# BROACHING PREDICTION WITH NONLINEAR HEEL-INDUCED HYDRODYNAMIC FORCES TAKEN INTO ACCOUNT

Hirotada HASHIMOTO*, Naoya UMEDA* and Akihiko MATSUDA**
* Department of Naval Architecture and Ocean Engineering, Osaka University (Japan)
**National Research Institute of Fisheries Engineering (Japan)

## Abstract

For realising more quantitative prediction of broaching and capsizing in following and quartering seas, the authors attempt to investigate the effect of nonlinear heel-induced hydrodynamic forces on these phenomena. Firstly we propose and conduct a new captive model experiment to obtain hydrodynamic forces with various heel angles up to 50 degrees in calm water. As a result, the data of heel-induced manoeuvring forces with respect to heel angle in calm water are provided. Then the comparisons between the numerical simulations with the nonlinear heel-induced hydrodynamic forces and without them are shown. These comparisons cover not only time series but also boundaries of ship motion modes. These comparisons demonstrate the effect of nonlinear heel-induced hydrodynamic forces in calm water is not negligibly small. With this effect capsizing more easily occurs and broaching does not so.

## NOMENCLATURE

| | |
|---|---|
| $c$ | wave celerity |
| $d$ | mean draft |
| $F_n$ | nominal Froude number |
| $g$ | gravitational acceleration |
| $GZ$ | righting arm |
| $GZ^{FK}$ | wave effect on righting arm with Froude-Krylov assumption |
| $GZ^{WL}$ | wave effect on righting arm induced by hydrodynamic lift |
| $H$ | wave height |
| $I_{xx}$ | moment of inertia in roll |
| $I_{zz}$ | moment of inertia in yaw |
| $J_{xx}$ | added moment of inertia in roll |
| $J_{zz}$ | added moment of inertia in yaw |
| $K'$ | $K' = K/(\rho L d^2 u^2/2)$ |
| $K^M_{NL}$ | nonlinear manoeuvring moment in roll |
| $K^R_{NL}$ | nonlinear heel-induced roll moment |
| $K_p$ | derivative of roll moment with respect to roll rate |
| $K_r$ | derivative of roll moment with respect to yaw rate |
| $K_r^W$ | wave effect on the derivative of roll moment with respect to yaw rate |
| $K_R$ | rudder gain |
| $K_v$ | derivative of roll moment with respect to sway velocity |
| $K_v^W$ | wave effect on the derivative of roll moment with respect to sway velocity |
| $K_w$ | wave-induced roll moment |
| $K_\delta$ | derivative of roll moment with respect to rudder angle |
| $K_\delta^W$ | wave effect on the derivative of roll moment with respect to rudder angle |

$K_\phi$ derivative of roll moment with respect to roll angle
$K_\phi'$ $K_\phi' = K_\phi/(\rho L d^2 u^2/2)$
$L$ ship length between perpendiculars
$m$ ship mass
$m_x$ added mass in surge
$m_y$ added mass in sway
$n$ propeller revolution number
$N'$ $N' = N/(\rho L^2 d u^2/2)$
$N^M_{NL}$ nonlinear manoeuvring moment in yaw
$N^R_{NL}$ nonlinear heel-induced yaw moment
$N_r$ derivative of yaw moment with respect to yaw rate
$N_r^W$ wave effect on the linear derivative of yaw moment with respect to yaw rate
$N_v$ derivative of yaw moment with respect to sway velocity
$N_v^W$ wave effect on the linear derivative of yaw moment with respect to sway velocity
$N_w$ wave-induced yaw moment
$N_\delta$ derivative of yaw moment with respect to rudder angle
$N_\delta^W$ wave effect on the derivative of yaw moment with respect to rudder angle
$N_\phi$ derivative of yaw moment with respect to roll angle
$N_\phi'$ $N_\phi' = N_\phi/(\rho L^2 d u^2/2)$
$OG$ vertical distance between water line and centre of gravity
$p$ roll rate
$r$ yaw rate
$R$ ship resistance
$t$ time
$T$ propeller thrust
$T_D$ time constant for differential control
$T_E$ time constant for steering gear
$u$ surge velocity
$v$ sway velocity
$X'$ $X' = X/(\rho L d u^2/2)$
$X^M_{NL}$ nonlinear manoeuvring force in surge
$X^R_{NL}$ nonlinear heel-induced surge force
$X_w$ wave-induced surge force
$X_\phi'$ $X_\phi' = X_\phi/(\rho L d u^2/2)$
$X_{rud}$ rudder-induced surge force
$Y'$ $Y' = Y/(\rho L d u^2/2)$
$Y^M_{NL}$ nonlinear manoeuvring force in sway
$Y^R_{NL}$ nonlinear heel-induced sway force
$Y_r$ derivative of sway force with respect to yaw rate
$Y_r^W$ wave effect on the derivative of sway force with respect to yaw rate
$Y_v$ derivative of sway force with respect to sway velocity
$Y_v^W$ wave effect on the derivative of sway force with respect to sway velocity
$Y_w$ wave-induced sway force
$Y_\phi'$ $Y_\phi' = Y_\phi/(\rho L d u^2/2)$
$Y_\delta$ derivative of sway force with respect to rudder angle
$Y_\delta^W$ wave effect on the derivative of sway force with respect to rudder angle
$Y_\phi$ derivative of sway force with respect to roll angle
$z_H$ vertical position of centre of sway force due to lateral motions
$\chi$ heading angle from wave direction
$\chi_c$ desired heading angle for auto pilot
$\delta$ rudder angle
$\phi$ roll angle
$\lambda$ wave length
$\theta$ pitch angle
$\rho$ water density
$\xi_G$ longitudinal position of centre of gravity from a wave trough
$\zeta_G$ vertical distance between centre of gravity and still water plane

## 1. INTRODUCTION

Recent model experiments (for example, [1]) demonstrate that a ship complying with the current Intact Stability Code (IS Code) of International Maritime Organisation (IMO) rarely capsizes in non-breaking beam waves but could occasionally capsize when she runs in following and quartering seas. July in 2002 at IMO, the Sub-committee on stability, load lines and fishing vessel safety has started to review the IS Code with introduction of direct assessment by physical or numerical tests. At this stage numerical models are required to provide not only qualitative agreement but also quantitative one with model experiments. Toward this direction, the International Towing Tank Conference (ITTC) had conducted benchmark testing of several numerical models by comparing them with capsizing model experiments in following and quartering seas, which cover ship capsize due to parametric rolling and broaching. As a result, it was confirmed that only a few numerical models could qualitatively predict capsizing and none could do it quantitatively. [2][3] Therefore existing numerical modelling techniques should be upgraded to realise a quantitatively prediction of capsizing in following and quartering seas. For this purpose, it is necessary to systematically examine all factors relevant to capsize in following and quartering seas further. Among them, the authors have already examined some factors, wave effects on linear manoeuvring coefficients [4] and those on roll restoring moment [5], nonlinearity of wave-induced surge force [6] and nonlinear sway-roll coupling [6] and so on. [7]

In this paper, we attempt to clarify the effect of heel-induced hydrodynamic forces in still water. So far this effect was taken into account as linear functions of roll angle and their derivatives were obtained from captive model test with heel angle of 5 degrees. This is because captive experiment with large heel angle is difficult because of the limitation of current procedure and setups. Obviously the relationship between the hydrodynamic forces and roll angle could be nonlinear if we predict ship motions up to capsizing. Thus, in this study, we firstly develop a new experimental procedure with a purpose-built ship model and experimental setup, which can realise captive tests up to the heel angle of 90 degrees. Then the mathematical model is upgraded by introducing nonlinear model of hydrodynamic forces as functions of roll angle, and is applied to prediction of ship motions in following and quartering waves. The comparison with and without this effect is provided, together with the existing free-running experiments.

## 2. NEW CAPTIVE MODEL EXPERIMENT WITH LARGE HEEL ANGLE

In this work a new 1/25 scaled model of the 135 gross tonnage purse seiner was used as the subject ship of the ITTC benchmark testing. Its body plan, general arrangement and principal particulars are shown in Figs.1-2 and Table 1, respectively. The ship model is completely watertight structure and has bulwarks, freeing ports and the super structures that are similar to the free-running model. [1] There are two poles that fix the model and adjust the model attitude. Captive model experiments were conducted at a seakeeping and manoeuvring basin of National Research Institute of Fisheries Engineering. The model was towed by a main towing carriage in long-crested regular waves, and model was equipped with a rudder but without a propeller. The model was completely fixed in 6 degrees of freedom. Surge, sway, heave force and roll, pitch, yaw moment acting on the towed model were detected by a dynamometer. Procedure of the experiment is as follows. Firstly displacement of ship attitude, sinkage and trim due to running, is estimated from existing resistance test and the effect of heel is done with hydrostatic calculation. By adjusting the length of poles and the angle of gimbals, the sinkage, trim and heel angle are set to be equal to those estimated values. Model experiments were conducted in still water for two Froude numbers and various heel angles. To correct running attitude with heel angle taken into account, additional experiments were also carried out for obtaining derivatives of hydrodynamic forces with respect to heave and pitch. Here the given values of heave and pitch for these additional experiments are 20% of the mean draft and initial trim respectively. Using such derivatives we can more accurately estimate all forces and moments in the case that ship is free in heave and pitch by solving the simultaneous equations of heave and pitch.

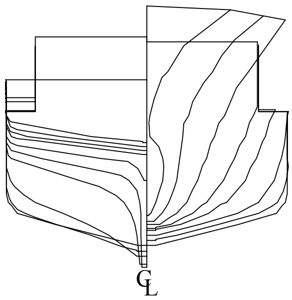

Fig.1 Body plan of the subject ship

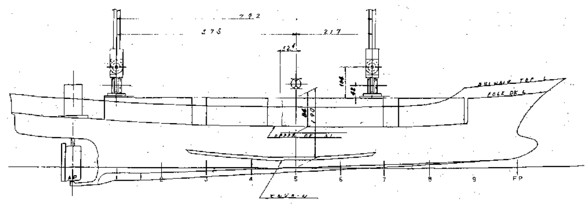

Fig.2 General arrangement of the subject ship

Table 1: Principal particulars of the subject ship

| *Items* | *Values* |
|---|---|
| length : $L_{pp}$ | 34.5 m |
| breadth : $B$ | 7.60 m |
| depth : $D$ | 3.07 m |
| mean draught : $d$ | 2.65 m |
| block coefficient : $C_b$ | 0.597 |
| longitudinal position of centre of gravity | 1.31 m aft |
| metacentric height : $GM$ | 1.00 m |
| natural roll period : $T_\phi$ | 7.4 s |
| rudder area : $A_R$ | 3.49 m$^2$ |
| Time constant of steering gear : $T_E$ | 0.63 s |
| proportional gain: $K_P$ | 1.0 |
| time constant for differential | 0.0 s |
| maximum rudder angle: $\delta_{max}$ | $\pm 35^{\circ}$ |

The surge force, X, the sway force, Y, the heave force, Z, the roll moment, K, the pitch moment, M and the yaw moment, N, are measured as functions of heave, pitch and Froude number. The definition of directions of the measured forces and moments is shown in Fig.3. The three moments are converted from the measured values around the centre of the dynamometer to that of ship gravity. The measured forces can be expanded as follows:

$$\begin{aligned} X(\zeta_G,\theta;\phi,F_n) &= X(\zeta_{G0},\theta_0;\phi,F_n) \\ &+ X_\zeta(\zeta_{G0},\theta_0;\phi,F_n)\times\zeta_G^* \\ &+ X_\theta(\zeta_{G0},\theta_0;\phi,F_n)\times\theta^* \end{aligned} \tag{1}$$

$$\begin{aligned} Y(\zeta_G,\theta;\phi,F_n) &= Y(\zeta_{G0},\theta_0;\phi,F_n) \\ &+ Y_\zeta(\zeta_{G0},\theta_0;\phi,F_n)\times\zeta_G^* \\ &+ Y_\theta(\zeta_{G0},\theta_0;\phi,F_n)\times\theta^* \end{aligned} \tag{2}$$

$$\begin{aligned} Z(\zeta_G,\theta;\phi,F_n) &= Z(\zeta_{G0},\theta_0;\phi,F_n) \\ &+ Z_\zeta(\zeta_{G0},\theta_0;\phi,F_n)\times\zeta_G^* \\ &+ Z_\theta(\zeta_{G0},\theta_0;\phi,F_n)\times\theta^* \end{aligned} \tag{3}$$

$$\begin{aligned} K(\zeta_G,\theta;\phi,F_n) &= K(\zeta_{G0},\theta_0;\phi,F_n) \\ &+ K_\zeta(\zeta_{G0},\theta_0;\phi,F_n)\times\zeta_G^* \\ &+ K_\theta(\zeta_{G0},\theta_0;\phi,F_n)\times\theta^* \end{aligned} \tag{4}$$

$$\begin{aligned} M(\zeta_G,\theta;\phi,F_n) &= M(\zeta_{G0},\theta_0;\phi,F_n) \\ &+ M_\zeta(\zeta_{G0},\theta_0;\phi,F_n)\times\zeta_G^* \\ &+ M_\theta(\zeta_{G0},\theta_0;\phi,F_n)\times\theta^* \end{aligned} \tag{5}$$

$$\begin{aligned} N(\zeta_G,\theta;\phi,F_n) &= N(\zeta_{G0},\theta_0;\phi,F_{nn}) \\ &+ N_\zeta(\zeta_{G0},\theta_0;\phi,F_n)\times\zeta_G^* \\ &+ N_\theta(\zeta_{G0},\theta_0;\phi,F_n)\times\theta^* \end{aligned} \tag{6}$$

Here $\zeta_{G0}$ and $\theta_0$ indicate the sinkage and trim angle, respectively, initially estimated:

$$\begin{aligned} \zeta_G^* &= \zeta_G - \zeta_{G0} \\ \theta^* &= \theta - \theta_0 \end{aligned} \tag{7}$$

These are assumed to be small. If ship model is free in heave and pitch, heave force and pitch moment are zero. Therefore $\zeta_G^*$, $\theta^*$ can be obtained by solving following simultaneous equations.

$$
\begin{aligned}
&Z(\zeta_{G0},\theta_0;\phi,F_n)+Z_\zeta(\zeta_{G0},\theta_0;\phi,F_n)\zeta_G^{\ *} \\
&+Z_\theta(\zeta_{G0},\theta_0;\phi,F_n)\theta^*=0 \\
&M(\zeta_{G0},\theta_0;\phi,F_n)+M_\zeta(\zeta_{G0},\theta_0;\phi,F_{nn})\zeta_G^{\ *} \\
&+M_\theta(\zeta_{G0},\theta_0;\phi,F_n)\theta^*=0
\end{aligned} \qquad (8).
$$

Then, the surge and sway forces, roll and yaw moment for the case in which model is free in heave and pitch can be estimated with Equations (1), (2), (4) and (6).

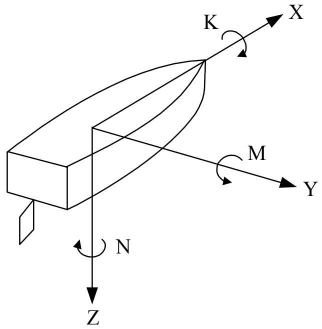


Fig.3 Definition of directions of the measured forces and moments

All experiments were conducted in still water and roll angles of this experiments are 0, 10, 20, 30, 40, 50 degrees and the nominal Froude numbers are 0.4877 and 0.5348. First one of the nominal Froude number corresponds to the case of the encounter frequency, $\omega_e$, of 0 with the wave steepness, H/λ, of 1/10 and the wave length to the ship length ration, λ/L, of 1.5 and second one does $\omega_e$ of 0 with H/λ of 1/10 and λ/L of 1.637. Here the second case corresponds to the condition of ITTC benchmark test of ship capsizing due to broaching. A photograph of this experimental setup is shown in Fig.4.

Fig.4 Setup of the captive model experiment.

## 3. EXPERIMENTAL RESULTS

The experimental results of the derivatives of sway force, yaw moment and roll moment with respect to roll angle from the tests with 20 and 5 degrees of heel angle as functions of the nominal Froude number are shown in Figs.5-6. Here the centre of moments is exactly under the centre of gravity, and is placed on the water plane. The absolute value of $Y_\phi$' from the roll angle of 20 degrees is as large as those with 5 degrees at a low speed region but is larger than those at high speed region. There is no significant difference in $N_\phi$' but is significant difference in $K_\phi$' between two roll angles. These differences can be explained as follows. Since a centre of sectional under-water area moves in horizontal direction due to heel, the heel hull has a hull-form-camber line. Therefore a lift force that reduces a righting moment acts on a submerged hull with forward velocity. [8] As a result, larger roll moment can be induced with larger roll angle and larger forward speed. The value of $K_\phi$' with Froude number of 0.2, however, is significantly large and it does not correspond above explanation. This is probably because that measured value is too small to be non-dimensionalise with forward velocity. Fig.7 shows the comparison between estimated ship attitudes by fore-mentioned analysis and those obtained from the conventional resistance test with 0 heel angle. These estimated ship attitude by solving Equation (8) are reasonably comparable to the resistance test results because it is known that the effect of heel angle on running attitude is negligibly small.

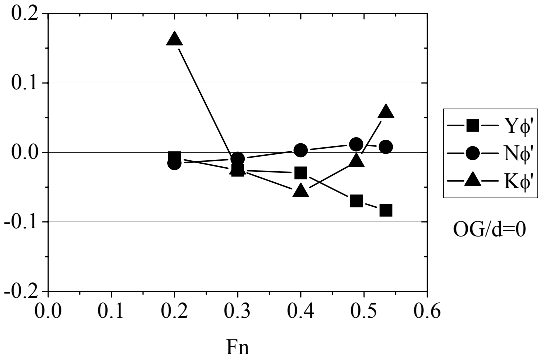


Fig.5 Experimental results of non-dimensional hydrodynamic derivatives with respect to heel angle ($\phi$=20deg.)

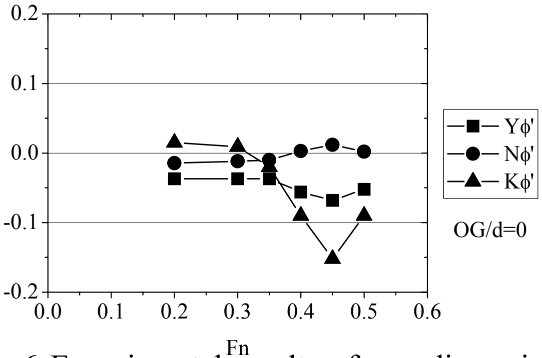


Fig.6 Experimental results of non-dimensional hydrodynamic derivatives with respect to heel angle ($\phi$=5deg.)

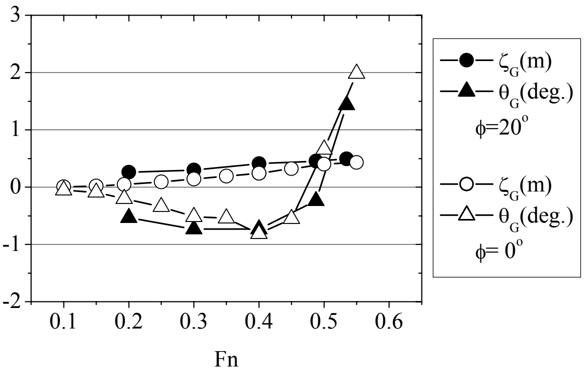


Fig.7 Ship attitude estimated from full captive tests and the one measured from resistance test with 0 heel angle (full scale values)

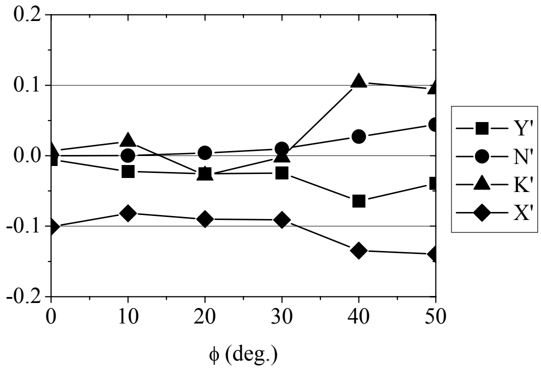


Fig.8 Experimental results of non-dimensional heel-induced hydrodynamic forces with Fn=0.4877

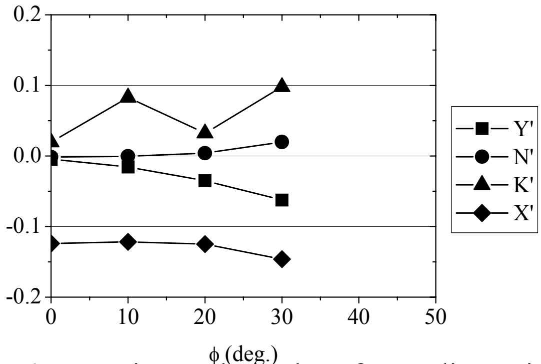


Fig.9 Experimental results of non-dimensional heel-induced hydrodynamic forces with Fn=0.5348

The heel-induced hydrodynamic surge, sway forces and roll moment and yaw moment with roll angle are shown in Figs.8-9. The characteristics of all forces and moments complicatedly change with roll angle. This nonlinearity can be found in both nominal Froude numbers. The surge force drastically changes over 20 degrees of roll angle. This is because that the deck starts to submerge and the bow flare violently disturbs water flow. Figs.10-11 show estimated ship attitudes as functions of heel angle. These results show that change of ship attitudes with respect to heel angle is not simple at all. This complex change of ship attitudes could induce those of the hydrodynamic forces.

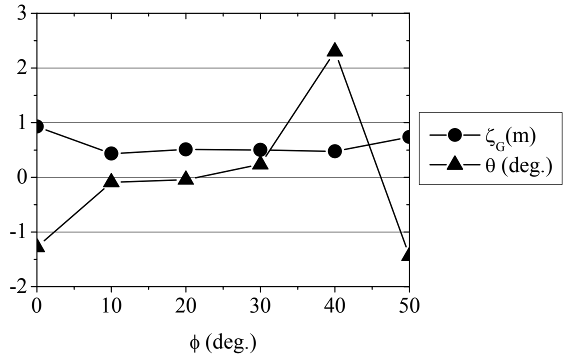


Fig.10 Estimated ship attitude with Fn=0.4877

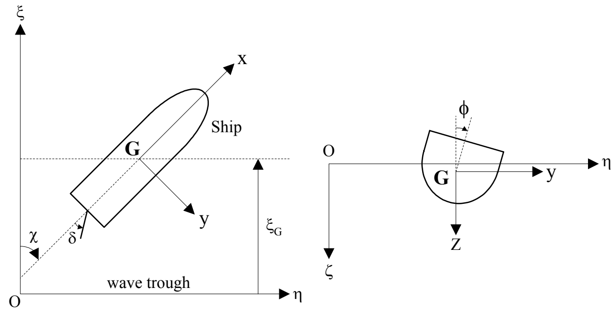


Fig.12 Co-ordinate systems

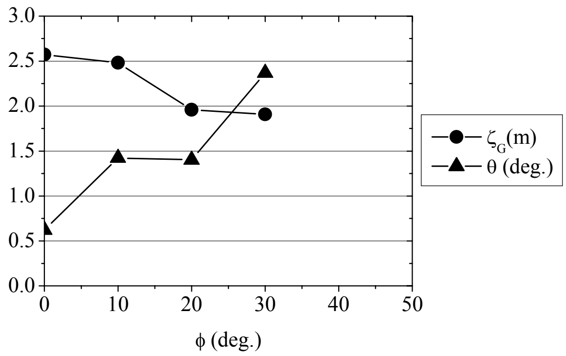


Fig.11 Estimated ship attitude with Fn=0.5348

## 4. MATHEMATICAL MODELLING

The mathematical model of the surge-sway-yaw-roll motion was developed by Umeda and Renilson [9] and Umeda [10] for capsizing associated with surf-riding in following and quartering waves. The details of this model can be found in the literature. [11] Two co-ordinate systems used here are shown in Fig.12: (1) a wave fixed with its origin at a wave trough, the $\xi$ axis in the direction of wave travel; and (2) an upright body fixed with its origin at the centre of ship gravity. The state vector, $\mathbf{x}$ and control vector, $\mathbf{b}$, of this system are defined as follows.

$$\mathbf{x} = (x_1, x_2, \cdots, x_8)^T = \{\xi_G/\lambda, u, v, \chi, r, \phi, p, \delta\}^T \quad (9)$$

$$\mathbf{b} = \{n, \chi_c\}^T \quad (10)$$

The upgraded dynamical system can be represented by the following state equation.

$$\dot{\mathbf{x}} = \mathbf{F}(\mathbf{x};\mathbf{b}) = \{f_1(\mathbf{x};\mathbf{b}), f_2(\mathbf{x};\mathbf{b}), \cdots, f_8(\mathbf{x};\mathbf{b})\}^T \quad (11)$$

where

$$f_1(\mathbf{x};\mathbf{b}) = (u\cos\chi - v\sin\chi - c)/\lambda \quad (12)$$

$$\begin{aligned} f_2(\mathbf{x};\mathbf{b}) = \{&T(u;n) - R(u) + \underline{X^R{}_{NL}(u,\phi)} \\ &+ X^M{}_{NL}(u,v,r;n) + X_{rud}(\xi_G/\lambda, u, \chi, \delta; n) \\ &+ X_w(\xi_G/\lambda, \chi)\}/(m+m_x) \end{aligned} \quad (13)$$

$$\begin{aligned} f_3(\mathbf{x};\mathbf{b}) = \{&-(m+m_x)ur + Y_v(u;n)v \\ &+ Y_v{}^W(\xi_G/\lambda, u, \chi; n)v + Y_r(u;n)r \\ &+ Y_r{}^W(\xi_G/\lambda, u, \chi; n)r + Y^M{}_{NL}(u,v,r;n) \\ &+ Y_\phi(u)\phi + \underline{Y^R{}_{NL}(u,\phi)} + Y_\delta(u;n)\delta \\ &+ Y_\delta{}^W(\xi_G/\lambda, u, \chi; n)\delta \\ &+ Y_w(\xi_G/\lambda, u, \chi; n)\}/(m+m_y) \end{aligned} \quad (14)$$

$$f_4(\mathbf{x};\mathbf{b}) = r \quad (15)$$

$$\begin{aligned} f_5(\mathbf{x};\mathbf{b}) = \{ & N_v(u;n)v + N_v{}^W(\xi_G/\lambda,u,\chi)v \\ & + N_r(u;n)r + N_r{}^W(\xi_G/\lambda,u,\chi)r \\ & + N^M{}_{NL}(u,v,r;n) + N_\phi(u)\phi \\ & + \underline{N^R{}_{NL}(u,\phi)} + N_\delta(u;n)\delta \\ & + N_\delta{}^W(\xi_G/\lambda,u,\chi;n)\delta \\ & + N_w(\xi_G/\lambda,u,\chi;n)\}/(I_{ZZ}+J_{ZZ}) \end{aligned} \quad (16)$$

$$f_6(\mathbf{x};\mathbf{b}) = p \quad (17)$$

$$\begin{aligned} f_7(\mathbf{x};\mathbf{b}) = [ & m_x z_H ur + K_v(u;n)v \\ & + K_v{}^W(\xi_G/\lambda,u,\chi;n)v + K_r(u;n)r \\ & + K_r{}^W(\xi_G/\lambda,u,\chi;n)r \\ & + K^M{}_{NL}(u,v,r;n) + K_P(u)p \\ & + K_\phi(u)\phi + \underline{K^R{}_{NL}(u,\phi)} + K_\delta(u;n)\delta \\ & + K_\delta{}^W(\xi_G/\lambda,u,\chi;n)\delta \\ & + K_w(\xi_G/\lambda,u,\chi;n) \\ & - mg\{GZ(\phi) + GZ^{FK}(\xi_G/\lambda,u,\chi,\phi) \\ & + GZ^{WL}(\xi_G/\lambda,u,\chi,\phi)\}]/(I_{xx}+J_{xx}) \end{aligned} \quad (18)$$

$$f_8(\mathbf{x};\mathbf{b}) = \{-\delta - K_R(\chi-\chi_C) - K_R T_D r\}/T_E \quad (19)$$

Here the underlined parts are newly added to the previous model [5] by fitting the experimental results.

In numerical simulation, hydrodynamic derivatives with respect to roll angle are obtained from Figs.5–6 as a function of nominal Froude number. In the case that the roll angle is less than 5 degrees all hydrodynamic derivatives correspond to the existing experimental data with 5 degrees of heel angle. In the case that the roll angle is larger than 5 degrees and less than 20 degrees, the derivatives are calculated with a linear interpolation of the derivatives with 5degrees and that with 20 degrees. In the case that the roll angle is larger than 20 degrees, the derivatives are derived from Figs.8-9. Although the experimental results in Figs.8-9 are obtained for only two Froude numbers, we assume that these results are applicable to all Froude number cases.

## 5. NUMERICAL RESULTS

The comparisons between the numerical results with nonlinear heel-induced hydrodynamic forces and without them as well as existing free running model experiments [1] are conducted. In the model used in the previous paper [5] hydrodynamic forces are linearly calculated with existing experimental result shown in Fig. 6. The comparison in the case that the ship experiences a periodic motion is shown in Fig.13. Ship motions calculated with large-heel-induced hydrodynamic forces are almost same as those without them. However, the roll with this effect is slightly larger. The reason of this outcome can be explained as follows. In this case the roll amplitude is greater than 5 degrees. Thus, the heel-induced hydrodynamic roll moment here is larger than that linearly estimated, and results in larger roll motion. The comparison in the case that the ship suffers surf-riding, broaching and capsizing is shown in Fig.14. The mathematical model with nonlinear heel-induced hydrodynamic forces provides shorter capsizing time than that without them. This is because that the value of $K_\phi$' shown in Fig.5 is positive at high forward velocity where ship occurs surf-riding. In addition, at the final stage, yaw angular velocity rapidly increases because heel-induced yaw moment nonlinearly increases with roll angle. This result corresponds to the model experiment well. These results indicate that the effect of heel-induced hydrodynamic forces is not negligibly small at least for this subject ship.

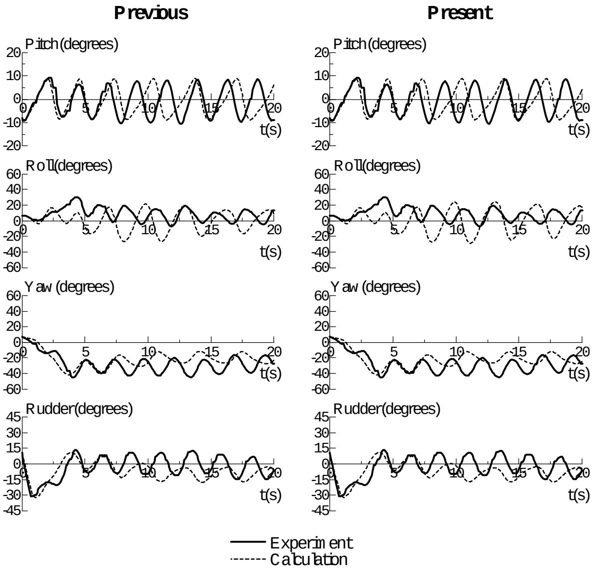


Fig.13 Comparisons between numerical results with and without the effect of nonlinear heel-induced hydrodynamic forces as well as the free running model experiment with $H/\lambda=1/10$, $\lambda/L=1.637$, $\chi_c=-30$ degrees and $F_n=0.3$

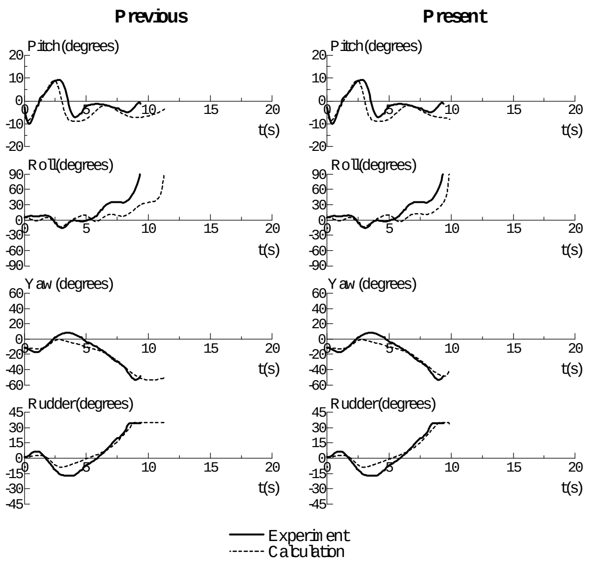


Fig.14 Comparisons between numerical results with and without the effect of nonlinear heel-induced hydrodynamic forces as well as the free running model experiment with $H/\lambda=1/10$, $\lambda/L=1.637$, $\chi_c=-10$ degrees and $F_n=0.43$

Comparison in boundaries of ship motion modes is shown in Fig.15. Procedure of this calculation can be found in the literature. [11] In the present model, the region of capsizing due to broaching and stable surf-riding become smaller than that with the previous model. The critical Froude numbers of ship capsizing with the present model are smaller than those with the previous model, especially in large auto pilot courses. These results suggest that the effect of the heel-induced hydrodynamic forces in still water is not small but more accurate mathematical modelling is required for more quantitative prediction.

Finally, in this research, we take just only heel-induced hydrodynamic forces in calm water into account and the numbers of the captive experiments are rather limited. Captive experiments for the heel-induced hydrodynamic forces in waves with the similar procedure are currently planed and more extensive experiments should be conducted for quantitative predictions.

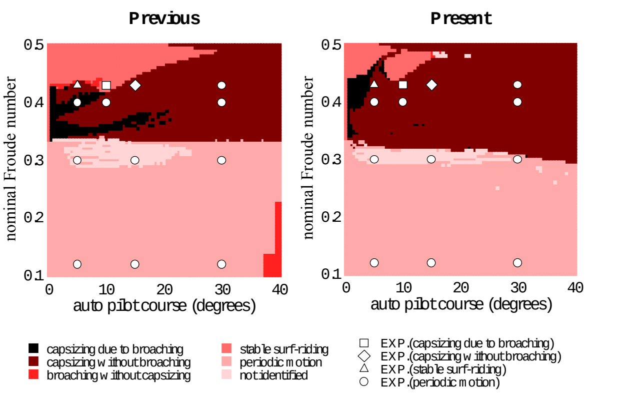


Fig.15 Comparison between numerical results with the nonlinear heel-induced hydrodynamic forces, those with previous mathematical model and the experimental results with $H/\lambda=1/10$, $\lambda/L=1.637$ and the initial periodic state for $F_n=0.1$, $\chi_c=0$ degrees

## 6. CONCLUSIONS

A mathematical model with nonlinear heel-induced hydrodynamic forces taken into account is provided with a new procedure of captive model experiment, and simulated results with this model are compared with the previous model and free running model experiments. As a result, the following conclusions are obtained:

1. The heel-induced hydrodynamic forces are not linear with respect to heel angle.

2. The mathematical model with heel-induced hydrodynamic forces in calm water taken into account provides the results in which ship is more easily to roll than previous model.

3. The present model provides smaller region of ship capsizing due to broaching and smaller one of stable surf-riding. At large heading angles the critical velocity of capsizing with present model is lower than that with previous model.

4. Nonlinear heel-induced hydrodynamic forces in waves should be taken into account with a similar method for obtaining a final conclusion.

## 7. ACKNOWLEDGEMENTS

This research was supported by a Grant-in Aid for Scientific Research of the Ministry of Education, Culture, Sports, Science and Technology of Japan (No. 13555270). The authors are grateful to Mr. S. Urano from Osaka University and Mr. J. N. Kang from Universities of Glasgow and Strathclyde for their help with the model experiments.

## 8. REFERENCES

[1]. Umeda, N. et al., 1999, Stability Assessment for Intact Ships in the Light of Model Experiments, *Journal of Marine Science and Technology,* 4:45-57.

[2]. Umeda, N. and Renilson, M.R., 2001, Benchmark Testing of Numerical Prediction on Capsizing of Intact Stability in Following and Quartering Seas, *Proceedings of the 5th International Workshop on Stability and Operational Safety of Ships*, Trieste, 6.1.1-10

[3]. Vassalos, D. et al., 2002, The Specialist Committee for the Prediction of Extreme Motions and Capsizing -Final Report and Recommendations to the 23rd ITTC-, *Proceedings of 23rd International Towing Tank Conference*, II:611-649.

[4]. Hashimoto, H. and Umeda, N., 2001, Importance of Wave effects on Manoeuvring Coefficients for Capsizing Prediction, *Proceedings of the 5th International Workshop on Stability and Operational Safety of Ships*, Trieste, 6.4.1-8.

[5]. Umeda, N. et al., 2002, Broaching Prediction in the Light of an Enhanced Mathematical Model with Higher Order Terms Taken into Account, *Journal of Marine Science and Technology,* 7:145-155.

[6]. Hashimoto, H. et al., 2002, Enhanced Approach for Broaching Prediction with Higher Order Terms Taken into Account, *Proceedings of the 6th International Workshop on Stability and Operational Safety of Ships,* New York.

[7]. Umeda, N. et al., 2000, Numerical Prediction of Extreme Motions and Capsizing for Intact Ships in Following/Quartering Seas, *Proceedings of the 4th Osaka colloquium on seakeeping performance of ships*, Osaka, 368-373.

[8]. Eda, H., 1980, Rolling and Steering Performance of High Speed Ships -Simulation Studies of Yaw-Roll-Rudder Coupled Instability-, *Proceedings of the 13th Symposium of Naval Hydrodynamics*, *J Soc Nav Archit Jpn*, 427-439.

[9]. Umead, N. and Renilson, M.R., 1992, Broaching -a Dynamic Behaviour of a Vessel in Following Seas-. *Wilson PA (ed) Manoeuvring and Control of Marine Craft*. Computational Mechanics Publications, Southampton, 533-543.

[10]. Umeda, N., 1999, Nonlinear Dynamics of Ship Capsizing due to Broaching in Following and Quartering Seas. *Journal of Marine Science and Technology,* 4: 16-26.

[11]. Umeda, N. and Hashimoto, H., 2002, Qualitative Aspects of Nonlinear Ship Motions in Following and Quartering Seas with High Forward Velocity, *Journal of Marine Science and Technology,* 6:111-121.