Prediction of Ship Operation Performance in Waves by Seakeeping-Maneuvering Coupled Analysis

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1 INTRODUCTION

Regarding to the Energy Efficiency Design Index (EEDI) regulations of International Maritime Organization (IMO), there has been a growing interest in the *fw* factor which represents the speed loss of ship in actual seaways. In order to predict the *fw* factor, the accurate computation of additional resistance due to environmental loads, such as waves and winds, is required as well as calm-water resistance. In addition, maneuvering performances in actual sea conditions should be considered along with seakeeping performances. Therefore, a time-domain seakeeping-maneuvering coupled analysis is required to account the time-varying quantities and their interaction effects in ship maneuvering in waves.

2 THEORETICAL BACKGROUNDS

Maneuvering in waves is a problem of excitation of ship by waves while the speed and heading angle are changed. Therefore, ship motion is decomposed into the two kinds of motion: wave-induced motion with high-frequency and maneuvering motion with low frequency. In order to effectively integrate seakeeping and maneuvering models, the two motions are treated separately.

In the case of seakeeping analysis, the boundary value problem is defined in a body-fixed coordinate system (*O-xyz*) which translates with forward speed (u_0), slip speed (v_0), and rotates with rotation speed (r_0) in space-fixed coordinate system (*O-XYZ*). Also, the problem should include the temporal and spatial variations due to the change of speed and heading angle. Based on the potential theory, the total velocity potential (ϕ) which satisfies the Laplace equation can be defined, and decomposed into steady-flow (Φ), incident wave (ϕ_I), and disturbed wave (ϕ_d) potentials. By adopting the decomposed variables, the linearized boundary value problem is derived as follows:

$$\nabla^2\phi = 0 \quad \text{in fluid domain} \tag{1}$$

$$\frac{\partial \zeta_d}{\partial t} - \left(\vec{U} - \nabla\Phi\right)\cdot\nabla\zeta_d = \frac{\partial^2\Phi}{\partial z^2}\left(\zeta_d + \zeta_I\right) + \frac{\partial \phi_d}{\partial z} - \nabla\Phi\cdot\nabla\zeta_I \quad \text{on } z = 0 \tag{2}$$

$$\frac{\partial \phi_d}{\partial t} - \left(\vec{U} - \nabla\Phi\right)\cdot\nabla\phi_d = -g\zeta_d - \nabla\Phi\cdot\nabla\phi_I \quad \text{on } z = 0 \tag{3}$$

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

where $\vec{m}_T = \left(m_1, m_2, m_3\right) = \left(\vec{n}\cdot\nabla\right)\left(\vec{U} - \nabla\Phi\right)$, $\vec{m}_R = \left(m_4, m_5, m_6\right) = \left(\vec{n}\cdot\nabla\right)\left(\vec{x}\times\left(\vec{U} - \nabla\Phi\right)\right)$

Here, ζ_I and ζ_d indicate elevations of incident and disturbed waves, respectively. Also, m_j term represents the interaction effects between steady and unsteady solutions when ship moves with a certain velocity, $\vec{U} = \left(u_0 - yr_0, v_0 + xr_0, 0\right)$. In the linearization, the steady flow which has a larger magnitude than other variables ($\Phi >> \phi_I, \phi_d$) is approximated by double-body flow.

In this study, the defined boundary value problem is solved by a B-spline 3D Rankine panel method. By using solutions of the problem, 6-DOF ship motions can be obtained according to the equation of motion such as

$$\left[M_{jk}\right]\left\{\ddot{\xi}_k\right\} = \{F_{H.D.j}\} + \{F_{F.K.j}\} + \{F_{Res.j}\} \quad (k, j = 1, 2, ..., 6) \tag{5}$$

where $[M_{jk}]$ is the mass matrix, and $\{F_{H.D.j}\}$, $\{F_{F.K.j}\}$, and $\{F_{Res.j}\}$ indicate hydrodynamic, Froude-Krylov, and restoring forces, respectively. The details can be found in Kim et al. (2011).

In the maneuvering problem, the modular type 4-DOF equation of motion is defined in the space fixed coordinate system as follow:

$$\begin{aligned} m(\dot{u}_0 - v_0 r_0) &= X_H + X_P + X_R + X_{WT} + X_{LP} + X_W \\ m(\dot{v}_0 + u_0 r_0) &= Y_H + Y_R + Y_{WT} + Y_{LP} + Y_W \\ I_{xx}\dot{p}_0 &= K_H + K_R + K_{WT} + K_{LP} + K_W \\ I_{zz}\dot{r}_0 &= N_H + N_R + N_{WT} + N_{LP} + N_W \end{aligned} \quad (6)$$

where X, Y, K, N represent surge and sway forces and roll and yaw moments, respectively. In this study, the maneuvering forces such as hull hydrodynamic, propulsion, and rudder forces expressed by subscripts, H, P, and R are obtained from the existing model for a given ship in calm water (Yasukawa et al., 2015). Also, the wind force (WT) is estimated by the regression formula considering general geometries of superstructures. On the other hand, linear and second-order wave-induced forces (LP and W) are computed in the seakeeping model. The temporal mean of second-order force indicates the wave drift force which is obtained by the near-field method, namely, direct integration of second-order pressure along the hull surface.

In this study, the seakeeping-maneuvering coupling method proposed by Seo and Kim (2011) is adopted to integrate wave-induced 6-DOF motions and slowly-varying maneuvering motions. Firstly, the velocity and position of ship are calculated in maneuvering model. Then these values are transferred to seakeeping model to redefine the boundary value problem. The computed ship motions and wave-induced forces in the seakeeping model are transferred to the maneuvering model to set up the equation of motion for maneuvering. Lastly, the trajectory tracking method is introduced in free-running simulation to predict the speed loss of ship following a desired route. To implement the course keeping, firstly, the error between the desired route and actual routed due to by environmental loads, should be defined. As shown in Fig. 1, a reference point is set at a certain distance from the ship on the desired route, and the angle between the route and the centerline of ship indicates the error. Then PID control for rudder angle is adopted to reduce the error.

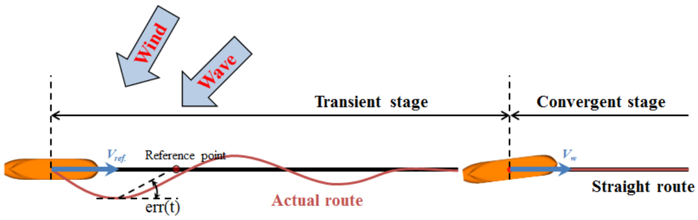


Fig. 1 Trajectory tracking method

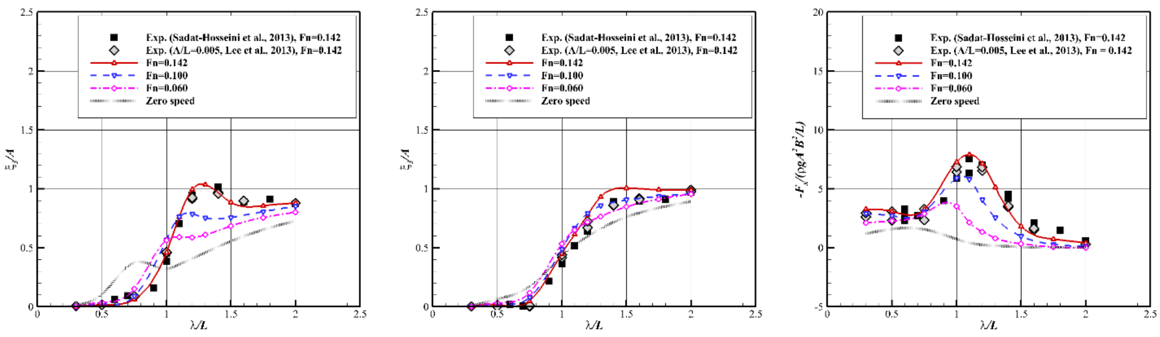
3 SIMULATION RESULTS

The well-known tanker, KVLCC2, is chosen for the simulation of actual ship operation. Before conducting the free-running simulation, the ship motion and wave-induced added resistance are computed for a constant forward speed. As shown in Fig. 2, the computation results for design speed (Fn=0.142) are in good agreements with the experimental data. When the speed of ship decreases, the peaks of motion response and added resistance are shifted to short-wave region. It should be noted that the double-body flow related variables must be calculated accurately to consider the influence of the forward speed. The steady-flow coupling terms in boundary conditions such as m_j term can affect hydrodynamic coefficients and distribution of disturbed waves around ship, which determines the accuracy of seakeeping quantities.

To validate the present seakeeping-maneuvering coupled analysis, the comparison with maneuvering model test data is carried out. Fig. 3 shows the starboard turning results (δ=35.0°) under short-crested waves of sea state 6 (H_S=6.0 m, T_{mean}=9.46 s). In the simulation, the ITTC spectrum is randomly discretized with respect to wave frequency and heading angle to generate irregular waves with 500 components. Also, to investigate the uncertainties to wave components, 10 realization is repeated for random phases.

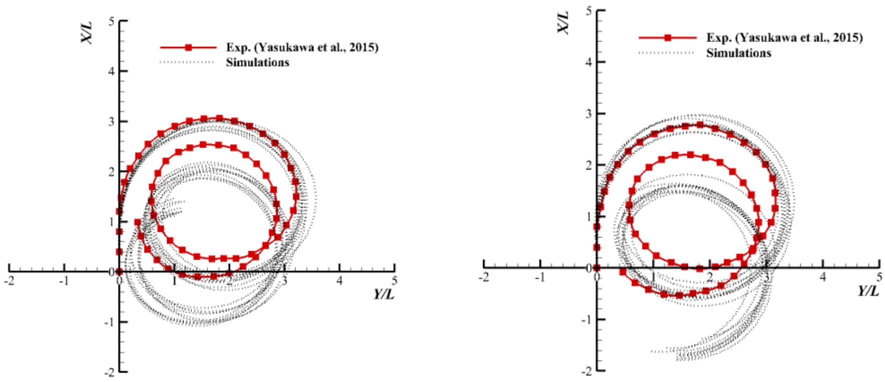
For the two initial speeds of ship in the given wave condition, Fn=0.119 and 0.092, the trajectories obtained by the coupled approach roughly agree with the experiment although the ship in computation is more drifted by waves than in experiment. The reason why the discrepancies relative to the experiment increases as the simulation continues is due to the inaccurate prediction for wave-induced drift forces in following waves. Further investigations of drift forces in various speeds and heading angles are required. In addition, simulation results are slightly different according to the wave phases, and this tendency is intensified as the initial speed decreases. These uncertainty in direct simulation for irregular waves is resulted from the high-frequency seakeeping quantities such as ship motions and wave-induced forces.

Therefore, stochastic analysis is needed to analyze the maneuvering performance in irregular waves considering the uncertainties.



(a) Heave motion (b) pitch motion (c) added resistance

Fig. 2 Motion responses and added resistance: KVLCC2, χ=180.0° (head sea)



(a) Fn=0.119 (13 knots) (b) Fn=0.092 (10 knots)

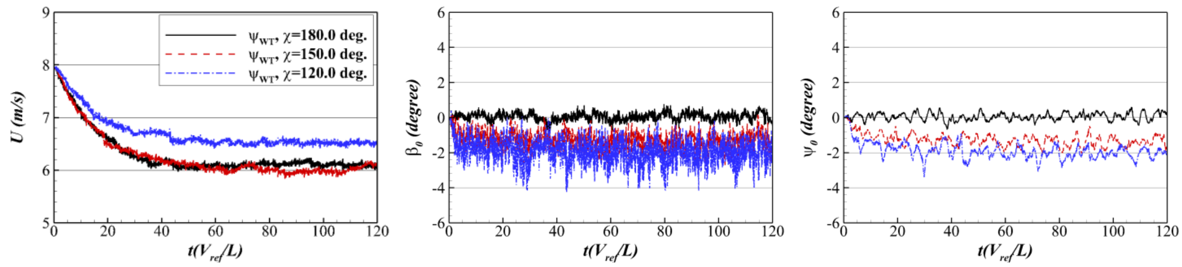
Fig. 3 Starboard turning trajectories: KVLCC2, Sea state 6 (H_S=6.0 m, T_{mean}=9.46 s), χ=180.0° (head sea)

Finally, the operational efficiencies in actual sea states are simulated. For this purpose, the Beaufort scales 6 to 8 are set to the representative sea conditions. In the free-running simulation, the speed change is directly calculated in time domain considering additional resistances induced by winds and waves while engine output is kept constant. As the simulation continues, the thrust, calm-water resistance, and environmental loads are balanced. Then speed of ship is considered to be converged if the velocity fluctuates within a certain range. By comparing the convergence speed and the reference speed (V_{ref}), it is possible to evaluate the speed loss of ship in the representative sea states.

Fig. 4 shows the simulation results for different directions of environmental loads. When the loads act on the side of ship, the trajectory tracking method based on rudder control is applied to allow the ship to advance along a straight route. The steering is performed so that the ship moves in the opposite direction of environmental loads. Therefore, not only the speed of ship but also the drift angle ($\beta_0=\tan^{-1}(-v_0/u_0)$) and yaw angle ($\psi_0$) converges to certain values. It can be seen that the fluctuation of variables is not well controlled because the high-frequency wave-induced forces greatly affect the ship operation in the severe sea state.

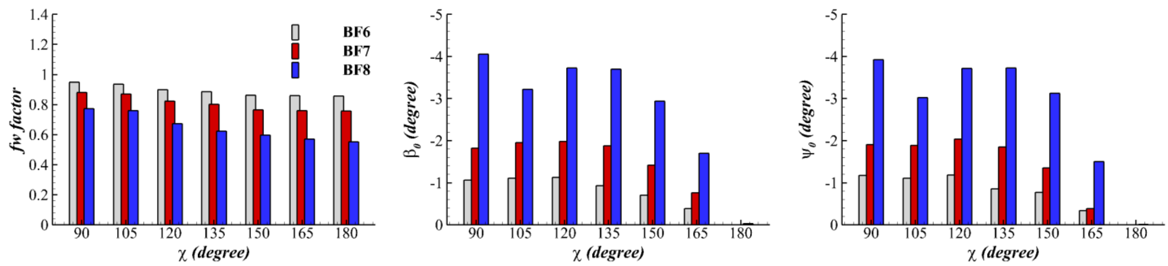
Fig. 5 shows the comparison of simulation results for various environmental conditions. As the sea states become more severe, the wind speed and wave height increase, so the speed loss becomes intensified. Also, the magnitude of wave-induced added resistance is determined by wave period as well as speed of ship as shown in Fig. 2. Therefore, when the mean period of sea state moves to a region where ship motion is large, the added resistance also greatly increases, thereby increasing the speed loss.

When the simulation results for different heading angles are compared, as the direction of loads is closer to 90.0° (beam sea), the convergent drift and yaw angle increase. On the other hand, the environmental loads in longitudinal direction decrease as the incident direction deviates from the front (head sea), so that the fw factor, (U/V_{ref}) is increased. However, if the ship advances at a slight angle, the hull hydrodynamic force increases. Therefore, for the directions of incidence in the range of 150.0°-180.0°, the magnitudes of speed loss are similar.



(a) Speed of ship (b) drift angle (c) yaw angle

Fig. 4 Time histories in free-running simulation: KVLCC2, Beaufort scale 7, *Fn* of V_{ref}=0.142



(a) Speed of ship (b) drift angle (c) yaw angle

Fig. 5 Convergent values in free-running simulation: KVLCC2, *Fn* of V_{ref}=0.142

4 CONCLUSIONS

Based on the free-running simulation results obtained by applying time-domain seakeeing-maneuvering coupled analysis, the following conclusions can be made.

- Uncertainties with respect to wave components are confirmed in the maneuvering simulations in irregular waves.
- In oblique waves or currents, a ship may advance with a yaw angle during straight course keeping, which results in speed loss.

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