Importance of Wave Effects on Manoeuvring Coefficients for Capsizing Prediction

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SUMMARY

The wave effects on manoeuvring coefficients, as second order terms of capsizing prediction, were estimated with a slender body theory and compared with the existing results of captive model experiments. Then numerical simulations were carried out with these wave effects and without them and compared with the results of free running model experiments. The comparison demonstrated that the wave effects on derivatives of manoeuvring forces with respect to yaw rate and rudder angle are not so essential for capsizing prediction but those with respect to sway velocity can be essential. Since the wave effects on manoeuvring coefficients do not improve agreements between the numerical prediction and model experiment for capsizing, it is expected to develop a consistent numerical model that takes all second order terms into account.

NOMENCLATURE

a	wave amplitude
a_H	interaction factor between hull and rudder
A_R	rudder area
c	wave celerity
d	mean draft
f_α	rudder lifting slope coefficient
F_n	nominal Froude number
g	gravitational acceleration
GZ	righting arm
H	wave height
I_{xx}	moment of inertia in roll
I_{zz}	moment of inertia in yaw
J	advance coefficient of propeller
J_{xx}	added moment of inertia in roll
J_{zz}	added moment of inertia in yaw
k	wave number
K_p	derivative of roll moment with respect to roll rate
K_r	derivative of roll moment with respect to yaw rate
K_R	rudder gain
K_T	thrust coefficient of propeller
K_v	derivative of roll moment with respect to sway velocity
K_w	wave-induced roll moment
K_δ	derivative of roll moment with respect to rudder angle
K_δ^W	wave effect on derivative of roll moment with respect to rudder angle
K_ϕ	derivative of roll moment with respect to roll angle
l_R	correction factor for flow-straightening effect due to yaw rate
L	ship length between perpendiculars
m	ship mass
m_x	added mass in surge
m_y	added mass in sway
m_y^{2D}	2-dimensional added mass in sway
n	propeller revolution number
N_r	derivative of yaw moment with respect to yaw rate
N_r'	$N_r' = N_r/(\rho L^3 du/2)$
N_r^W	wave effect on derivative of yaw moment with respect to yaw rate
N_v	derivative of yaw moment with respect to sway velocity
N_v'	$N_v' = N_v/(\rho L^2 du/2)$
N_v^W	wave effect on derivative of yaw moment with respect to sway velocity
N_w	wave-induced yaw moment
N_δ	derivative of yaw moment with respect to rudder angle
N_δ^W	wave effect on derivative of yaw moment with respect to rudder angle
N_ϕ	derivative of yaw moment with respect to roll angle
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
u_w	wave particle velocity in x direction
v	sway velocity
v_w	wave particle velocity in y direction
w_p	effective propeller wake fraction
x_H	longitudinal position of centre of interaction force between hull and rudder
x_R	longitudinal position of rudder
X_w	wave-induced surge force
X_{rud}	rudder-induced surge force
Y	lateral force
ΔY	sectional lateral force
Y_r	derivative of sway force with respect to yaw rate
Y_r'	$Y_r' = Y_r/(\rho L^2 du/2)$
Y_r^W	wave effect on derivative of sway force with respect to yaw rate
Y_v	derivative of sway force with respect to sway velocity
Y_v'	$Y_v' = Y_v/(\rho L du/2)$
Y_v^W	wave effect on derivative of sway force with respect to sway velocity

Y_w	wave-induced sway force
Y_δ	derivative of sway force with respect to rudder angle
Y_δ^W	wave effect on derivative of sway force with respect to rudder angle
Y_ϕ	derivative of sway force with respect to roll angle
z_H	vertical position of centre of sway force due to lateral motions
χ	heading angle from wave direction
χ_c	desired heading angle for auto pilot
δ	rudder angle
ε_R	wake ratio between propeller and hull
ϕ	roll angle
Φ	velocity potential
γ_R	flow-straightening effect coefficient
κ_p	interaction factor between propeller and rudder
λ	wave length
θ	pitch angle
ρ	water density
ω	wave frequency
ξ_G	longitudinal position of centre of gravity from a wave trough
ζ_G	vertical distance between centre of gravity and still water plane
ζ_r	relative wave elevation for each section
ζ_w	wave elevation

1. INTRODUCTION

Since capsizing prediction in following and quartering seas is an important issue for ship safety, benchmark testing for intact stability has been conducted at ITTC[1].

Some mathematical models for capsizing in high-speed region, associated with surf-riding and broaching, have been proposed and compared with free running model experiments. In particular, a mathematical model by Umeda et al.[2-3] qualitatively well predicts such phenomena[4]. In this model, wave steepness, sway velocity and yaw rate are assumed to be small. Thus higher order terms of these small quantities are consistently neglected. As a result, this model considers ship resistance, propeller thrust, lateral righting moment, added inertia force, linear wave exciting forces and linear manoeuvring forces and neglects the second order wave forces, nonlinear manoeuvring forces in calm water and wave effect on the linear manoeuvring forces.

These higher order terms can be candidates of new elements for improving prediction accuracy. Among them mathematical models considering only nonlinear calm-water manoeuvring forces as a higher order term had been proposed by Renilson[5], Spyrou[6], de Kat[7] et al. but importance of these forces on capsizing prediction had not been clarified. Thus the authors[4] examined these effects by conducting comparisons between numerical results with and without the nonlinear calm-water manoeuvring forces and then confirmed these effects on capsizing prediction are rather small.

Hydrodynamic studies on the wave effects on linear manoeuvring forces had started with Hamamoto[8-10]. Then, Son and Nomoto[11] reported that there is a significant difference in stability index of ship lateral motion between a mathematical model with and without these effects. Since their prediction of these hydrodynamic forces is based on the results of PMM tests, we cannot directly apply their results into the present numerical model. Therefore, in this paper, firstly mathematical method for prediction of manoeuvring forces in following and quartering waves by a slender body theory is proposed and comparisons between numerical estimations and existing results of captive model experiments[10-13], such as PMM or CMT, are presented. Secondly we apply this hydrodynamic method into existing model by Umeda et al.[2-3] and compare with the original mathematical model for examining the importance of these effects on capsizing prediction. Because the encounter frequency is low for a ship running in following and quartering seas, we focus on the wave effects on manoeuvring damping forces and neglect the ones on added inertia forces.

2. MATHEMATICAL MODELLING

The numerical model of the surge-sway-yaw-roll motion was developed by Umeda & Renilson[2] and Umeda[3] for capsizing associated with surf-riding in quartering waves. (*Original model*) In cases of ship runs with relatively high forward velocity in following and quartering waves, the encounter frequency becomes very small. Thus, hydrodynamic forces acting on the ship consist mainly of lift components and wave-making components are negligibly small. Therefore, a manoeuvring mathematical model focusing on hydrodynamic lift components can be recommended for broaching.

To take the wave effect of manoeuvring forces into account, the authors modified the above-mentioned model. Two co-ordinate systems used here are shown in Fig.1: (1) a wave fixed with its origin at a wave trough, the ξ 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:

$$\mathbf{x} = (x_1, x_2, \cdots, x_8)^T = \{\xi_G/\lambda, u, v, \chi, r, \phi, p, \delta\}^T \tag{1}$$

$$\mathbf{b} = \{n, \chi_c\}^T \tag{2}$$

The modified dynamical system can be represented by the following state equation:

$$\dot{\mathbf{x}} = \mathbf{F}(\mathbf{x};\mathbf{b}) = \{f_1(\mathbf{x};\mathbf{b}), f_2(\mathbf{x};\mathbf{b}), \cdots, f_8(\mathbf{x};\mathbf{b})\}^T \tag{3}$$

where

$$f_1(\mathbf{x};\mathbf{b}) = \{u\cos\chi - v\sin\chi - c\}/\lambda \tag{4}$$

$$f_2(\mathbf{x};\mathbf{b}) = \{T(u;n) - R(u) + \underline{X_{rud}(\xi_G/\lambda, u, \chi, \delta; n)} + X_w(\xi_G/\lambda, \chi)\}/(m+m_x) \tag{5}$$

$$
\begin{aligned}
f_3(\mathbf{x};\mathbf{b}) = \{ & -(m+m_x)ur + Y_v(u;n)v \\
& + \underline{Y_v{}^W(\xi_G/\lambda,u,\chi;n)v} + Y_r(u;n)r \\
& + \underline{Y_r{}^W(\xi_G/\lambda,u,\chi;n)r} + Y_\phi(u)\phi \\
& + Y_\delta(u;n)\delta + \underline{Y_\delta{}^W(\xi_G/\lambda,u,\chi;n)\delta} \\
& + Y_w(\xi_G/\lambda,u,\chi;n)\}/(m+m_y)
\end{aligned} \tag{6}
$$

$$
f_4(\mathbf{x};\mathbf{b}) = r \tag{7}
$$

$$
\begin{aligned}
f_5(\mathbf{x};\mathbf{b}) = \{ & N_v(u;n)v + \underline{N_v{}^W(\xi_G/\lambda,u,\chi)v} \\
& + N_r(u;n)r + \underline{N_r{}^W(\xi_G/\lambda,u,\chi)r} \\
& + N_\phi(u)\phi + N_\delta(u;n)\delta \\
& + \underline{N_\delta{}^W(\xi_G/\lambda,u,\chi;n)\delta} \\
& + N_w(\xi_G/\lambda,u,\chi;n)/(I_{ZZ}+J_{ZZ})
\end{aligned} \tag{8}
$$

$$
f_6(\mathbf{x};\mathbf{b}) = p \tag{9}
$$

$$
\begin{aligned}
f_7(\mathbf{x};\mathbf{b}) = \{ & m_x z_H ur + K_v(u;n)v + K_r(u;n)r \\
& + K_P(u)p + K_\phi(u)\phi + K_\delta(u;n)\delta \\
& + \underline{K_\delta{}^W(\xi_G/\lambda,u,\chi;n)\delta} \\
& + K_w(\xi_G/\lambda,u,\chi;n) + mgGZ(\phi)\}/(I_{xx}+J_{xx})
\end{aligned} \tag{10}
$$

$$
f_8(\mathbf{x};\mathbf{b}) = \{-\delta - K_R(\chi-\chi_C) - K_R T_D r\}/T_E \tag{11}.
$$

Here the underlined parts are newly added to the original model.

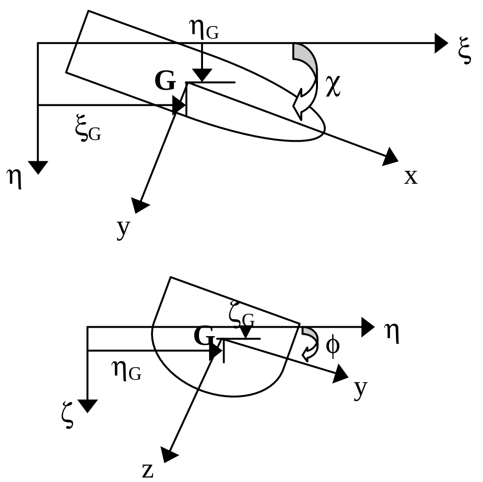


Fig.1. Co-ordinate systems

For the wave effect of linear manoeuvring forces, Hamamoto[8] and then Renilson[9] applied a slender body theory for lateral motions of a simplified hull form without a free surface condition. Later on Fujino et al.[10] utilised a high-speed slender body theory, which considers a free surface condition. In this paper the authors also develop a slender body theory but for an actual hull form, and ignore the free surface condition because the encounter frequency is too small for unsteady wave-making phenomena.

Within the theoretical framework of a slender body theory with a rigid-wall water surface condition[14], the sectional lateral force, $\Delta Y(x)$, can be calculated with the two-dimensional added-mass in sway $m_y{}^{2D}(x)$ as follows:

$$
\Delta Y(x) = -\left(\frac{\partial}{\partial t} - u\frac{\partial}{\partial x}\right)(v+xr)m_y{}^{2D}(x) \tag{12}.
$$

Then we consider an incident wave defined with the following elevation, ζ_W, and the velocity potential, Φ.

$$
\zeta_W = a\cos(kx\cos\chi - ky\sin\chi + k\xi_G) \tag{13}
$$

$$
\Phi = -ace^{-k\zeta}\sin k(x\cos\chi - y\sin\chi + \xi_G) \tag{14}.
$$

In case of a ship in waves, the added-mass can change because of relative wave elevation to the ship, ζ_r, and wave particle velocities, e.g. u_w and v_w, are added to flow velocities. These elements can be modelled as follows:

$$
\zeta_r(x,\xi_G,\chi) = \zeta_G(\xi_G,\chi) - x\theta(\xi_G,\chi) - \zeta_W(x,\xi_G,\chi) \tag{15}
$$

$$
\begin{aligned}
u_w &= \frac{\partial\Phi}{\partial x} \\
&= -a\omega e^{-k\zeta}\cos\chi\cos k(x\cos\chi - y\sin\chi + \xi_G)
\end{aligned} \tag{16}
$$

$$
\begin{aligned}
v_w &= \frac{\partial\Phi}{\partial y} \\
&= a\omega e^{-k\zeta}\sin\chi\cos k(x\cos\chi - y\sin\chi + \xi_G)
\end{aligned} \tag{17}.
$$

Here the heave motion, ζ_G, and pitch motion, θ, can be calculated as the limit of the solution set of a strip theory at zero encounter frequency[15].

Thus, the sectional lateral force in waves can be calculated as

$$
\begin{aligned}
\Delta Y = & -\{\dot{v} + x\dot{r} - \dot{v}_w\}m_y{}^{2D}(x,\zeta_r) \\
& + (u-u_w)\left(r - \frac{\partial v_w}{\partial x}\right)m_y{}^{2D}(x,\zeta_r) \\
& + (u-u_w)(v+xr-v_w)\frac{\partial}{\partial x}m_y{}^{2D}(x,\zeta_r)
\end{aligned} \tag{18}.
$$

Then, integrating the sectional force along the ship, the total lateral force acting on hull can be obtained as

$$
\begin{aligned}
Y = & \int_L \Delta Y dx \\
= & -\int_L (\dot{v} + x\dot{r})m_y{}^{2D}(x,0)dx \\
& - \int_L (\dot{v} + x\dot{r})\zeta_r(x,\xi_G,\chi)\frac{\partial}{\partial z}m_y{}^{2D}(x,0)dx \\
& + \int_L \dot{v}_w m_y{}^{2D}(x,0)dx \\
& - \left[uv_w m_y{}^{2D}(x,0)\right]_L \\
& + u\left[(v+xr)m_y{}^{2D}(x,0)\right]_L \\
& - 2r\int_L u_w m_y{}^{2D}(x,0)dx \\
& + u\left[(v+xr)\zeta_r(x,\xi_G,\chi)\frac{\partial}{\partial z}m_y{}^{2D}(x,0)\right]_L
\end{aligned} \tag{19}.
$$

$$-\left[u_w(v+xr)m_y^{2D}(x,0)\right]_L + \int_L \frac{\partial u_w}{\partial x}(v+xr)m_y^{2D}(x,0)dx$$

This expression for the hull force and similar formula of the rudder-induced force enables us to provide the wave effect on Y_v and Y_r as follows:

$$\begin{aligned} Y_v^W(\xi_G/\lambda,u,\chi) &= u\left[\zeta_r(x,\xi_G)\frac{\partial}{\partial z}m_y^{2D}(x,0)\right]_L \\ &-\left[u_w(x,\xi_G,\chi)m_y^{2D}(x,0)\right]_L \\ &+\int_L \frac{\partial u_w(x,\xi_G,\chi)}{\partial x}m_y^{2D}(x,0)dx \\ &+\frac{3}{2}(1+a_H)\rho A_R f_\alpha \gamma_R u_w(x,\xi_G,\chi) \end{aligned} \quad (20)$$

$$\begin{aligned} Y_r^W(\xi_G/\lambda,u,\chi) &= u\left[x\zeta_r(x,\xi_G)\frac{\partial}{\partial z}m_y^{2D}(x,0)\right]_L \\ &-\left[u_w(x,\xi_G,\chi)xm_y^{2D}(x,0)\right]_L \\ &-2\int_L u_w(x,\xi_G,\chi)m_y^{2D}(x,0) \\ &+\int_L \frac{\partial u_w(x,\xi_G,\chi)}{\partial x}xm_y^{2D}(x,0)dx \\ &+\frac{3}{2}(1+a_H)\rho A_R f_\alpha \gamma_R l_R u_w(x,\xi_G,\chi) \end{aligned} \quad (21).$$

The first term of each formula indicates the effect of relative wave elevation and the rest does the effect of wave particle velocity.

Similarly, N_v^W and N_r^W can be obtained as follows:

$$\begin{aligned} N_v^W(\xi_G/\lambda,u,\chi) &= u\left[x\zeta_r(x,\xi_G)\frac{\partial}{\partial z}m_y^{2D}(x,0)\right]_L \\ &-\int_L u\zeta_r(x,\xi_G)\frac{\partial}{\partial z}m_y^{2D}(x,0)dx \\ &-\left[xu_w(x,\xi_G,\chi)m_y^{2D}(x,0)\right]_L \\ &+\int_L \frac{\partial u_w(x,\xi_G,\chi)}{\partial x}xm_y^{2D}(x,0)dx \\ &+\int_L u_w(x,\xi_G,\chi)m_y^{2D}(x,0)dx \\ &+\frac{3}{2}(x_R+a_H x_H)\rho A_R f_\alpha \gamma_R u_w(x,\xi_G,\chi) \end{aligned} \quad (22)$$

$$\begin{aligned} N_r^W(\xi_G/\lambda,u,\chi) &= u\left[x^2\zeta_r(x,\xi_G)\frac{\partial}{\partial z}m_y^{2D}(x,0)\right]_L \\ &-\int_L ux\zeta_r(x,\xi_G)\frac{\partial}{\partial z}m_y^{2D}(x,0)dx \\ &-\left[x^2u_w(x,\xi_G,\chi)m_y^{2D}(x,0)\right]_L \\ &+\int_L \frac{\partial u_w(x,\xi_G,\chi)}{\partial x}x^2m_y^{2D}(x,0)dx \\ &+\int_L xu_w(x,\xi_G,\chi)m_y^{2D}(x,0)dx \\ &+\frac{3}{2}(x_R+a_H x_H)\rho A_R f_\alpha \gamma_R l_R u_w(x,\xi_G,\chi) \end{aligned} \quad (23).$$

We can estimate manoeuvring coefficients in waves by adding these changes into the calm-water value obtained by model experiment.

Furthermore, the wave effects on Y_δ and N_δ can be calculated by

$$\begin{aligned} Y_\delta^W(\xi_G/\lambda,u,\chi) &= (1+a_H)\frac{\rho}{2}A_R f_\alpha\{2\varepsilon_R(1-w_p)u \\ &\times\sqrt{1+\kappa_p\frac{8K_T}{\pi J^2}}u_w(x,\xi_G,\chi) \end{aligned} \quad (24)$$

$$\begin{aligned} N_\delta^W(\xi_G/\lambda,u,\chi) &= (x_R+a_H x_H)\frac{\rho}{2}A_R f_\alpha\{2\varepsilon_R(1-w_p)u \\ &\times\sqrt{1+\kappa_p\frac{8K_T}{\pi J^2}}u_w(x,\xi_G,\chi) \end{aligned} \quad (25).$$

These mean the change of rudder-induced forces is due to the change of wave particle velocity.

3. PREDICTIONS OF HULL MANOEUVRING COEFFICIENTS IN WAVES

Comparisons between numerical results and experimental data in wave effect on the hull manoeuvring coefficients were carried out to confirm the accuracy of a prediction formula, (20)-(23). Firstly for the RR17 trawler, whose body plan is given in Fig.2, comparisons between the numerical results and experimental data are shown in Fig.3. Here the wave steepness is 1/16, the wave length-to-ship length ratio is 1.11. The experimental values were obtained through PMM tests in waves at Osaka University by Nishimura[12]. The calculated values of N_r agree well with the measured ones. The calculations of Y_r and N_v shows only qualitative agreement with the experiments and those of Y_v are acceptable only in amplitude. Secondly, for the SR108 container ship whose body plan is given in Fig.4, comparisons are shown in Fig.5. The experimental values were obtained by Son and Nomoto[11] at Osaka University with the same experimental procedure as the trawler. Here the calculations show reasonably good agreement except for Y_v.

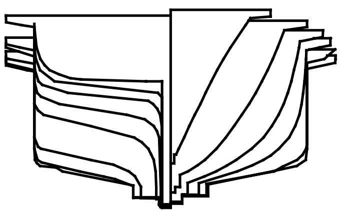


Fig.2 Body plan of the RR17 trawler

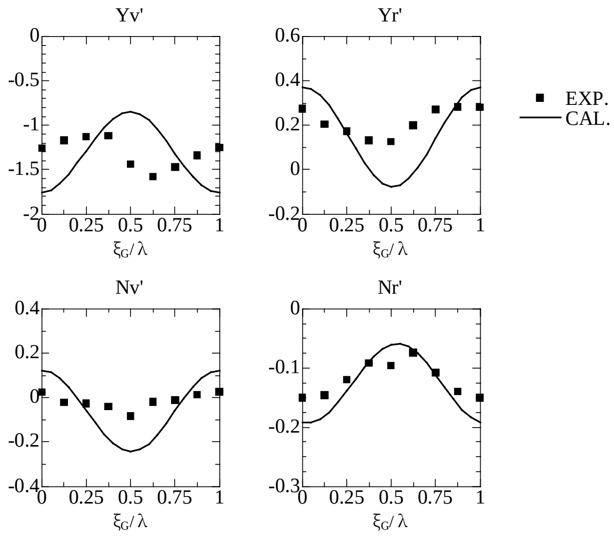


Fig.3 Comparison of manoeuvring coefficients between calculation and experiment[12] for the RR17 trawler with H/λ=1/16, λ/L=1.11, χ=0 degrees and F_n=0.447

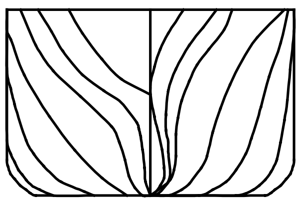


Fig.4 Body plan of the SR108 container ship

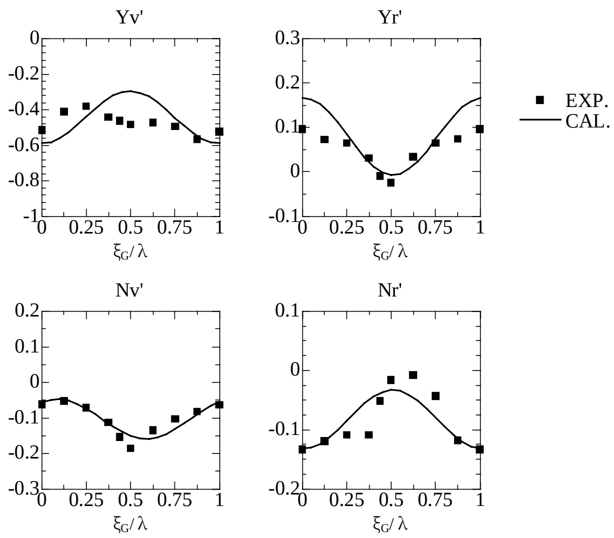


Fig.5 Comparison of manoeuvring coefficients between numerical results and experimental data[11] for container ship with H/λ=1/16, λ/L=1.1, χ=0 degrees and F_n=0.443

For the 135 gross tones purse seiner, known as the ITTC Ship A-2, the captive model experiments were recently carried out with the circular motion technique of a X-Y towing carriage of a seakeeping and manoeuvring basin of National Research Institute of Fisheries Engineering (NRIFE) by Matsuda et al[13]. Body plan of this ship are shown in Fig.6. Here the wave steepness of 1/50, the wave length-to-ship length ratio of 1.5, the non-dimensional yaw rate of 0.2 and the heading angle of 0 and 30 degrees were used. As shown in Figs.7-8, the calculated values of Y_r and N_r provide similar tendency of the measured ones. The measured values here were obtained as the balance by subtracting all other measured forces in Eqs.(6) and (8) from the total measured forces. Thus, these results suggest that the expressions of Eqs.(6) and (8) are reasonable.

As a whole, it is concluded that the prediction formulas of Eqs.(20)-(23) can explain the wave effect on N_r quantitatively, those on Y_r and N_v qualitatively and that on Y_v in amplitude.

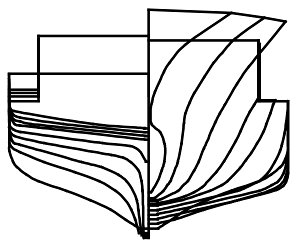


Fig.6 Body plan of the ITTC Ship A-2

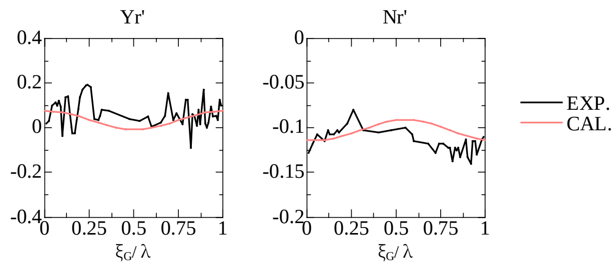


Fig.7 Comparison of Y_r' and N_r' between calculation and experiment[13] for the ITTC Ship A-2 with H/λ=1/50, λ/L=1.5, χ=0 degrees and F_n=0.4

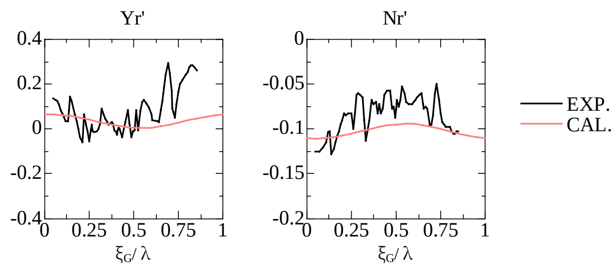


Fig.8 Comparison of Y_r' and N_r' between calculation and experiment[13] for the ITTC Ship A-2 with H/λ=1/50, λ/L=1.5, χ=30 degrees and F_n=0.4

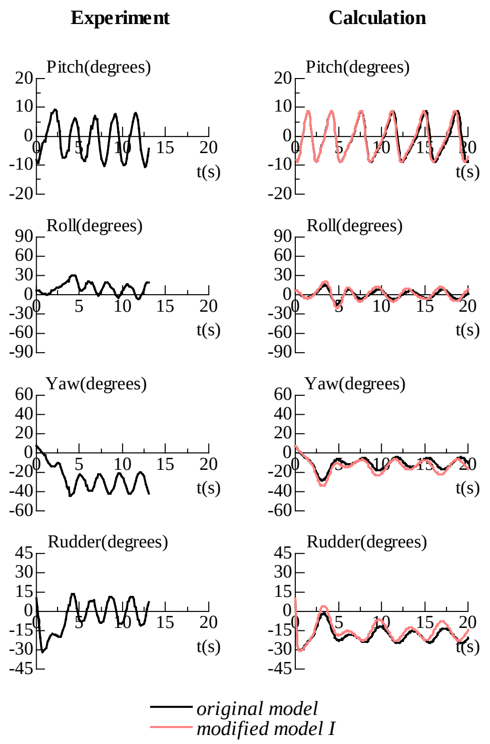
4. PREDICTIONS OF EXTREME SHIP MOTIONS WITH AND WITHOUT WAVE EFFECTS ON MANOEUVRING COEFFICIENTS

Numerical calculations of extreme motions for the ITTC Ship A-2 were carried out by the numerical model with the wave effects on manoeuvring coefficients and that without them and compared also with the free running model experiments at a seakeeping and manoeuvring basin of NRIFE[16]. Here the initial conditions of numerical runs were adjusted to be equal to those in the experiments.

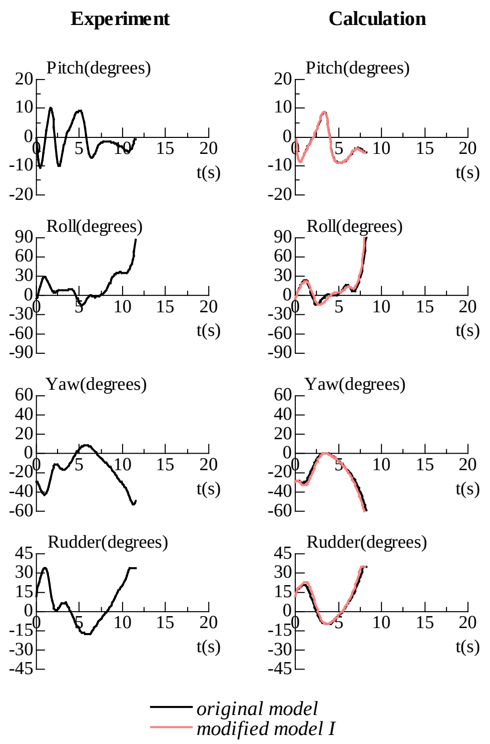
Firstly, the mathematical model only with the wave effects on Y_δ , N_δ and K_δ as higher order terms, (*Modified model I*), was used for numerical calculation. As shown in Fig.9, there is no significant difference between the original and extended models. Therefore, the wave effects on Y_δ , N_δ and K_δ can be regarded as negligibly small.

Secondly, the mathematical model with the wave effects on Y_r, N_r, Y_δ, N_δ and K_δ as higher order terms, (*Modified model II*), was adopted. As can been seen in Fig.10(a), in case of a ship experiencing a stable periodic motion, the new numerical result is almost same as the original numerical result. In Fig.10(b), in case of capsizing due to broaching, it is also rather same as the original calculation. Therefore, we can conclude that the changing of Y_r and N_r in waves is not so important for capsizing prediction in following and quartering seas.

Finally, numerical calculation with mathematical model considering the wave effects on all manoeuvring coefficients, (*Modified model III*), was carried out. In Fig.11(a), in case of periodic motion, absolute value of the average yaw angle is larger than that of the original one and closer to the value of model experiment. This is because some constant yaw moment appears as a result of the product of time-varying manoeuvring coefficient and periodic sway velocity. Some improvements in the pitch and rudder angle are also found. On the other hand, in case of capsizing due to broaching which is shown in Fig.11(b) the yaw angle is rapidly increasing up to positive value and continued to increase despite the opposite steering effort and finally capsized due to this broaching. In this case, capsizing occurred with positive yaw angle while with negative angle in experiment. Because yaw motion here is very different from original numerical model, we examined the components of yaw moment and found manoeuvring force relates to N_v is very large in positive direction and that is very small in original numerical model. This is because the value of manoeuvring forces related to N_v in still water is too small to change ship motion. However, it should be noted that the prediction accuracy for N_v is generally not so satisfactory. Thus, further effort to improve prediction of N_v is necessary. It is also noteworthy that this paper has examined some of higher order terms only and other terms, such as the wave effects of roll moment, have not yet been examined. The final conclusion on the agreements between the experiments and numerical predictions should have been provided only after a consistent second order mathematical model, which include all second order terms, will be established.

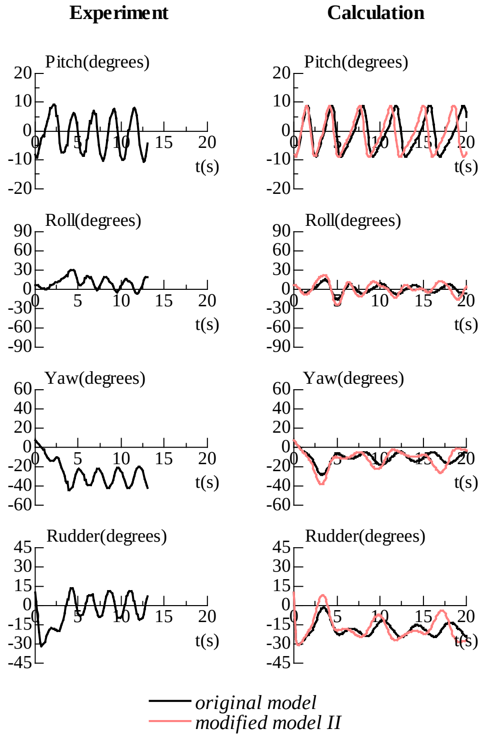


(a) with H/λ=1/10, λ/L=1.637, F_n=0.3 and χ_c=-30 degrees

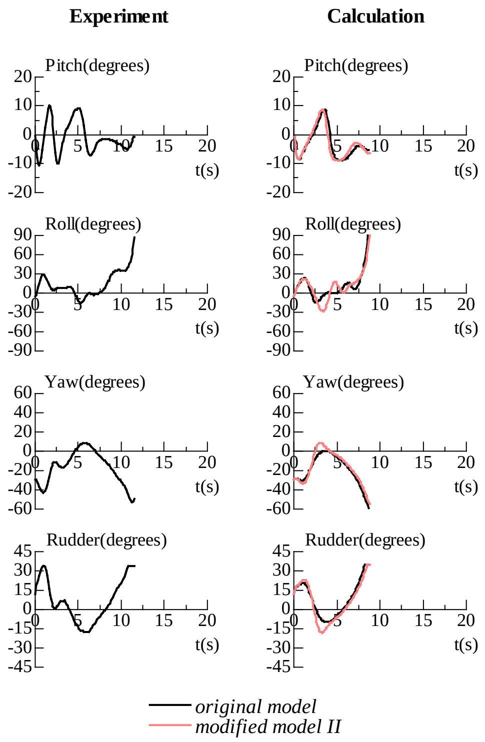


(b) with H/λ=1/10, λ/L=1.637, F_n=0.43 and χ_c=-10 degrees

Fig.9 Comparison between the numerical results with the mathematical model considering the wave effect on Y_δ, N_δ and K_δ, those with original mathematical model and the experimental results

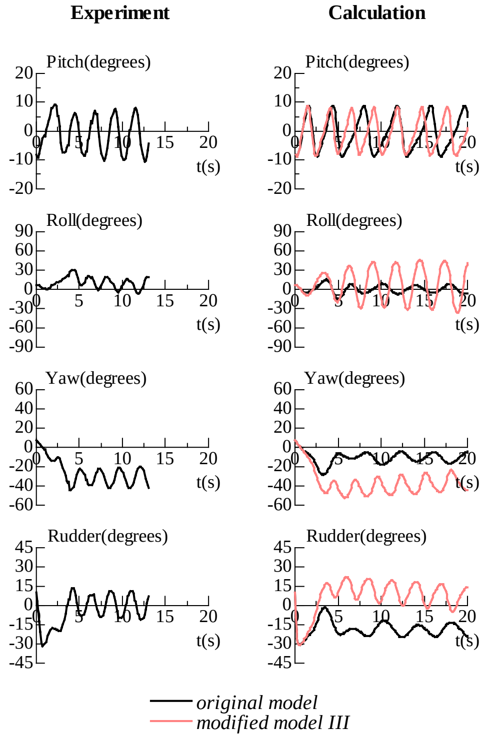


(a) with H/λ=1/10, λ/L=1.637, F_n=0.3 and χ_c=-30 degrees

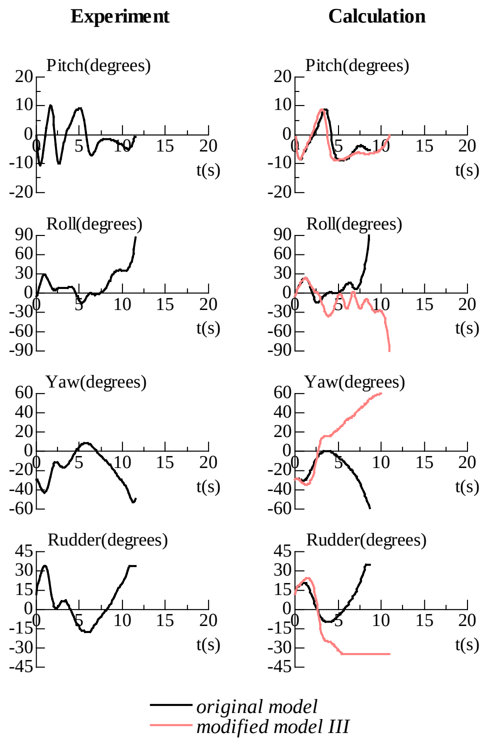


(b) with H/λ=1/10, λ/L=1.637, F_n=0.43 and χ_c=-10 degrees

Fig.10 Comparison between the numerical results with the mathematical model considering changing of Y_r, N_r, Y_δ, N_δ and K_δ, those with original mathematical model and the experimental results



(a) with H/λ=1/10, λ/L=1.637, F_n=0.3 and χ_c=-30 degrees



(b) with H/λ=1/10, λ/L=1.637, F_n=0.43 and χ_c=-10 degrees

Fig.11 Comparison between the numerical results with the mathematical model considering the wave effects on all manoeuvring coefficients, those with original mathematical model and the experimental results

5. CONCLUSIONS

The following conclusions can be drawn:

1. The wave effects on the derivatives of manoeuvring forces with respect to yaw rate can be fairly well predicted by a slender body theory, while those respect to sway velocity can be done only in amplitude.
2. The wave effects on the derivatives of manoeuvring forces with respect to yaw rate and rudder angle are not so important for capsizing prediction, while those respect to sway velocity can be significant.
3. The numerical model without the wave effects on the manoeuvring coefficients currently provides better prediction for extreme motions and capsizing than that with them.
4. It is expected to develop a consistent numerical model that takes all second order terms into account.
5. It is also important to improve prediction accuracy for the wave effects on the derivatives of manoeuvring forces with respect to sway velocity.

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