Effects of Ship Motion on Ship Maneuvering in Waves

Min-Guk Seo, Yonghwan Kim
Seoul National University, Seoul, Korea

1. Introduction

Ship maneuvering performance is typically predicted in calm water conditions. This provides very valuable information at the initial ship design stage. However, since the ship always sails in waves, the maneuvering performance of the ship in seaway may be significantly different from calm water condition. Therefore, if the effect of waves and the corresponding motion responses can be included in mathematical model, the estimation will be much more reliable.

In order to predict maneuvering performance of ship in waves, some simplified mathematical models have been developed by several researchers. McCreight(1986) developed a nonlinear maneuvering model in waves, which the hydrodynamic force related to wave-induced motion such as wave exciting forces, added mass and wave damping are evaluated in a body-fixed coordinate system by using the strip method. Fang et al.(2005) developed a mathematical model to calculate the hydrodynamic forces depending on encounter frequency in time domain simulation. However, these models did not consider the 2nd-order wave drift forces. Recently, the 2nd-order wave effect was considered more accurately by Skejic and Faltinsen(2008). In order to calculate the 2nd-order wave drift force, they proposed a two-time-scale model that separated low-frequency motion(maneuvering motion) and high-frequency motion(seakeeping motion).

The above methods adopted 2D strip method to calculate wave induced motion. Recently, Lin(2006) estimated the ship maneuvering performance in waves using a 3D panel method. The nonlinear ship motion program, LAMP(Large Amplitude Motion Program), was extended to ship maneuvering problem.

In the present study, maneuvering performance in waves is calculated using the time-domain nonlinear ship motion program WISH(Wave Induced load and SHip motion analysis) which applies a B-spline Rankine panel method. In this study, WISH has been extended to two main parts: the extensions to large lateral motions and the integration of seakeeping and maneuvering problems. To this end, the 2nd-order wave drift force is calculated using direct pressure integration method, and the MMG model is cooperated with the seakeeping model.

The developed computer program is verified through the comparison with published experiment data, e.g. turning test of S-175 containership in calm water and in waves. Computational results show good correspondence with the experiment.

2. Theoretical and Computational Background

When the vessel is traveling with non-constant speed in waves, the problem becomes more complicated than conventional seakeeping problems. Although the principal forms of boundary value problem are same with conventional equations, those should include the temporal and spatial variations due to the change of heading speed and angle. Also, to solve this boundary value problem, the strong influences of nonlinear viscous component have to be considered.

In order to solve maneuvering problem in waves, the present study uses two coordinate systems. One is a space-fixed coordinate system $\vec{X}=(X,Y,Z)$ with the positive Z-axis pointing upwards, and the other is a body-fixed coordinate system $\vec{x}=(x,y,z)$ which translates with forward speed, u_0, slip speed, v_0, and rotates with rotation, r_0.

2.1 Seakeeping Problem

Ship motion sailing in waves can be decomposed into the two kind of motion: wave induced motion regarded as high frequency motion and maneuvering motion regarded as low frequency motion. Maneuvering motion is slow varying compared with wave induced motion, therefore the two motion equations are treated separately.

In the case of wave-induced motion, the adoption of potential theory is a typical approach. Under the assumption of inviscid, incompressible flow with irrotational motion, velocity potential ϕ can be defined and decomposed into multiple components, i.e. basis flow, incident wave, and disturbed flow, along with wave elevation.

$$\phi(\vec{x},t)=-\vec{U}\cdot\vec{x}+\phi_I(\vec{x},t)+\phi_d(\vec{x},t) \tag{1}$$

$$\zeta(\vec{x},t)=\zeta_I(\vec{x},t)+\zeta_d(\vec{x},t) \tag{2}$$

where $\vec{U}\cdot\vec{x}$ indicates uniform flow potential and ϕ_I, ζ_I are the incident velocity potential and wave elevation. In addition, ϕ_d , ζ_d are the disturbed component of potential and elevation. Then, the well-known linearized boundary value problem is as follows:

$$\nabla^2\phi=0 \quad \text{in fluid domain} \tag{3}$$

$$\frac{\partial\phi_d}{\partial n}=\sum_{j=1}^{6}\left(\frac{\partial\xi_j}{\partial t}n_j+\xi_j m_j\right)-\frac{\partial\phi_I}{\partial n} \quad \text{on body surface} \tag{4}$$

$$(m_1,m_2,m_3)=0,$$

$$(m_4,m_5,m_6)=(-Vn_z,Un_z,-Un_y+Vn_x)$$

$$\frac{\partial \zeta_d}{\partial t} - \vec{U}\cdot\nabla\zeta_d = \frac{\partial \phi_d}{\partial z} \quad \text{on} \quad z=0 \tag{5}$$

$$\frac{\partial \phi_d}{\partial t} - \vec{U}\cdot\nabla\phi_d = \frac{\partial}{\partial t}(\vec{U}\cdot\vec{x}) - g\zeta_d \quad \text{on} \quad z=0 \tag{6}$$

where

$$\vec{U} = U\vec{i} + V\vec{j} = (u_0 - yr_0)\vec{i} + (v_0 + xr_0)\vec{j}$$
$$\vec{\delta} = \vec{\xi}_T + \vec{\xi}_R \times \vec{x}.$$

$\vec{\delta}$ and ζ are ship displacement and wave elevation. m_i is the m-term which contains an interaction term between steady and unsteady solutions.

The ship motion can be obtained by solving the equation of motion such as

$$[M_{jk}]\{\ddot{\xi}_k\} = \{F_{F.K.j}\} + \{F_{H.D.j}\} + \{F_{Res.j}\} \tag{7}$$

where $[M_{jk}]$ is the mass matrix of ship, $\{F_{F.K.j}\}$, $\{F_{H.D.j}\}$, $\{F_{Res.j}\}$ are Froude-Krylov, hydrodynamic and restoring forces, respectively.

2.2 Maneuvering Problem

In the ship maneuvering problem, 4-DOF motions are considered in the space-fixed coordinate system. Modular-type equations are used, and these equations of motion are expressed as follow:

$$\begin{aligned} m(\dot{u}_0 - v_0 r_0) &= X_H + X_P + X_R + X_W \\ m(\dot{v}_0 + u_0 r_0) &= Y_H + Y_R + Y_W \\ I_{xx}\dot{p}_0 &= K_H + K_R + K_W \\ I_{zz}\dot{r}_0 &= N_H + N_R + N_W \end{aligned} \tag{8}$$

where X, Y, K, N represent surge, sway, roll and yaw directional component, and H, P, and R written as subscripts of X, Y, K, and N denote the hydrodynamic forces on the ship hull, propeller, and rudder, respectively. In addition, subscript W denotes the 2nd-order wave drift force which should be obtained from the seakeeping problem. The hull force consists of linear and nonlinear components due to motion, turning, resistance and so on. Some part of the hull force is considered by potential theory described above. The other parts of the hull force components can be obtained from some empirical formulae or model test. The propeller and rudder force can be obtained from empirical formulae.

2.3 Interaction between Maneuvering and Seakeeping

To solve the two problems at the same time, firstly ship velocity and position are calculated at maneuvering module. Then these values are transferred to seakeeping module. In the seakeeping module, the hydrodynamic forces and motion responses are obtained by using by those. Then the 2nd-order drift forces and hydrodynamic forces are transferred to maneuvering module to set up the equation of motion for maneuvering. This cycle is continued during simulation.

The mean drift force considered in this study is the component from the linear solution, i.e. mean drift force. However, it should be mentioned that this force varies in time since the heading angle and encounter frequency change during maneuvering. That is, a new formulation is needed for such space- and time-varying effects, and the following equation is derived and applied in this study.

$$\begin{aligned} \vec{F}_W = &\ \rho g \int_{WL} \frac{1}{2}\left(\eta - (\xi_3 + \alpha_1 y - \alpha_2 x)\right)^2 \cdot \vec{n}dl \\ &- \rho\iint_{S_B} g(\bar{z} + Z_0)\cdot\vec{n}_2 dS \\ &- \rho\iint_{S_B} \frac{1}{2}\nabla(\phi_I + \phi_d)\cdot\nabla(\phi_I + \phi_d)\cdot\vec{n}dS \\ &- \rho\iint_{S_B} g(\xi_3 + \alpha_1 y - \alpha_2 x)\cdot\vec{n}_1 dS \\ &- \rho\iint_{S_B}\left(\frac{\partial(\phi_I + \phi_d)}{\partial t} - \vec{U}\cdot\nabla(\phi_I + \phi_d)\right)\cdot\vec{n}_1 dS \\ &- \rho\iint_{S_B}\vec{\delta}\cdot\nabla\left[\frac{\partial(\phi_I + \phi_d)}{\partial t} - \vec{U}\cdot\nabla(\phi_I + \phi_d)\right]\cdot\vec{n}dS \end{aligned} \tag{9}$$

where

$$\vec{n}_1 = \begin{Bmatrix} \vec{\xi}_R \times \vec{n} \\ \vec{\xi}_T \times \vec{n} + \vec{\xi}_R \times (\vec{x}\times\vec{n}) \end{Bmatrix}, \quad \vec{n}_2 = \begin{Bmatrix} H\vec{n} \\ H(\vec{x}\times\vec{n}) + \vec{\xi}_T \times (\vec{\xi}_R \times \vec{n}) \end{Bmatrix}$$

$$H = \frac{1}{2}\begin{bmatrix} -(\xi_5^2 + \xi_6^2) & 0 & 0 \\ 2\xi_4\xi_5 & -(\xi_4^2 + \xi_6^2) & 0 \\ 2\xi_4\xi_6 & 2\xi_5\xi_6 & -(\xi_4^2 + \xi_5^2) \end{bmatrix}$$

2.4 Numerical Method

To solve the seakeeping problem, a three-dimensional Rankine panel method is applied. Particularly, WISH program which was developed under the support of Korean shipbuilding industry has been extended to maneuvering problem. The maneuvering terms have been considered by using MMG model. Some terms in MMG model, which are related to seakeeping problem, have been treated by WISH. By doing so, those cannot be doubled and more accurate prediction is possible.

3. Numerical Results and Discussion

In order to validate numerical results, the turning tests of S-175 containership in calm water and in waves are performed and compared with the experimental data obtained by Yasukawa and Nakayama(2006). The principal particulars of S-175 containership applied in these test are summarized in Table 1, and an example of solution panels is shown in Fig. 1.

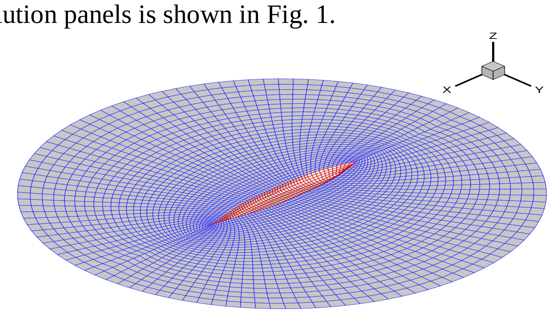


Fig. 1 Example of solution grids for S-175 containership

Table 1 Principal Particulars of S-175 containership

Model	**S-175**
Hull particulars	
Length, *Lpp*	175.0 *m*
Breadth, *B*	25.4 *m*
Draught, *d*	9.5 *m*
Displacement	24,739 ton
Propeller particulars	
Diameter, D_P	6.507 *m*
Pitch/Diameter ratio, *p*	0.73
Rudder particulars	
Area, A_R	32.46 m^2
Aspect ratio,	1.83

3.1. Turning Test Result in Calm Water

The comparison of turning trajectories in calm water is shown in Fig.2. In this test, initial velocity of the ship is 6.212m/s (Fn = 0.15), rudder angle is ±35 deg and propeller revolution is 1.42 rps. The propeller revolution is set up to accomplish the ship speed 6.212 m/s (Fn = 0.15) in still water. Fig.2 shows that the computational results well agree with the experimental result.

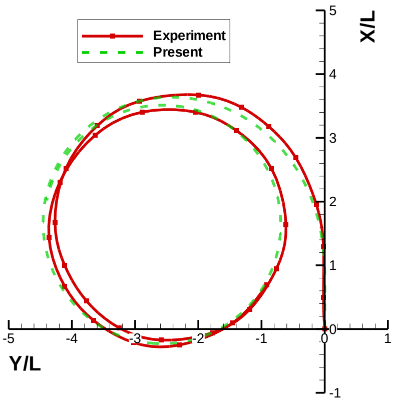


Fig. 2 Comparison of turning trajectories in calm water

3.2. Turning Test Result in Regular Wave

Head sea($\chi = 180°$) and beam sea($\chi = 90°$) cases are considered when the ratios of wave length to ship length (λ / L) are 0.7, 1.0, and the height of incident wave is 3.5m, i.e. $H_W / L = 0.02$. When the trough of incident wave passes midship, the ship rudder starts steering.

Wave contours around S-175 containership during starboard turning in waves are shown in Fig. 3. These figures show that diffracted wave patterns are changed as the ship is turning.

Figs. 4 and 5 show starboard turning trajectories in regular waves when wave direction to the ship is 180 deg and 90 deg, respectively, when the ratios of wave length to ship length(λ / L) are 0.7 and 1.0. As shown in the figures, when wave length is short, the drift distance is large. As easily understood, this is because lateral drift force and yaw drift moment become large in short wave length.

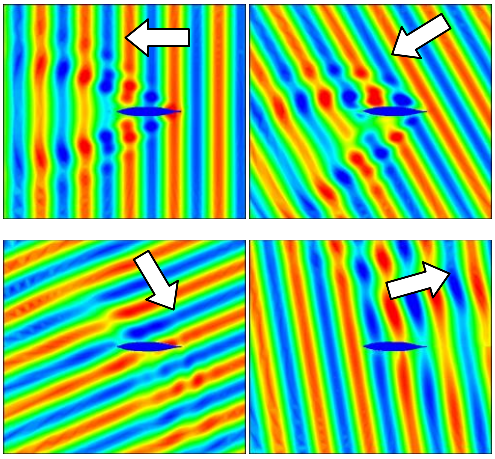
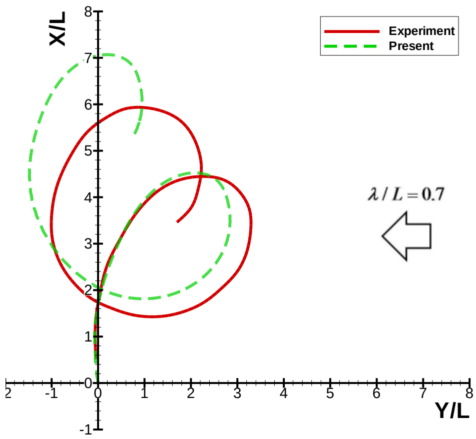
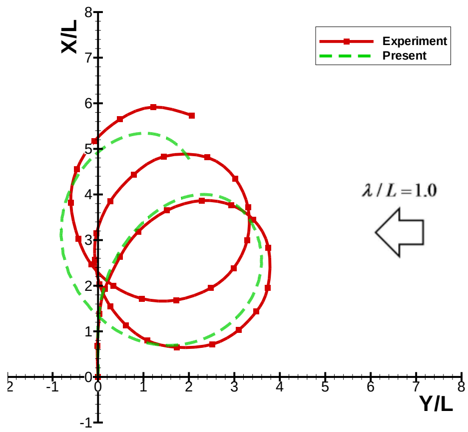


Fig. 3 Wave contours of turning test in waves ($\lambda / L = 0.7$, $\chi = 180°$, $\delta = -35°$)



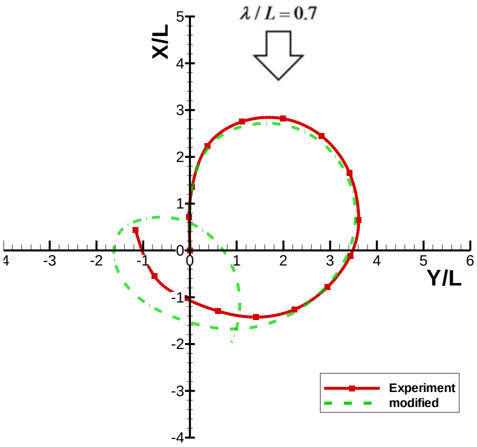
(a) $\lambda / L = 0.7$



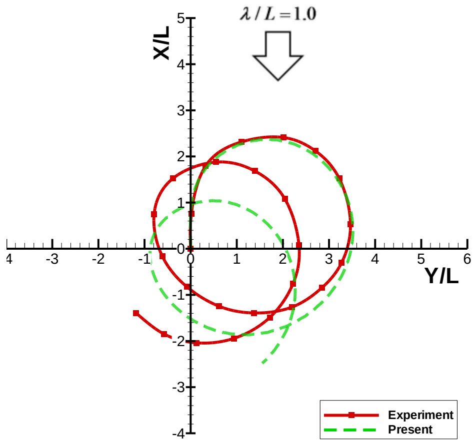
(b) $\lambda / L = 1.0$

Fig. 4 Comparison of turning trajectories in regular waves($\chi = 90°$, $\delta = -35°$)

Besides, the turning trajectories are moved in both the horizontal and perpendicular directions with respect to wave progress direction. These tendencies are shown in the test results conducted by Ueno et al (2003). The trajectories of numerical computation roughly agree with the experiment, although the trajectories of computation are more drift than those of experiment. The reason of this maybe comes from that wave drift force is over/under estimated during simulation.



(a) $\lambda / L = 0.7$



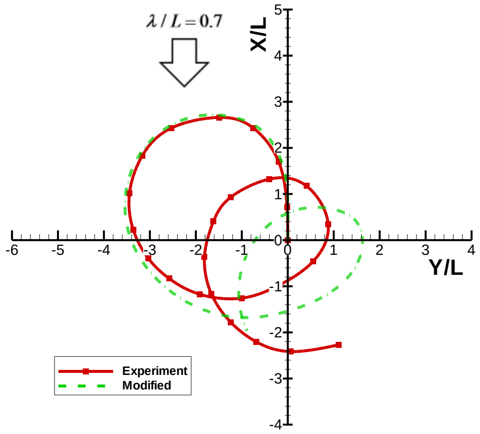
(b) $\lambda / L = 1.0$

Fig. 5 Comparison of turning trajectories in regular waves($\chi = 180°$, $\delta = -35°$)

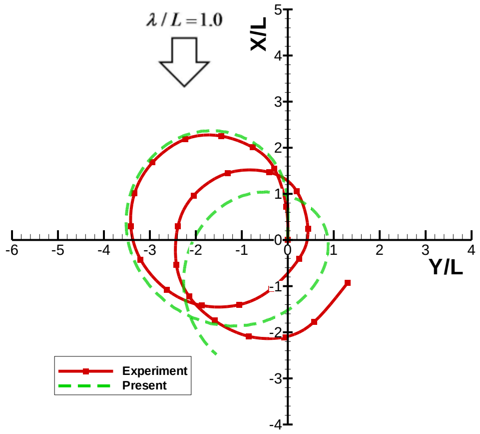
The comparisons of port turning trajectories in regular waves are shown in Fig.6 at head sea. Port turning trajectories show the similar tendency of drift magnitude and direction.

4. Conclusions

In the present study, analysis on ship maneuvering performance in waves by using a time-domain Rankine panel method is conducted. To this end, seakeeping and maneuvering problems are coupled and solved simultaneously. Also the 2nd-order wave drift force is calculated using a direct pressure integrated method. In order to validate present method, turning tests with S-175 containership in calm water and in incident waves are computed, and the simulation results are compared with experimental data. It is shown that, although there are some needs for improvement, the present method can roughly capture the maneuvering performance in waves.



(a) $\lambda / L = 0.7$



(b) $\lambda / L = 0.7$

Fig. 6 Comparison of turning trajectories in regular waves($\chi = 180°$, $\delta = 35°$)

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