Comparative study of prediction methods of power increase and propulsive performances in regular head short waves of KVLCC2 using CFD

Cheol-Min Lee a, Jin-Hyeok Seo a, Jin-Won Yu b, Jung-Eun Choi b, Inwon Lee a, b, * 

a Department of Naval Architecture and Ocean Engineering, Pusan National University, Busan, South Korea 
b Global Core Research Center for Ships and Offshore Plants, Pusan National University, Busan, South Korea

A R T I C L E   I N F O
Article history:
Received 6 November 2018 
Received in revised form 28 January 2019 
Accepted 19 February 2019 
Available online 21 February 2019

Keywords: 
Power increase 
Speed loss 
Propulsion performances 
Regular short head waves 
KVLCC2 
CFD 
Taylor expansion 
Direct powering 
Load variation 
Resistance and thrust identity method

A B S T R A C T
This paper employs computational tools to predict power increase (or speed loss) and propulsion performances in waves of KVLCC2. Two-phase unsteady Reynolds averaged Navier-Stokes equations have been solved using finite volume method; and a realizable k-ε model has been applied for the turbulent closure. The free-surface is obtained by solving a VOF equation. Sliding mesh method is applied to simulate the flow around an operating propeller. Towing and self-propulsion computations in calm water are carried out to obtain the towing force, propeller rotating speed, thrust and torque at the self-propulsion point. Towing computations in waves are performed to obtain the added resistance. The regular short head waves of λ/LPP = 0.6 with 4 wave steepness of H/λ = 0.007, 0.017, 0.023 and 0.033 are taken into account. Four methods to predict speed-power relationship in waves are discussed; Taylor expansion, direct powering, load variation, resistance and thrust identity methods. In the load variation method, the revised ITTC-78 method based on the ‘thrust identity’ is utilized to predict propulsive performances in full scale. The propulsion performances in waves including propeller rotating speed, thrust, torque, thrust deduction and wake fraction, propeller advance coefficient, hull, propeller open water, relative rotative and propulsive efficiencies, and delivered power are investigated.

© 2019 Production and hosting by Elsevier B.V. on behalf of Society of Naval Architects of Korea. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

1. Introduction

The ship speed in the actual seas decreases at constant power condition or the power increases to maintain ship speed constant. The prediction of power increase (or speed loss) of ocean-going ships is essential to design hull form, to analyze speed sea trial tests, to estimate the weather factor in EEDI formula (MEPC 66/21 Annex 5, 2014), fuel consumption and sea margin, and to find the optimal seaway route for eco-operation. Speed loss in the actual seas depends on the resistance, propulsion, ship machinery, sea-keeping, automatic control and maneuvering, etc. Speed losses are usually categorized as voluntary or involuntary (Faltinsen et al., 1980). The former occurs when the ship master actively reduces the ship speed to avoid damage, danger or severe discomfort. The latter is due to the added resistance in seaway; wind, wave, water temperature, roughness (or fouling), rudder angle, drift angle, etc. This involuntary speed loss is included by adding a sea margin. The sea margin has a typical value between 15% and 20% on the maximum continuous rotating power (Eide, 2015).

A lot of researches have been performed to predict the RAM by computational or experimental methods. The RAM composes of three components - vertical motions, diffraction and viscous effects (Arribas, 2007). The first is known as drift force which has a second order nature (Faltinsen, 1990), mainly caused by wave radiation via the ship motion and becomes larger as the ship motions increase. This is significant in the resonance frequency region of heave and pitch motions. The second is the diffraction force of the incident waves on the ship which is primarily due to wave diffractions. This component is the most significant in short waves, where the ship motion is nearly negligible. The third is damping forces associated with the forced heave and pitch motions in calm water, and insignificant compared to hydrodynamic damping of ship motions. These three components involve energy dissipation. A major part of this energy is transmitted to the wave radiating from the hull and a
Nomenclature

Alphabetical symbols

\( B \) ship breadth
\( C_{AV} \) added resistance coefficient in waves \( \left( = \frac{R_{AV}}{\rho g C_{Tm} L_{PP}} \right) \)
\( C_B \) block coefficient
\( C_F \) frictional resistance coefficient, non-dimensionized by \( \rho g S_0 V^2 \)
\( C_N \) trial correction for propeller rate of revolution at speed
\( C_P \) trial correction for delivered power
\( C_T \) total resistance coefficient in calm water, non-dimensionized by \( \rho g S_0 V^2 \)
\( C_V \) viscous resistance coefficient, non-dimensionized by \( \rho g S_0 V^2 \)
\( D \) ship depth, diameter of propeller
\( F_N \) Froude number \( \left( = \frac{V}{\sqrt{g C_{Tm}}} \right) \)
\( f_w \) weather factor in EEDI formula
\( g \) gravitational constant \( (-9.81 \text{ m/sec}^2) \)
\( H \) wave height \( [\text{m}] \)
\( J \) propeller advance coefficient \( \left( = \frac{V_A}{(nD_p)} \right) \)
\( k \) wave number \( (-2\pi/\lambda) \)
\( K_T \) propeller thrust coefficient \( \left( = \frac{T}{(n^2D_p^4)} \right) \)
\( K_{T\%} \) percentage ratio of the computed value of \( K_{TM} \) to that of the experiments
\( K_Q \) propeller torque coefficient \( \left( = \frac{Q}{(n^2D_p^5)} \right) \)
\( K_{Q\%} \) percentage ratio of the computed value of \( K_{QM} \) to that of the experiments
\( k_{yy} \) moment of inertia
\( L_{CB} \) longitudinal center of buoyancy forward of midship
\( L_{FL} \) length at waterline
\( n \) propeller rotating speed
\( p \) static pressure
\( PD \) delivered power
\( PE \) effective power
\( Q \) propeller torque
\( R \) radius of propeller (b) resistance
\( R_{AV} \) added resistance due to waves
\( R_{AVM\%} \) percentage ratio of the \( R_{AV} \) to the \( R_{FM}^C \)
\( R_N \) Reynolds number \( \left( = \frac{V L_{PP}}{\nu} \right) \)
\( R_T \) total resistance
\( R_{T\%} \) percentage ratio of the computational value to the theoretical
\( S_{0m} \) sea margin due to waves
\( S_0 \) wetted surface area
\( t \) thrust deduction fraction \( \left( = \frac{T_M + FD - R_{FM}^C}{T_M} \right) \)
\( T \) draft, (b) wave period, (c) propeller thrust
\( TF \) towing force
\( U, W \) velocity component in \( (x,z) \)
\( V \) ship speed
\( V_A \) propeller advance speed
\( x, y, z \) coordinate
\( w \) wave fraction
\( \Delta C_f \) roughness allowance coefficient

\( \Delta P_D \) power increase due to waves at constant speed condition
\( \Delta R \) external towing force
\( \Delta t \) time step
\( \Delta V \) speed loss due to waves at constant power condition
\( \zeta \) wave elevation
\( \eta_D \) propulsive efficiency \( \left( = \frac{R}{\eta_O \eta_H} \right) \)
\( \eta_H \) hull efficiency \( \left( = \frac{(1 - t)}{(1 - w)} \right) \)
\( \eta_O \) propeller-open-water efficiency
\( \eta_{R\%} \) relative rotative efficiency \( \left( = \frac{Q_D}{Q} \right) \)
\( \lambda \) (a) wave length (b) scale ratio
\( \nu \) fluid kinematic viscosity
\( \xi_i \) translatory and angular displacements in \( x, y, \) and \( z \) directions (1: surge, 2: sway, 3: heave: 4: roll, 5: pitch, 6: yaw)
\( \xi_n \) overload factor of propeller rotating speed
\( \xi_{P\%} \) overload factor of propulsion efficiency
\( \rho \) fluid density
\( \varphi \) percentage ratio of \( \varphi \) in waves to \( \varphi \) in calm water, where \( \varphi = \Delta V, R_p, n, T, Q, PD, t, w, \eta_D, \eta_H, \eta_O, \eta_{R\%}, \eta_{P\%}, PD \)
\( \omega \) wave frequency
\( \nabla \) displacement volume

Subscripts

a amplitude
\( C \) calm water
e encounter wave
M model scale
O (a) circular wave (b) normal self-propulsion condition (c) open water
P propeller
S ship scale
X external towing force for the load variation

Superscripts

C calm water
SP self-propulsion
W waves

Acronyms

BN Beaufort number
DOF degrees of freedom
EEDI energy efficiency design index
FS Fourier series
ITTC International Towing Tank Conference
JBC Japanese bulk carrier
KCS KRISO container ship
KRISO Korea Research Institute for Ship and Ocean Engineering
KVLCC2 KRISO very large crude oil carrier 2
MEPC Marine Environment Protection Committee
QN M torque and revolution method
RANS Reynolds averaged Navier-Stokes
RTIM resistance and thrust identity method
SIMPLE semi-implicit method for pressure-linked equations
SM sliding mesh method
TNM thrust and revolution method
VOF volume of fluids
very small part of the energy is lost due to viscous friction. Therefore, $R_{AW}$ is considered a non-viscous phenomenon. This is important when scaling from model experiments to full scale. Gerritsma and Beukelman (1972) proposed $C_{AW}$ using quadratic wave amplitude; however, $R_{AW}$ does not show quadratic dependency (Kim et al., 2017a).

The direct powering method in which the speed loss (or power increase) in waves is directly predicted by reading off the ship speed-delivered power curve, has commonly been used to analyze speed sea trial test results in ship yards because of the simplicity in spite of the lack of theoretical background. Journee (1976b) discussed that $R_{AW}$ was the largest part of the total resistance; and predicted the speed loss at head sea conditions using empirical formulas. Pripic-Orsic and Faltinsen (2009, 2012) discussed the speed loss in actual sea states in the time domain by implementing a thrust loss model based on experimental data; and developed a time domain numerical model to predict the speed loss in irregular sea. Baree (2010) obtained the $R_{AW}$ using Maruo’s and Fuji-Takahashi’s methods for Series 60; and discussed that the lower speeds/head and bow seas have more effect on the ship performance than the higher speeds/other headings. Rathje et al. (2011) studied a container ship in waves using RANS solver to simulate the large thrust loss in the head waves at the constant thrust condition. Chuang and Steen (2011) explored the use of time- and frequency-domain simulation in the prediction of speed loss in waves; derived speed-loss formula using the Taylor expansion method, and pointed out that the speed loss predicted from the model tests would be underestimated if towing force was not taken into account; the speed loss reached peak value when wave length approached ship length; and the speed loss increased linearly with increasing wave elevation in the long wave range (Chuang and Steen, 2013). Three different methods to predict power increase in irregular waves based on regular wave test results are described in the ITTC-recommended procedures and guidelines 7.5-02-07-02.2 (2014); QNM, TNM, and RTIM. In the RTIM, the resistance tests in waves, and the resistance, propeller-open-water and self-propulsion tests in calm water are utilized assuming thrust deduction and wake fractions in waves are the same as those in calm water. In the TNM, the self-propulsion tests in waves, and propeller-open-water and self-propulsion tests in calm water are utilized assuming wake fraction in waves is the same as that in calm water. In the QNM, only the self-propulsion tests in waves are utilized; resistance and propeller-open-water tests in calm water and in waves are unnecessary since propeller rotating speed and torque variations are directly reflected to the delivered power. Kim et al. (2017b) employed the 2-D linear potential theory to estimate the added resistance and ship speed loss of the S175 container ship due to wind and waves; pointed out that the speed loss for the wave and wind directions from head to bow seas is higher than the speed loss from beam directions and following sea directions.

The propulsion point will change since the thrust has to balance the $R_{AW}$. Journee (1976a) showed that the $R_{AW}$ quadratically varied with the wave amplitude; the added propeller rotating speed, thrust and torque are linear to the $R_{AW}$; the propulsive efficiency is not influenced by the wave motion but only by a decreasing propeller loading. When propeller is working close to the free surface, additional wave motion will be set up by the propeller and lead to reduced thrust. Faltinsen et al. (1980) explained the ‘Wagner effect’, which led to large thrust loss due to the ventilation and propeller out-of-water. As long as the propeller is fully submerged, the ventilation and out-of-water effects can be excluded. Thus, the propeller-open-water characteristics don’t change in waves (McCarthy et al., 1961; Nakamura and Naito, 1975). Nakamura and Naito (1975) performed the resistance and self-propulsion tests in regular and irregular waves for a container ship, and discussed that the propeller open-water efficiency in irregular waves decreased with the increase of the wave height; the propeller rotating speed, thrust and torque considerably increased in regular head waves than those in regular following waves; the self-propulsion factors in waves are considered to be almost the same values as those in calm water; the wake on the propeller plane is reduced in waves, especially close to the propeller hub and becomes more uniform (Guo et al., 2012); the wake velocity (1-w) slightly increased as the wave height increased; the self-propulsion factors in regular head waves considerably varied with wave length, especially in the range of $\lambda/LPP = 1.0$–1.5 where ship motions were severe; the thrust deduction fraction had a strong relationship with wave induced motion; these added amounts had their peaks when the ship motions were severe, showing the close resemblance with the $R_{AW}$.

Benchmark tests for the self-propulsion computations solving RANS equations of the KCS (3000 TEU container ship) and JBC (180k DWT bulk carrier) models were carried out at the Tokyo 2015CFD workshop (http://www.t2015.mri.go.jp), in which the direct self-propulsion computations were feasible to predict the resistance, thrust and torque at the given propeller rotating speed and ship speed. The self-propulsion point could be obtained applying load variation method (Choi et al., 2009, 2010; Seo et al. 2010) or using a speed controller to modify the propeller rotating speed until the target speed was reached (Carrica et al., 2010; Castro et al., 2011). Kayano et al. (2013) performed full-scale experiments of a 6,720 G.T. training ship, and clarified that the power increase in the waves was due to not only added resistance but also change of propulsive efficiency; thrust measurement was important to calculate the propulsive efficiency and the self-propulsion factors; wake coefficient was largely affected by ship’s condition such as displacement and trim, not propeller loading. Taskar et al. (2016) suggested that the sea margin include the effect of drop in propulsive efficiency in waves.

This paper discussed the speed loss (or power increase) and propulsive performances in waves for KVLCC2 (300k DWT VLCC). Towing and self-propulsion computations in calm water are applied to obtain the resistance, propeller rotating speed, thrust and torque at the self-propulsion point. Towing computations in waves are applied to obtain $R_{AW}$. The regular short head waves $\lambda/LPP = 0.6$ with 4 wave steepness of $H/\lambda = 0.007, 0.017, 0.023$ and 0.033 are taken into account. Computational methods and conditions are described in Section 3. The results using four methods to predict speed-power relationships in waves are discussed in Section 4; Taylor expansion, direct powering, load variation, and RTIM methods. In the load variation method, the revised ITTC–78 method based on the ‘thrust identity’ is utilized to predict propulsive performances in full scale. The resistance and propulsive performances in waves including propeller rotating speed, thrust, torque, thrust deduction and wake fraction, propeller advance ratio, hull, propeller-open-water, relative rotative and propulsive efficiencies, and delivered power are discussed. Viscous solver of STAR-CCM + v11.04 is utilized.
2. Objective ship and calculation conditions

The objective ship is KVLCC2, which was designed by the KRISO to provide data for both explication of flow physics and CFD validation for a modern 300k DWT tanker with bulbous bow and stern. No full-scale ship exists.

The principal dimensions of ship (KVLCC2) at full-load draft and propeller (KP458) are listed in Table 1.

The design speed ($V_S$) is 15.5 knots, which corresponds to $V_M = 1.136$ m/s, $F_N = 0.142$ and $R_{NM} = 7.113 \times 10^3$.

The body plans and side view of KVLCC2 are presented in Fig. 1. The resistances in calm water and in waves are obtained from the towing computations. The propulsive performances are obtained from the towing and self-propulsion computations in calm water. The regular short head waves of $\lambda/L_{PP} = 0.6$ with 4 wave steepness of $H/\lambda = 0.007$, 0.017, 0.023 and 0.033 have been taken into account. The wave heights in full scale are 1.28, 3.16, 4.44 and 6.41 m with the same wave length of 192.0 m, which correspond to BN 4, 6, 7 and 8, respectively. Note that the corresponding BF is for the regular short waves, which may not be the same as that for the short crested irregular waves.

At the towing computations, a rudder is not fitted to the model ship; double-body model is used to obtain form factor; calmwater and regular short head wave conditions have been taken into account; the heave and pitch motions are free; the range of the velocity is 14.0–15.5 knots ($V_M = 1.026–1.136$ m/s) with 0.5 knots ($\Delta V_M = 0.037$ m/s) interval. At the self-propulsion computations, a propeller and a rudder are fitted to the model ship; calm water condition is taken into account; the heave and pitch motions are free; the range of the velocity is 14.0–15.5 knots with 0.5 knots interval; 4 propeller rotating speeds while keeping the ship speed constant are applied.

3. Computational methods and conditions

The ship is advancing at constant forward speed $V_S$ in sinusoidal waves with an arbitrary heading. This is assumed to be the same as a fixed ship with flow coming from upstream to down in sinusoidal waves with an encounter frequency. The ship fixed on a right-handed coordinate system ($x,y,z$) is defined as positive $x$ in the flow direction, positive $y$ in the starboard, and positive $z$ upward, as shown in Fig. 2. The origin is the intersection point of the midship, the centerplane and the undisturbed free surface. Here, surge to bow, sinkage to downward and trim by head are negative.

3.1. Theoretical background

The governing equations are the continuity and the two-phase unsteady RANS equations. A realizable $k-\varepsilon$ model is applied for the turbulent closure. The free-surface is obtained by solving a VOF equation. This study does not go into what the computational method is, the details of which may be found in STAR-CCM + user guide (CD Adapco, 2016). The computations are carried out at the towing and self-propulsion conditions. The SM is employed to simulate the flow around an operating propeller. The time history of the computational results for encounter wave elevation, resistance, sinkage and trim are analyzed by FS.

To solve the governing equations, the flow domain is subdivided into a finite number of cells and the equations are changed into algebraic form via the discretization process. The cell-centered finite volume method is used for the space discretization. The convective terms are discretized using the second order upwind scheme. The SIMPLE algorithm is applied to the velocity-pressure coupling. The temporal discretization is the second order Adams-Bashforth scheme. A high-resolution interface-capturing scheme to compute the evolution of free surface by solving VOF equation was employed.

3.2. Computational domain and boundary conditions

In the case of towing and self-propulsion computations, half and full domains are used, respectively. The computational domain and boundary conditions at the towing computations are present in Fig. 3. The computational domain is a shape of rectangular with $-1.5 < x/L_{PP} < 2.5$, $0 < y/L_{PP} < 1.5$, and $-1.0 < z/L_{PP} < 0.0$. The fluid is water for the region of $-1.0 < z/L_{PP} < 0.0$ and air for $0.0 < z/L_{PP} < 0.5$ at the initial condition. Grid damping zone is applied in the region of $2.5 < x/L_{PP} < 4.5$ including numerical damping zone of $3.8 < x/L_{PP} < 4.5$ to ensure that no unwanted wave reflection occurs at the boundaries of the solution domain.

### Table 1

Principal dimensions of ship and propeller.

<table>
<thead>
<tr>
<th>Ship (KVLCC2)</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda$</td>
<td>1.00</td>
</tr>
<tr>
<td>LPP [m]</td>
<td>320.0</td>
</tr>
<tr>
<td>LWL [m]</td>
<td>325.5</td>
</tr>
<tr>
<td>B [m]</td>
<td>58.0</td>
</tr>
<tr>
<td>D [m]</td>
<td>30.0</td>
</tr>
<tr>
<td>T [m]</td>
<td>20.8</td>
</tr>
<tr>
<td>$V_{m}^{\uparrow}$ [m/s]</td>
<td>312.622</td>
</tr>
<tr>
<td>$V_{m}^{\downarrow}$ [m/s]</td>
<td>2.609</td>
</tr>
<tr>
<td>$S_0$ [m$^2$]</td>
<td>27.194</td>
</tr>
<tr>
<td>$C_S$</td>
<td>0.8098</td>
</tr>
<tr>
<td>LCB [%LPP]</td>
<td>3.48</td>
</tr>
<tr>
<td>$k_{y}/L_{PP}$</td>
<td>0.25</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Propeller (KP458)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of propeller blade</td>
<td>4</td>
</tr>
<tr>
<td>$D_p$ [m]</td>
<td>0.200</td>
</tr>
<tr>
<td>Pitch-diameter ratio at 0.7 $R_p$</td>
<td>0.721</td>
</tr>
<tr>
<td>Expanded area ratio</td>
<td>0.431</td>
</tr>
<tr>
<td>Hub-diameter ratio</td>
<td>0.155</td>
</tr>
<tr>
<td>Rotation direction</td>
<td>clockwise</td>
</tr>
</tbody>
</table>
No-slip conditions are applied on the hull surface. Standard wall function is utilized. Velocity inlet and pressure outlet boundary conditions are applied for the inlet and outlet boundary plane, respectively. Symmetry condition is applied on symmetry and side boundary plane. Slip wall boundary condition is applied on top and bottom boundary plane.

The first order linear wave theory is applied for the inlet boundary plane expressed as:

\[ \zeta(x, t) = \zeta_0 \cos(k_0 x - \omega t) \] (1)

\[ U(x, z, t) = \omega_0 \zeta_0 e^{k_0 z} \cos(k_0 x - \omega t) \] (2)

\[ W(x, z, t) = \omega_0 \zeta_0 e^{k_0 z} \sin(k_0 x - \omega t) \] (3)

\[ p(x, z, t) = \frac{\omega_0^2 \zeta_0^2 e^{k_0 z}}{k_0} \cos(k_0 x - \omega t) - \frac{\omega_0^2 \zeta_0^2 e^{2k_0 z}}{2} \] (4)

### 3.3. Grid generation

The grid generation is performed in the CFD code STAR-CCM+ using the trimmed mesh technique. A prismatic layer is generated near the wall to resolve the boundary layer. Five layers are used. The distance of the 1st grid from the hull is \( y_+ \approx 120 \). Fine grids are set near free-surface. More than 50 cells per wave length and 20 cells per wave height for the \( l/L = 0.6 \) and \( H/\lambda = 0.017 \) are used. Total grid number is 2.7 M.

### 3.4. Wave generation test

Wave generation tests are performed to know the mesh’s quality and to find the computational parameters which give high resolution. This is done using background grid, in which there is no hull. The under-relaxation factors are set to 0.2 for momentum and 0.8 for pressure. The time step is set 0.0025 s, corresponding to 1/500 of the \( T_e \), with the number of iterations per time step of 20. The maximum physical time sets 60 s.

The \( \%R \) for the wave length and height are listed in Table 2. The wave-generation test results are listed in Table 2. The wave lengths are nearly same within differences of 0.9%. The wave heights show differences within 5.0%. The computed wave amplitude is used for the non-dimensionalization.

Fig. 5 displays snapshot of the computational results and theoretical values expressed in Eq. (1). The time of \( t/T_e = 0.7 \) is randomly selected. The waves are well damped in the grid and numerical damping zones.

### 3.5. Operating propeller test

The SM is applied to simulate the flow around an actuating propeller. The computed results obtained from the moving reference frame method are used as the initial condition. Before applying the SM at the self-propulsion computations, the computational parameters are selected through the case study at the propeller-open-water computation at \( \beta = 0.4 \), where \( V_{A} = V_{M} = 1.136 \text{ m/s and } n_{M} = 30.0 \text{ rps.} \) Computational domain and view of grid generation are displayed in Fig. 6, which dimension is 0.8DP in longitudinal- and 1.2DP in radial-direction, rotates with the same propeller rotating speed. The cell number is 0.68 M.

The \( K_T \) and \( K_Q \) are compared with those of the experiments \( (K_{TM} = 0.1757 \) and \( 10K_{QM} = 0.2067 \) at \( \beta = 0.4 \), http://www.simman2008.dk/KVLCC/KVLCC2/kvlcc2_geometry.html).

The results of the case studies using various time steps, sub-iteration numbers and order of the Adams-Bashforth scheme are listed in Table 3. The computations using larger \( \Delta t \) are utilized as the initial condition for the computations using the smaller \( \Delta t \), that is, the propeller rotation angle corresponding to the \( \Delta t \) changes to 10.0 → 5.0 → 2.5 → 1.0 deg.
The minimum KT% is selected as a criterium since the magnitude of KT is much larger than that of KQ. The Dt is 0.00009 s corresponding to the 1/C14 propeller rotating angle, relaxation factor is 0.2, and a sub-iteration number of 45 are employed. The propellers rotate eight times.

3.6. Verification and validation

Verification of the computational results using the present grid system is not performed. However, the computational results are validated by comparing with the experiments (Kim et al., 2001). Fig. 7 displays the comparison of the computational results with the experiments of the wave pattern, wave profile on the hull and wave cuts at the towing computations in calm water. The computational results show good agreement with the experiments. Therefore, the trimmed mesh on the free surface as shown in Fig. 4 and cell numbers near free surface are applicable to simulating the free surface around present model ship.

Fig. 8 displays the comparison of the computational results with the experiments of the axial velocity contours and velocity vectors on the propeller plane at the towing computations in calm water. The dashed line denotes a circle of propeller plane. The shape of an ‘island’ of low-speed region is well displayed not only in the computational results but also in the experiments. The nominal wake of the computational result is 0.531, which is slightly lower than that of the experiment of 0.561. Therefore, the present grid system is applicable to simulating the flow around a propeller under the self-propulsion condition.

At the self-propulsion computations, full domain is used. The same grid system is used as that at the towing computation except adding propeller block as shown in Fig. 9. The cell number of the propeller block is 1.0 M.

The same values of relaxation factors, Dt and sub-iteration numbers are used as those at the operating propeller test. The propellers rotate four times. Fig. 10 displays the time histories of

<table>
<thead>
<tr>
<th>( H/\lambda )</th>
<th>( \lambda/\text{m} )</th>
<th>( H/\text{m} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theory</td>
<td>CFD</td>
<td>RST</td>
</tr>
<tr>
<td>0.007</td>
<td>3.895</td>
<td>3.880</td>
</tr>
<tr>
<td>0.017</td>
<td>3.895</td>
<td>3.861</td>
</tr>
<tr>
<td>0.023</td>
<td>3.895</td>
<td>3.866</td>
</tr>
<tr>
<td>0.033</td>
<td>3.895</td>
<td>3.908</td>
</tr>
</tbody>
</table>

Fig. 4. Overset and trimmed grid system.

Fig. 5. Snapshot of wave profile of wave-generation tests using CFD at \( t/T_\pi = 0.7 \) in \( \lambda/\lambda = 0.6 \) and \( H/\lambda = 0.017 \).
propeller thrust and torque coefficients at the conditions of $n_M = 7.83$ rps at the design speed. The time averaged values, which are the 0th terms in the FS of the resistance, thrust and torque are used.

The calculation was done by 60 cores (2.67 GHz Xeon processors) Linux Cluster. The computing times at the towing computations in calm water and in waves, and self-propulsion computations in calm water are 10 h, 24 h and 48 h, respectively.

4. Results

The towing computations in calm water and in regular short head waves are discussed. The self-propulsion computations in calm water are also discussed. Four methods to predict power increase (or speed loss) are described and the results are compared; Taylor expansion, direct powering, load variation, RTIM.

4.1. Towing computations in calm water and in waves

The RAW is the difference between the RTW and RTC at the same ship speed. The resistance, sinkage and trim in calm water and in regular head waves in model scale at $\lambda_{LPP} = 0.6$ with various steepnesses at various ship speeds are listed in Table 4. Some of results are compared with the experiments (Yu et al., 2017).
that the $z_e$ is the computed value as discussed in Table 2.

The ship is sunken in calm water and in regular short head waves of $\lambda/L = 0.6$, where the magnitudes are nearly same along the wave steepness. The ship is trimmed to bow in calm water and in regular short head waves of $\lambda/L = 0.6$, where the magnitude increases as the wave steepness increases. The RAWM% for various model ship speeds in $H/\lambda = 0.007$ and 0.017 are 3.2–4.0% and 20.1–22.8%, respectively. As the wave steepness increases, the $R_{AW}$ rapidly increases (i.e., the RAWM% increases from 4.0% at $H/\lambda = 0.007–72.6\%$ at $H/\lambda = 0.033$).

The $C_{AW}$ vs. wave steepness at the design speed in model scale is displayed in Fig. 11. If the $R_{AW}$ has quadratic dependence on wave amplitude as mentioned in the previous work (Gerritsma and Beukelman, 1972), the $C_{AW}$ becomes constant along the wave steepness. However, the $C_{AW}$ does not show the quadratic dependency. As the wave steepness increases, the quadratic dependency becomes weaker. The computational values of $C_{AW}$ are less than those of the experiments by 5.1–10.9% at the design speed.

4.2. Self-propulsion computations in calm water

In order to predict speed performance, it is necessary to obtain a self-propulsion point of a ship. The self-propulsion point may be found in the results of the towing and the self-propulsion computations under- and over-loaded propeller conditions for the given $V_M$ (Choi et al., 2009, 2010; Seo et al., 2010). In model scale, TF, which is the difference in force between the $R_{TM}$ and the $T_M$, is zero at the self-propulsion point.

$$TF = R_{TM}^P - T_M$$  \(5\)

In a full ship scale, however, the TF should be corrected by the FD (Choi et al., 2009, 2010) as follows;

$$FD = \frac{1}{2} \rho S_M V_H^2 (1 + k)(C_{FM} - C_{FS}) - \Delta C_F$$  \(6\)

Here, $C_F$ is obtained from the ITTC-1957 model-ship correlation line (ITTC-recommended procedures and guidelines 7.5-02-03-01.4). The form factor $(1 + k = 1.230)$ is obtained from the towing computation applying the double-body model;

$$1 + k = C_{VM}/C_{FM}$$  \(7\)

It is assumed that $C_{VM}$ is the same as the total resistance coefficient of the double-body model.

The changes of the TF ($\Delta TF = TF_X - FD$, where the FD denotes that for the normal self-propulsion condition) are selected as (ITTC-recommended procedures and guidelines 7.5-04-01-01.2);

$$\frac{\Delta R_S}{R_{TS}} = -\frac{TF_X - FD}{R_{TM} - FD} = [-0.1, 0.0, +0.1, +0.2]$$  \(8\)

$$TF_X = FD - [-0.1, 0.0, +0.1, +0.2] \cdot (R_{TM}^C - FD)$$  \(9\)

Note that the positive $(X = 3.4)$, negative $(X = 1)$ and zero $(X = 2$ or FD) values in the square bracket denote over-, under-loaded and normal self-propulsion conditions, respectively.

The self-propulsion computations in calm water are carried out to obtain $R_{TM}$, $T_M$ and $Q_M$ at four propeller rotating speeds including a self-propulsion point while keeping the ship speed constant. Four model ship speeds of 1.026–1.136 m/s (14.0–15.5 knots in full scale) with 0.037 m/s interval (0.5 knots in full scale) are taken into account.

Fig. 12 displays the procedure to obtain $n_{sb}$, $T_M$ and $Q_M$ for various TFs at the design speed. The values of the $n_{sb}$, $T_M$ and $Q_M$ for various TFs are obtained from reading off the self-propulsive computational results. As the $\Delta R_S$ increases, the TF decreases. The $n_{sb}$, $T_M$ and $Q_M$ increase due to the decreased TF to balance the over-loaded propeller.

A speed-powering prediction in full scale is performed utilizing the revised ITTC-78 method based on the ‘thrust identity’ (ITTC-recommended procedures and guidelines 7.5-02-03-01.4; Choi et al., 2009, 2010). The propeller-open-water characteristic curves obtained from the experiments (http://www.simman2008.dk/KVLCC/KVLCC2/kv1cc2_geometry.html) are utilized. Resistance and propulsive performances at normal load condition $(\Delta R_S/R_{TS} = 0.0)$ in full scale where $C_P = 1.0$ and $C_N = 1.0$ are listed in Table 5.

The ratio of the $n_{sb}$ at the over- and under-loaded conditions to that at the normal load condition are plotted against the $\Delta R/R_{TS}^P$ in model and full scale in Fig. 13(a) and (b), respectively. The $\zeta_P$ is the slope of the linear curve going through $(0,1)$ and fitted to the data points with least square method. The effect on the propeller rotating speed $(\Delta n/n_{sb})$ against $\Delta PD/PD^S$ is plotted in Fig. 13(c). The
n is the slope of the linear curve going through (0,0) and fitted to the data points with least square method. The \( \zeta_p \) and \( \zeta_n \) are useful to correct propulsion efficiencies and shaft rotation rates of the sea trial tests as discussed in ITTC-recommended procedures and guidelines 7.5-04-01-01.2. The \( \zeta_p \) and \( \zeta_n \) are also applicable to predict the delivered power and propeller rotating speed using Taylor expansion and direct powering methods.

### 4.3. Power increase or speed loss in waves

The \( \Delta V \) is defined as the difference between the speed in calm water and that in waves at constant power condition. And the \( \Delta PD \) is defined as the difference between the delivered power in waves and that in calm water at constant speed condition:

\[
\Delta V = V^C - V^W \text{ at constant power}
\]

\[
\Delta PD = PD^W - PD^C \text{ at constant speed}
\]

The \( f_w \) and \( sm \) are:

\[
f_w = \frac{V^W}{V^C} \text{ at constant power}
\]

\[
sm = \frac{PD^W - PD^C}{PD^C} \times 100[\%] \text{ at constant speed}
\]

Four methods to predict speed-power relationship in waves are discussed; Taylor expansion (Chung and Steen, 2011), direct powering, load variation, and RTIM methods. These methods are applicable to predict speed loss (or power increase) in waves when towing and self-propulsion computations in calm water, and towing computations in waves are available. Some of the results exceed the interpolation region. In this paper, the results within the interpolation region are to be discussed.

---

<table>
<thead>
<tr>
<th>( V_s ) [knots]</th>
<th>( V_M ) [m/s]</th>
<th>( H/\lambda )</th>
<th>( \zeta_{TM} ) [m]</th>
<th>( R_{TM} ) [N]</th>
<th>( R_{AWM} ) [N]</th>
<th>RAWM%</th>
<th>CFD</th>
<th>Exp (Yu et al., 2017)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.0</td>
<td>1.026</td>
<td>0.000</td>
<td>0.000</td>
<td>24.32</td>
<td>–</td>
<td>4.137</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>14.5</td>
<td>1.062</td>
<td>0.000</td>
<td>0.000</td>
<td>25.91</td>
<td>–</td>
<td>4.109</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>15.0</td>
<td>1.099</td>
<td>0.000</td>
<td>0.000</td>
<td>27.63</td>
<td>–</td>
<td>4.094</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>15.5</td>
<td>1.136</td>
<td>0.000</td>
<td>0.000</td>
<td>29.34</td>
<td>–</td>
<td>4.072</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>14.0</td>
<td>1.026</td>
<td>0.007</td>
<td>0.013</td>
<td>25.09</td>
<td>0.77</td>
<td>3.2</td>
<td>2.241</td>
<td>–</td>
</tr>
<tr>
<td>14.5</td>
<td>1.062</td>
<td>0.007</td>
<td>0.013</td>
<td>26.80</td>
<td>0.89</td>
<td>3.4</td>
<td>2.609</td>
<td>–</td>
</tr>
<tr>
<td>15.0</td>
<td>1.099</td>
<td>0.007</td>
<td>0.013</td>
<td>28.66</td>
<td>1.03</td>
<td>3.7</td>
<td>2.955</td>
<td>–</td>
</tr>
<tr>
<td>15.5</td>
<td>1.136</td>
<td>0.007</td>
<td>0.013</td>
<td>30.53</td>
<td>1.19</td>
<td>4.0</td>
<td>3.426</td>
<td>3.864</td>
</tr>
<tr>
<td>14.0</td>
<td>1.026</td>
<td>0.017</td>
<td>0.032</td>
<td>29.87</td>
<td>5.55</td>
<td>22.8</td>
<td>2.843</td>
<td>–</td>
</tr>
<tr>
<td>14.5</td>
<td>1.062</td>
<td>0.017</td>
<td>0.032</td>
<td>31.56</td>
<td>5.65</td>
<td>21.8</td>
<td>2.886</td>
<td>–</td>
</tr>
<tr>
<td>15.0</td>
<td>1.099</td>
<td>0.017</td>
<td>0.032</td>
<td>33.40</td>
<td>5.77</td>
<td>20.9</td>
<td>2.921</td>
<td>–</td>
</tr>
<tr>
<td>15.5</td>
<td>1.136</td>
<td>0.017</td>
<td>0.032</td>
<td>35.24</td>
<td>5.90</td>
<td>20.1</td>
<td>3.050</td>
<td>3.242</td>
</tr>
<tr>
<td>15.5</td>
<td>1.136</td>
<td>0.023</td>
<td>0.045</td>
<td>39.42</td>
<td>10.08</td>
<td>34.4</td>
<td>2.834</td>
<td>3.002</td>
</tr>
<tr>
<td>15.5</td>
<td>1.136</td>
<td>0.033</td>
<td>0.065</td>
<td>50.63</td>
<td>21.29</td>
<td>72.6</td>
<td>2.601</td>
<td>2.737</td>
</tr>
</tbody>
</table>

---

Fig. 10. Time histories of propulsion coefficients at the conditions of \( n_M = 7.83 \) rps at the design speed.

---

Table 4

Total resistance, added resistance, sinkage and trim in calm water in regular head waves in model scale at \( \lambda/LPP = 0.6 \) with various wave steepnesses at various ship speeds.

---

Fig. 11. Added resistance coefficient vs. wave steepness at the design speed in model scale (\( \lambda/LPP = 0.6 \)).
4.4. Taylor expansion method

The $R_{TM}^W$ can be expressed as a function of ship speed and approximated by Eq. (14):

$$R_{TM}^W = R_{TM} + R_{AW} - \left(\frac{dR_{TM}}{dV} + \frac{dR_{AW}}{dV}\right)\Delta V_M$$

The $\Delta V_M$ is predicted at constant power condition in calm and in waves ($P_{DM}=P_{DW}$) as expressed in Eq. (15):

$$\frac{(R_{TM}^C - FD C)\cdot V_M^C}{\eta_{DM}} = \frac{(R_{TM}^W - FD W)\cdot V_M^W}{\eta_{DM}}$$

Note that the TF should be applied to obtain correctly scaled propeller loading.

Inserting Eq. (14) into Eq. (15), and neglecting higher order terms, then the $\Delta V_M$ can be expressed as Eq. (16):

$$\Delta V_M = V_M^C \frac{R_{TM}^C + R_{AW} - (R_{TM}^C - FD C)\eta_{DM}^P}{R_{TM}^C + R_{AW} - FD W + (\frac{dR_{TM}}{dV} + \frac{dR_{AW}}{dV}) V_M^W}$$

If we assumed that the towing force in calm water is the same as that in waves ($FD C=FD W=FD$), Eq. (16) becomes

$$\Delta V_M = V_M^C \frac{R_{TM}^C + R_{AW} - FD W}{R_{TM}^C + R_{AW} - FD + (\frac{dR_{TM}}{dV} + \frac{dR_{AW}}{dV}) V_M^W}$$

The Eq. (17) is actually an expression for the speed loss due to waves in model scale when the delivered power is kept constant. If the overload factors ($\xi_p$ and $\xi_n$) are available, the $\eta_{DM}^W$ may be obtained as expressed in Fig. 13(a):

$$\frac{\eta_{DM}^W}{\eta_{DM}^P} = \frac{\xi_p}{R_{TM}} R_{AW} + 1$$

The $\Delta V_S$ can be obtained from the Froude’s assumption.
### Table 6

Speed loss in regular head short waves of \(\lambda/LPP = 0.6\) at various ship speeds using Taylor expansion method.

<table>
<thead>
<tr>
<th>(H/\lambda)</th>
<th>(V_S) [knots]</th>
<th>(V_M) [m/s]</th>
<th>(R_{RAW}) [N]</th>
<th>(\Delta R_{RAW}) [N]</th>
<th>(\Delta V_M) [m/s]</th>
<th>(\Delta V_M)%</th>
<th>(\Delta V_S) [kts]</th>
<th>(\Delta V_S)%</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.007</td>
<td>14.0</td>
<td>1.026</td>
<td>0.77</td>
<td>3.2</td>
<td>0.020</td>
<td>2.0</td>
<td>0.27</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>14.5</td>
<td>1.062</td>
<td>0.89</td>
<td>3.4</td>
<td>0.022</td>
<td>2.0</td>
<td>0.30</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>15.0</td>
<td>1.099</td>
<td>1.03</td>
<td>3.7</td>
<td>0.024</td>
<td>2.2</td>
<td>0.33</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>15.5</td>
<td>1.136</td>
<td>1.19</td>
<td>4.0</td>
<td>0.028</td>
<td>2.4</td>
<td>0.37</td>
<td>2.4</td>
</tr>
<tr>
<td>0.017</td>
<td>14.0</td>
<td>1.026</td>
<td>5.55</td>
<td>22.8</td>
<td>0.135</td>
<td>13.2</td>
<td>1.84</td>
<td>13.1</td>
</tr>
<tr>
<td></td>
<td>14.5</td>
<td>1.062</td>
<td>5.65</td>
<td>21.8</td>
<td>0.128</td>
<td>12.1</td>
<td>1.75</td>
<td>12.1</td>
</tr>
<tr>
<td></td>
<td>15.0</td>
<td>1.099</td>
<td>5.77</td>
<td>20.9</td>
<td>0.125</td>
<td>11.4</td>
<td>1.71</td>
<td>11.4</td>
</tr>
<tr>
<td></td>
<td>15.5</td>
<td>1.136</td>
<td>5.90</td>
<td>20.1</td>
<td>0.130</td>
<td>11.4</td>
<td>1.76</td>
<td>11.4</td>
</tr>
<tr>
<td>0.023</td>
<td>15.5</td>
<td>1.136</td>
<td>10.08</td>
<td>34.4</td>
<td>0.210</td>
<td>18.5</td>
<td>2.86</td>
<td>18.5</td>
</tr>
<tr>
<td>0.033</td>
<td>15.5</td>
<td>1.136</td>
<td>21.29</td>
<td>72.6</td>
<td>0.390</td>
<td>34.3</td>
<td>5.31</td>
<td>34.3</td>
</tr>
</tbody>
</table>

### 4.6. Load variation method

The \(R_{RAW}\) is assumed to be the external towing force, since the \(R_{RAW}\) is mainly caused by a non-viscous phenomenon. Then the FD in waves (FD\(^W\)) can be expressed as:

\[
FD^W = FD - R_{RAW} \quad (26)
\]

The self-propulsion point due to \(R_{RAW}\) may be found from the towing and the self-propulsion computations for the given \(V_M\). The values of \(n_{M,TM}\) and \(Q_{M}\) at the self-propulsion point are obtained from reading off those of the self-propulsive computational results at the value of \(T^W\) in the same way as discussed in Fig. 12.

Fig. 14 displays towing force, propeller rotating speed, thrust and torque versus ship speed at self-propulsion point in model scale in calm water and in regular head short waves using load-variation method. At model ship speed constant condition, as the wave steepness increases, the TF decreases. The \(n_{M,TM}\) and \(Q_{M}\) increase due to the decreased TF to balance the over-loaded propeller.

A speed-powering prediction in full scale is performed utilizing the revised ITTC-78 method as previously discussed. Fig. 15 displays the resistance and propulsion characteristics versus ship speed in calm water and in regular head waves (\(\lambda/LPP = 0.6\)) using load-variation method. At constant ship speed condition, the resistance in waves (\(R = R_{TS} + \Delta R\)) increases due to the \(R_{RAW}\) [Fig. 15(a)]; the \(n\), \(T\) and \(Q\) in waves increase to balance the propeller load [Fig. 15(b), (c), (d)]. The \(t\) ([1-T/R]) decreases with increasing the \(R\) (although \(T\) also increases, the increasing rate of \(R\) is greater than that of \(T\) [Fig. 15(e)]. The \(w\) also decreases with similar tendency to the \(t\) [Fig. 15(f)]. Thus, the \(\eta_{PS} = [1-t]/[1-w]\) decreases with decreasing the \(w\) (although the \(t\) also decreases, the decreasing rate of \(w\) is greater than that of \(t\) [Fig. 15(g)]. The \(J = V_S(1-w)/(\pi D_P)\) decreases with increasing the \(n\) (although the \(w\) also decreases).

### Table 7

Power and propeller-rotating-speed increases in regular head short waves of \(\lambda/LPP = 0.6\) at various ship speeds using direct powering method.

<table>
<thead>
<tr>
<th>(H/\lambda)</th>
<th>(V_S) [knots]</th>
<th>(R_{RAW}) [kN]</th>
<th>(\Delta R_{RAW}) [kN]</th>
<th>(\Delta P_{DC}) [kW]</th>
<th>(\Delta P_{DC}) [kW]</th>
<th>(\Delta n) [rpm]</th>
<th>(\Delta n) [rpm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.007</td>
<td>14.0</td>
<td>95</td>
<td>6.3</td>
<td>1394</td>
<td>9.5</td>
<td>1.38</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>14.5</td>
<td>110</td>
<td>6.8</td>
<td>1656</td>
<td>10.1</td>
<td>1.53</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>15.0</td>
<td>126</td>
<td>7.3</td>
<td>1952</td>
<td>10.7</td>
<td>1.72</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>15.5</td>
<td>146</td>
<td>7.9</td>
<td>2425</td>
<td>12.0</td>
<td>1.93</td>
<td>2.6</td>
</tr>
<tr>
<td>0.017</td>
<td>14.0</td>
<td>683</td>
<td>45.3</td>
<td>12326</td>
<td>84.0</td>
<td>12.19</td>
<td>18.5</td>
</tr>
<tr>
<td></td>
<td>14.5</td>
<td>696</td>
<td>43.2</td>
<td>12573</td>
<td>76.7</td>
<td>11.60</td>
<td>17.0</td>
</tr>
<tr>
<td></td>
<td>15.0</td>
<td>710</td>
<td>41.2</td>
<td>12777</td>
<td>69.8</td>
<td>11.27</td>
<td>15.9</td>
</tr>
<tr>
<td></td>
<td>15.5</td>
<td>726</td>
<td>39.5</td>
<td>14170</td>
<td>70.3</td>
<td>11.29</td>
<td>15.4</td>
</tr>
<tr>
<td>0.023</td>
<td>15.5</td>
<td>1241</td>
<td>67.6</td>
<td>28748</td>
<td>142.7</td>
<td>22.90</td>
<td>31.3</td>
</tr>
<tr>
<td>0.033</td>
<td>15.5</td>
<td>2621</td>
<td>142.7</td>
<td>120935</td>
<td>600.4</td>
<td>96.35</td>
<td>131.5</td>
</tr>
</tbody>
</table>
Thus the $h_O$ decreases with the same tendency to the $J$ [Fig. 15(i)]. The $h_R$ ($\frac{Q_0}{Q}$) decreases with increasing the $Q$ [Fig. 15(j)]. The $h_D$ consequently decreases due to the reduced $h_H$, $h_O$ and $h_R$ [Fig. 15(k)]. The delivered power rapidly increases to maintain the ship speed constant as shown in Fig. 15(l) due to the $R_{AW}$ [Fig. 15(a)] and the decreased $\eta_D$ [Fig. 15(k)].

To know these characteristics at constant delivered power condition, it is necessary to investigate the resistance and
propulsion characteristics versus delivered power (PD = PDF + ΔPD) in calm water and in waves using load-variation method as displayed in Fig. 16. The ship speed in waves rapidly decreases as the PD increases [Fig. 16(a)], the so called ‘speed loss in waves’. The RT, T, Q, t, w and ηH in calm water are nearly same as those in waves at the constant PD condition [Fig. 16(b),(d),(e),(f),(g),(h)]. The n slightly decreases at the constant PD condition as the RAW increases [Fig. 16(c)]. The J, ηO, ηR and ηD significantly decreases at the constant PD condition as the RAW increases [Fig. 16(i),(j),(k),(l)]. The J decreases as the RAW increases due to the speed loss in waves (although the n decreases) [Fig. 16(i)]. The J shows similar tendency to the J [Fig. 16(j)]. The ηR decreases as the RAW increases [Fig. 16(k) since the Q% decreases due to the decreased J]. The ηD consequently decreases due to the reduced ηO and ηR [Fig. 16(l)].

Fig. 16. Resistance and propulsion characteristics versus delivered power in calm water and in regular head waves (λ/LPP = 0.6) using load-variation method.

The effect of wave steepness on the propulsion performances in regular head waves (λ/LPP = 0.6) at design speed is present in Fig. 17. As the wave steepness increases, the RT% rapidly increases as discussed in Table 4 and Fig. 11; the T% and Q% are linear to the RT%; the n% moderately increases comparing to the RT%; the decreasing rate of w% is greater than that t%, thus the ηH% decreases; the ηO% decreases since the J% decreases due to the increasing n% (although w% decreases); the ηR% decreases since the Q% increases; thus, the ηD% rapidly decreases since the ηH%, ηO% and ηR% decrease; totally, the PD% rapidly decreases due to not only increasing the RT% but also the decreasing the ηD% (or not only increasing the n% but also increasing Q%). Note that the ΔPD% is the wave component of the sea margin, which mainly consists of wave, wind and fouling.

4.7. Resistance and thrust identity method (RTIM)

The power increase in waves is calculated according to the ITTC-recommended procedures and guidelines 7.5-02-07-02.2 (2014). Fig. 18 displays the procedure to obtain PD% at constant ship speed condition utilizing the propeller-open-water characteristic curves applying the RTIM.

The RWT is obtained from Eq. (23). The t and w in waves are assumed to be the same as those in calm water, that is, tW = tS and wW = wS. Then thrust in waves and Kf/Jf can be obtained:

\[ T_w = \frac{RWT}{T - tS} \]  

(27)
On the KT/J curve, JS is obtained; see Fig. 18(A) and (B).

\[ JS = \left( \frac{1}{C_0} \right) n S \]

The nS is calculated by using Eq. (29). At this JS value, power coefficient KP is obtained on the KP curve; see Fig. 14(C). By using this KP value, the power in waves is calculated by

\[ PD_W = 2\pi \cdot n_S \cdot Q_S = 2\pi \cdot K_P \cdot \rho_S \cdot \left( 1 - w_S \right)^3 \cdot V_S^3 \cdot D_p^2 \]  \hspace{1cm} (31)

The power increase in regular head short waves of \( \lambda/LPP = 0.6 \) at various ship speeds using the RTIM are listed in Table 8.

4.8. Comparison of the results using four methods

The delivered powers and propeller rotating speeds for various ship speeds in calm water and in regular head waves using four methods are compared in Fig. 19. At the condition of PD = 20,144 kW in regular head waves of \( \lambda = 192.0 \text{ m} \) and \( H = 1.28 \text{ m} \) corresponding to BN = 4 [Fig. 19(a)], the ship speed is 15.50 knots (design speed) with propeller rotating speed of 73.28 rpm in calm water; 15.13 knots using Taylor expansion method, 14.97 knots with 72.40 rpm using direct powering method, 14.96 knots with 72.44 rpm using load variation method, and 15.06 knots with 72.54 rpm using RTIM. In regular head waves of \( \lambda = 192.0 \text{ m} \) and \( H = 3.16 \text{ m} \) corresponding to BN = 6 [Fig. 19(b)], the delivered power to maintain the ship speed constant needs 1.70 times using direct power method (34,314 kW), 1.62 times using load variation method (32,724 kW) or 1.50 times using RTIM (30,257 kW) of that in calm water (20,114 kW). Note that the increased delivered power in \( \lambda = 192.0 \text{ m} \) and \( H = 3.16 \text{ m} \) is due to not only the increased resistance (39.5% of the RTS) but also the reduced propulsive efficiency (14.2% of the \( h_D \)).

The magnitude order of the PD in waves of \( \lambda/LPP = 0.6 \) and \( H/l = 0.017 \) is Taylor expansion < RTIM < load variation < direct powering method. In waves of \( \lambda/LPP = 0.6 \) and \( H/\lambda = 0.007 \), the differences between the load variation and the direct powering method are very small. This is seemed to be due to the assumption that the \( R_{AW} \) acts on the external towing force in load variation method.

The \( f_w \) and \( sm \) in regular head waves of \( \lambda/LPP = 0.6 \) and \( H/\lambda = 0.007 \) corresponding to BF = 4 using four methods are summarized in Table 9. In the case of \( \lambda/LPP = 0.6 \) and \( H/\lambda = 0.017 \) corresponding to BF = 6, the \( f_w \)s are out of range at PD = 20,144 kW as shown in Fig. 19(b).
5. Conclusions

- Power increase (or speed loss) and propulsion performances in regular short head waves with varying levels in steepness of KVLCC2 have been predicted through computational tools.
- A comparative study utilizing four prediction methods has been performed - Taylor expansion, direct powering, load variation, resistance and thrust identity methods. The magnitude order of the increased delivered power in waves of $l/L_{PP} = 0.6$ and $H/l = 0.007$ is Taylor expansion $<$ RTIM $<$ load variation $<$ direct powering method.
- At constant ship speed condition in waves; resistance, propeller rotating speed, thrust and torque increase to balance overloaded propellers. As a result, thrust deduction and wake fraction, hull efficiency are scarcely varied; propeller advance coefficient, propeller-open-water, relative rotative and propulsive efficiencies, and ship speed significantly decrease.
- As the wave steepness increases; quadratic dependency of added resistance due to waves becomes weaker; delivered power more rapidly decreases due to not only increasing added resistance but also decreasing the propulsive efficiency.

Acknowledgements

This work was supported by the National Research Foundation of Korea grant funded by the Korea government (MSIT) (No. 2011-0030013) and by the Industrial Strategic Technology Development Program (No. 10076439) funded by the Ministry of Trade, Industry and Energy, to which deep gratitude is expressed.

References

Abdel-Maksoud, Hamburg, Germany, 1: 8.


