiments. Therefore, at the case to be assumed in comparatively calm weather, it is thought that the method not to be considered a dynamic influence of the flooded water is useful to calculate the rolling motion easily (Vassalos, 2000; Hasegawa, 2000). However, the influence on dynamic effect of the flooded water is not ignored when slope of the incident waves is large. In this section, the dynamic effect of the flooded water is considered.

The calculation results with dynamic effect of the flooded water or not are shown in Fig.15. The wave conditions in the calculation are same as Fig.13. Roll amplitudes of the calculations and the experimental results with 8% water are compared with each other. Not considering the dynamic effect of the flooded water, water surface on the deck is always horizontally ($\varphi=\chi$). Rolling motion in case of $\varphi=\chi$ is not reduced by the effect of flooded water in the calculation since there is no phase difference. It is understood in the figure to overestimate roll amplitude in case of not considering dynamic influence in the region on synchronization.

Next, we investigate effect of H_w/λ for the ship with 8% water on deck as shown in Fig.16. In the figure, the experimental results of 1/50, 1/35 H_w/λ are also presented. The wave period is the same as the natural roll period of the ship (T_w=2.1 sec).

In the present calculation, average heel transfers to near 0 degree by the influence of the flooded water in case of large wave slope (Cal.(present)). Roll amplitude of the results is same level for the results of the experiments.

However, the results of calculation not considered the dynamic effect of the flooded water (Cal.($\varphi=\chi$)) are not same trend for the results of the experiments. It can be said that movement of the flooded water will play a very important role for rolling motion in waves. The movement of the flooded water should be considered more detail to estimate the ship motion exactly.

CONCLUTIONS

In order to assess the safety of damaged Ro-Ro passenger ships with flooded water, rolling motion of the ship in beam waves is calculated, and the results are compared with the results of the experiments. To summarize our results and considerations, we can explain as follows;

(1) The results of the present calculation method, which used the equation of rolling motion of two degree of freedom affected from the flooded water, are corresponding to about the experiment results. The effectiveness of the calculation method is shown in this paper.

(2) Nonlinear rolling motion affected from the flooded water on deck is presented in the calculation as well as in the experiment.

(3) Dynamic influence of the flooded water is important for rolling motion in the high wave slope at synchronization region. Therefore, in case that safety of damaged Ro-Ro passenger ships is considered, it is necessary to use the model including the effect of dynamic motion of the flooded water on deck.

There are, however, many points on motion of flooded water on deck that must be solved to estimate the ship motion exactly, and 3-dimentional effect of the ship and the flooded water should be also considered in the calculation in the future research.

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