Prediction method of hydrodynamic forces acting on the hull of a blunt-body ship in the even keel condition

Donghoon Kang · Kazuhiko Hasegawa

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Abstract The mathematical modeling group (MMG) model is well known and is widely used in the field of ship maneuverability. However, the MMG model can be applied only after determination of the hydrodynamic coefficients either from comprehensive captive model tests or from general empirical data. Around the cruising speed, when a ship's drift angle is relatively small, several methods have been developed to predict hydrodynamic coefficients from the ship's principal particulars, e.g., Kijima's method. Kijima's method is efficient in predicting the ship's maneuverability at the initial design stage and is even able to assess the effect of changes in stern design. Similarly, for the low speed range when a ship's drift angle is relatively large, several methods for predicting the ship's hydrodynamic coefficients have been proposed, based on captive model tests, such as those by Kose, Kobayashi, and Yumuro. However, most of the methods developed for low speeds cannot be applied to general ship types without additional experiments being performed. In contrast, Karasuno's method uses theoretical and empirical approaches to predict the hydrodynamic forces, even for large drift motions. Although Karasuno's model utilizes the ship's principal particulars and is applicable to a general vessel, it has not been widely used. This is because the form of Karasuno's model is relatively complicated and its accuracy around the cruising speed is less than that for other methods that have been specifically developed for the cruising speed range. A practical method for predicting hydrodynamic forces for the entire operating speed range of blunt-body ships is proposed in this article. It is based on the MMG model and predicts hydrodynamic coefficients based on a ship's principal particulars. A regression model for the proposed method has also been proposed by analyzing 21 different blunt-body ships. Finally, simulations of a very large 4-m crude carrier (VLCC) model using the proposed method were carried out and the results compared with free-running experiments (both at the cruising speed and at low speeds) to validate the efficacy of the model.

Key words Hydrodynamic force · Low speed · Highly oblique motion · MMG model

List of symbols

\( a_w \) ratio of hydrodynamic force induced on ship hull by rudder action to the rudder force

\( a_{x2}, a_{x4}, b_{x1}, b_{x2} \) hydrodynamic coefficients of the surge force

\( a_{y1}, a_{y3}, a_{y5}, c_{y1}, d_{y1}, c_{y1} \) hydrodynamic coefficients of the sway force

\( a_{n2}, a_{n4}, a_{n2}, d_{n0}, d_{n2}, e_{n0} \) hydrodynamic coefficients of the yaw moment

\( A_r \) rudder area

\( B \) ship breadth

\( C_b \) block coefficient

\( C_{pa} \) prismatic coefficient of the aft hull

\( C_{Kb}, C_{RP} \) coefficients of inflow velocity for the starboard and port rudder, respectively

\( C_{wa} \) water plane area coefficient of the aft hull
\( d \)  
ship draft

\( D_r \)  
propeller diameter

\( e_a \)  
sternt hull form parameter (1)  
defined by Mori\(^1\)

\( e_s \)  
sternt hull form parameter (2)  
defined by Mori

\( K \)  
sternt hull form parameter (3)  
defined by Mori

\( \sigma_u \)  
sternt hull form parameter (4)  
defined by Mori

\( F_{NS}, F_{NP} \)  
rudder normal force for the  
starboard and port rudder, respectively

\( h_r \)  
ruddering height

\( I_z \)  
yaw moment of inertia

\( J_z \)  
advance ratio

\( J_m \)  
amended yaw moment of inertia

\( k \)  
ship aspect ratio

\( L \)  
ship length

\( m \)  
ship mass

\( m_s \)  
amended mass in surge

\( m_p \)  
amended mass in sway

\( N_H, N_R, N_A = \frac{1}{2} \rho L^2 u^2 \cdot (N_H^0, (N_R^0, (N_A^0)} \)  
yaw moment components of  
hull, rudder, and wind acting  
on the ship

\( n \)  
propeller revolutions

\( P \)  
propeller pitch

\( r = r' \cdot (U/L) \)  
yaw rate at ship’s center

\( \rho \)  
wetted surface area

\( t_r \)  
coefficient for additional drag of  
the rudder

\( u \)  
surge velocity

\( U \)  
ship velocity

\( v \)  
sway velocity

\( x_0 \)  
longitudinal center of gravity of the  
ship

\( x_h \)  
ratio of hydrodynamic moment  
induced on the ship hull by  
rudder action to the rudder force

\( x_r \)  
x-coordinate of the rudder  
location

\( x_i \)  
longitudinal center of gravity  
of added mass of the ship

\( X_H, X_R, X_A = \frac{1}{2} \rho L d u^2 \cdot (X_H^0, (X_R^0, (X_A^0)} \)  
x-axis components of hull,  
propeller, rudder, and wind  
force acting on the ship

\( X_M \)  
measured force in the x-axis  
direction during the captive  
model test

\( \nu \)  
hydrodynamic coefficient for  
surge force from Hasegawa’s chart

\( Y_{HR}, Y_{HR}, Y_A = \frac{1}{2} \rho L d u^2 \cdot (Y_{HR}^0, (Y_{HR}^0, (Y_A^0)} \)  
\( \alpha_{sR}, \alpha_{sR} \)  
rudder inflow angle

\( \beta \)  
rudder inflow angle

\( \delta_m, \delta_p \)  
starboard and port rudder  
angles

\( \epsilon \)  
wake ratio between propeller  
and rudder

\( \gamma_r \)  
flow straightening factor

\( \omega_r \)  
effective wake fraction

\( \psi_r \)  
angle of wind encounter

\( \odot \) Springer

**Introduction**

Most vessels are tested for their maneuverability during sea trials before delivery; however, maneuvering trials are usually few and are carried out only to check conformance with International Maritime Organization (IMO) standards.\(^1\) It is difficult to use full-scale trials for assessing the maneuverability of a vessel in detail, because they are very expensive and time consuming. Model tests are usually carried out instead of full-scale trials, but they are also relatively expensive and time consuming. In recent years, the need for assessing the maneuverability of vessels has gradually increased for meeting the requirements of design, operation, and simulator facility. In response to this requirement, prediction methods for assessing the maneuverability of vessels have been developed. The IMO has also developed standards for assessing maneuvering performance criteria of vessels using numerical methods at the design stage. From a practical point of view, Kijima\(^2\) and Lee\(^3\) have proposed regression models for assessing hydrodynamic forces acting on the hull (hereinafter, hull forces) using a database of model ship tests. These regression models were developed based on the mathematical modeling group (MMG) model,\(^4\) and are easy to adopt at the design stage. This is because these models are able to predict hull forces using a ship's principal particulars. Kijima's regression model is additionally able to assess the effect of changes in the stern shape, and this model's efficacy at the design stage has been verified. Similarly, Lee's regression model predicts hull forces using parameters of the stern hull form, and it also utilizes propeller particulars as a parameter of the regression model. However, the above-mentioned IMO
standards and regression models are only concerned with behavior at the cruising speed.

When a vessel departs from or arrives in a port, it undergoes various complicated maneuvering operations, e.g., course alteration, acceleration, and deceleration. These maneuvering operations are not performed in any particular order; they are performed either individually or in conjunction with one another at various speeds. Although the duration of low-speed operations is short compared to cruising-speed conditions, they are crucial to the safe operation of a ship. This is because low-speed maneuvers are usually performed in restricted areas and are vulnerable to external forces, such as currents, wind, and waves. Despite this fact, low-speed maneuvers are not the central concern for design and research of most ships. Therefore, a need to extend performance assessment to low-speed operations has evolved from simulations and real experience. Several methods have been developed for predicting ship motion at low speeds, such as those of Kose, Kobayashi, Yamuro, and Karasuno. Kose, Kobayashi, and Yamuro’s methods were developed for a specific ship having captive model test results, and their results match well with those of the experiments. However, none of the above methods is yet established for a general ship type. Karasuno has proposed a component-type mathematical model for predicting hull forces. Karasuno’s model is developed theoretically and empirically using a simplified vortex model and is able to express highly oblique motion of a ship. Karasuno’s model can also predict hull forces using a ship’s principal particulars, as the Kijima model does; however, it cannot assess the effect of changes in the stern design.

In this article, a practical prediction method for hull forces from the cruising speed to low-speed maneuvers for a blunt-body ship is proposed. The prediction method was developed based on the MMG model to increase its adaptability for a general vessel type. When selecting the equations for the hull forces, the ability to accurately estimate hull forces from the cruising speed to low speeds was the principal focus of this research. For operations around the cruising speed, the results of Kijima’s model are used to generate the hydrodynamic forces and moments for the proposed model, while the results of Karasuno’s model are used to generate the hydrodynamic forces and moments for the low-speed range where relatively large drift motions are experienced. The proposed method is distinct from Lee’s model in the sense that the propeller details need not be fixed for the analysis.

A regression model is proposed for easy application of the proposed method. The regression model has been designed so that the hydrodynamic coefficients can be predicted by using a ship’s design parameters only. Twenty-one different blunt-body ships were analyzed with the proposed method to build the regression model. Finally, a very large 4-m crude carrier (VLCC) model was simulated with the proposed method and regression model, and the results of the simulations were compared with the equivalent free-running experiments.

**Range of consideration**

The characteristics of a maneuvering ship can be expressed in terms of its nondimensional yaw rate (hereinafter \( \dot{\gamma} \)) and drift angle (hereinafter \( \beta \)). To analyze a ship’s performance, including that at low speed, the range of consideration of \( \dot{\gamma} \) and \( \beta \) should first be determined. If an unrealistic operating range is considered, then the accuracy of the predicted hydrodynamic hull forces will be reduced.

It is well known that a ship maneuvering at its cruising speed performs with small \( \dot{\gamma} \) and \( \beta \) values compared with the values for low-speed maneuvering. Free-running experiments of berthing were carried out to recognize the characteristics of a ship maneuvering at low speed. Table 1 shows the principal particulars of the ship that was used in the experiment. The experiment was conducted as per Endo’s berthing procedure. However, during the experiments, the model ship was initially decelerated from half speed to slow speed and only one course alteration was considered; the above procedure was followed because of the restricted nature of the experimental area.

Figure 1 shows the trajectory of the model ship and the time histories of the parameters. From the time histories of \( v \) and \( r \) it can be concluded that the ship smoothly berthed without being disturbed by external factors such as wind. It may be noted that the increments in \( v \) and \( r \) after 190 s were caused by the propeller reversing effect. The characteristics of this experiment is shown in Fig. 2 using \( \dot{\gamma} \) and \( \beta \). Figure 2 shows the duration of each combination of \( \dot{\gamma} \) and \( \beta \) as a percentage of the total duration of the experiment. The ship’s performance is mainly in the region of small \( \dot{\gamma} \) and \( \beta \); the maximum values of \( \dot{\gamma} \) and \( \beta \) were 1.6 and 90°, respectively. It is noted that the ship’s performance is mostly distributed in the first quadrant; this is because the ship performed

<table>
<thead>
<tr>
<th>Table 1. Principal dimensions of the model ship</th>
</tr>
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<tbody>
<tr>
<td>( L )</td>
</tr>
<tr>
<td>( B )</td>
</tr>
<tr>
<td>( d )</td>
</tr>
<tr>
<td>( C_0 )</td>
</tr>
</tbody>
</table>

The rudder was a mariner type super VecTwin
The characteristics of those two experiments in case 2 show the differences between the two different ships' performances. The time histories of the two different propulsion systems in case 2 from the experiments show a significant difference in the increase in total ship velocity because of the increase in total ship velocity by the wind. Although the total ship velocity was increased by the wind, the total ship velocity was decreased by the wind and the total ship velocity was increased by the wind and the total ship velocity was decreased. This is because the wind and the current flow in the opposite direction. In case 1, the wind's influence on the ship's motion is more pronounced. In case 2, the wind's influence on the ship's motion is less significant. The ship's motion is affected by wind, and the direction of the wind changes. The ship's motion is affected by the wind and the current flow in the opposite direction. The ship's motion is affected by wind and the current flow in the opposite direction. The ship's motion is affected by wind and the current flow in the opposite direction. The ship's motion is affected by wind and the current flow in the opposite direction.
Fig. 4. Characteristics of ship performance for berthing experiments from the time of propeller stop

Fig. 5. Experimental and calculated values of $Y_H$ and $N_H$ at $r' = 0$

Considering the above results, the ranges of $r'$ and $\beta$ to be considered in the current work were set as $(0 \leq r' \leq 1.6, \ 0^\circ \leq \beta \leq 90^\circ)$ and $(-1.6 \leq r' \leq 0, -90^\circ \leq \beta \leq 0^\circ)$ respectively. In astern motion, relatively large values of $r'$ and $\beta$ occur in the second and fourth quadrants; because the astern condition was not researched in this work, the corresponding range of $r'$ and $\beta$ were ignored.

**Base calculation of hull forces**

In this research, the hull forces calculated by Kijima's method and Karasuno's method are used as a reference, but the range over which these methods give accurate results must first be determined. The hull forces of the VLCC Esso Osaka were calculated using Kijima's and Karasuno's methods and compared with experimental results. Figures 5 and 6 show the results of experiments and those of Kijima's and Karasuno's methods for $Y_H$ and $N_H$ for the Esso Osaka under different conditions. The conditions for the calculations and experiments are $r' = 0$ for Fig. 5 and $\beta = 0$ for Fig. 6.

From Fig. 5, it can be observed that Karasuno's method well represents the trend of experimental results up to $\beta = 90^\circ$. As expected, the results using Kijima's method have a marked deviation from the experimental data for $\beta > 20^\circ$. From Fig. 6 it can be observed that Kijima's method accurately represents experiment results for small $\beta$. Generally, Kijima's method matches...
well with the experimental results below drift angles of 20°, while Karasuno’s method well describes the trend of the overall experimental data.

Considering the accuracy and continuity of Kijima’s and Karasuno’s methods, Kijima’s method was used up to β = 30°, while Karasuno’s method was used for the rest of range to calculate the hull forces of a ship. These are considered as base data for this research. It is noted that the experimental data for $X_N$ for the Esso Osaka have not been published, so the comparison for $X_N$ has been omitted here. It is well known that $X_N$ from Hasegawa’s chart" well expresses $X_N$ for small β values; Kijima’s method also uses $X_N$ for expressing $X_N$. In the current work, the base data for $X_N$ was generated by using $X_N$ up to β = 30°, while for β > 30° the base data for $X_N$ was generated by using Karasuno’s method.

**Equations of ship maneuvering**

The equations of a maneuvering ship were written as per the MMG model. The mathematical model of ship maneuvering was described based on three degrees of freedom: surge, sway, and yaw. The equations of ship maneuvering motion are written as:

\[
\begin{aligned}
(m + m_o) \ddot{u} - m \cdot \dot{v} \cdot r + x_o \cdot r^2 &= X \\
(m + m_o) \ddot{v} + (m \cdot x_o + m_r \cdot x_r) \dot{r} + m \cdot u \cdot r &= Y \\
(I_z + m \cdot x_o^2 + J_z + m_r \cdot x_r^2) \ddot{r} + (m \cdot x_o + m_r \cdot x_r) \dot{r} + m \cdot x_o \cdot u \cdot r &= N
\end{aligned}
\]

The external forces $X$, $Y$, and moment $N$ consist of hull, rudder, and wind components as follows:

\[
\begin{aligned}
X &= X_H + X_r + X_K + X_A \\
Y &= Y_H + Y_r + Y_A \\
N &= N_H + N_r + N_A
\end{aligned}
\]

(1)

The coordinate system and the definition of various parameters are shown in Figure 7.

**Expression of hull forces**

To develop and select the equations for expressing the hull forces as mentioned above, the ability to accurately and continuously estimate the hull forces for the entire range of ship speeds is regarded as important. The physical meanings of terms that are components of the equations were not considered important. Equations 3–5 are used for expressing the hull forces of a ship. Equation 3, for the surge force, was developed by estimating the surge force for a wide range of $r^*$ and β values. Equations 4 and 5 for the sway force and yaw moment were taken from Yumuro’s proposal:

\[
\begin{aligned}
X_N &= (ax^2 \cdot \sin^2 (\beta) + ax^4 \cdot \sin^3 (2\beta)) \cdot \cos (\beta) \\
&+ bx \cdot \sin (\beta) \cdot r^* \\
&+ bx^2 \cdot \sin (2\beta) \cdot r^* \cdot \text{sign} (\cos (\beta)) + R'(u)
\end{aligned}
\]

(3)

\[
\begin{aligned}
Y_N &= (ay^1 + cy^2 \cdot r^2) \cdot \sin (\beta) \\
&+ ay^3 \cdot \sin (3\beta) + ay^5 \cdot \sin (5\beta) \\
&+ (dy^1 \cdot r^* + ey^1 \cdot r^3) \cdot \cos (\beta)
\end{aligned}
\]

(4)

\[
\begin{aligned}
N_N &= (an^2 + cn^2 \cdot r^2) \cdot \sin (2\beta) \\
&+ an^4 \cdot \sin (4\beta) + dn^2 \cdot r^* \\
&+ en^3 \cdot r^* \cdot \cos (2\beta)
\end{aligned}
\]

(5)

The results obtained from Kijima’s and Karasuno’s methods are used as the base data, as mentioned earlier. The base data were posited as the results of experiments and analyzed as per the method of analyzing experimental data\textsuperscript{3,11} to generate hydrodynamic coefficients such as ax2 and dn2 in Eqs. 3–5. The analysis to determine whether the developed and selected equations well express the base data was carried out for the Esso
Osaka. The hydrodynamic coefficients in Eqs. 3–5 were
determined by the above-mentioned analysis method.
Hull forces and moments for the *Esso Osaka* were
calculated again using the determined coefficients for
$-90^\circ \leq \beta \leq 90^\circ$ so as to validate the equations; the results
are shown in Figs. 8–10. It can be observed that
Eqs. 3–5 match well with the base data for the range
$-90^\circ \leq \beta \leq 90^\circ$ and $-1.6 \leq r' \leq 1.6$. This range of pa-
rameters was earlier shown to define the domain of low-
speed as well as cruising-speed maneuvering. Equations
3–5 can be used for simulating berthing maneuvers in
which the ship decelerates from cruising speed to low
speed, which until now has been difficult with other
models, as described earlier. It may also be noted that
although the equations are designed for $|\beta| \leq 90^\circ$, they
are also able to express the tendency of the hull forces
for $|\beta| \geq 90^\circ$.

Regression model for a blunt-body ship

A regression model for a blunt-body ship at even keel is
here proposed for easy application of the above method.
The hull forces and moments were calculated for 21 dif-
f erent blunt-body ships using the proposed method,
and the hydrodynamic coefficients for each ship were
The regression model is shown in Eq. 7:

\[ y = \frac{a}{x} + b \]

where \( y \) is the original value from the base data, \( x \) is the predicted value using the regression model, and \( a \) and \( b \) are the coefficients of the regression equation.

The regression model is given by:

\[ y = a \frac{x}{b} + c \]

where \( y \) is the original value from the base data, \( x \) is the predicted value using the regression model, and \( a \), \( b \), and \( c \) are the coefficients of the regression equation.

Table 3: Regression parameters for the regression model

<table>
<thead>
<tr>
<th>Sign and ship</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>-D</td>
<td>c</td>
<td>0.50</td>
</tr>
<tr>
<td>-R</td>
<td>p</td>
<td>0.35</td>
</tr>
<tr>
<td>-D</td>
<td>q</td>
<td>0.45</td>
</tr>
<tr>
<td>-R</td>
<td>r</td>
<td>0.20</td>
</tr>
</tbody>
</table>

The regression model is given by:

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where \( y \) is the original value from the base data, \( x \) is the predicted value using the regression model, and \( a \), \( b \), and \( c \) are the coefficients of the regression equation.

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Fig. 12. Experimental data and calculations for $Y_h$

$$an2 = \frac{B}{L} \left( 0.07093 + 1.1936 \frac{d}{B} \right)$$
$$an4 = K \left( -0.052545 + 0.42428 \frac{C_d B}{K} \right)$$
$$cn2 = \frac{d}{B} \left( -0.14737 + 0.43812 \frac{d (1 - C_d)}{B} e_r \right)$$
$$dn0 = -0.06338 - 1.253 \frac{d (1 - C_d)}{B} K$$
$$dn2 = k (0.46815 - 0.82503 C_d e_r)$$
$$cn0 = -0.04755 + 0.10488 K$$

(9)

To validate the above equations, the *Esso Osaka* was analyzed with the regression model and the hull forces and moments were compared to the experimental data.\(^8\) Figures 12 and 13 show the results for the sway force and yaw moment. The calculations of the sway force match well with the experimental data. For the yaw moment, the calculation does not match well with the experimental data for $30^\circ < \beta < 70^\circ$. There are two reasons for this. First, the yaw moments predicted by Karasumo’s method are slightly larger than those determined by experimental data. Second, the slope of the yaw moment predicted by Kijima’s method for $\beta \leq 30^\circ$ is such that it tends to increase the yaw moment for $\beta \geq 30^\circ$. The result of these two factors is that the predicted yaw moment is higher. However, the overall tendency of the calculated yaw moment is still reasonable and the calculations match well with the experimental data in the region of small $\beta$ and $\beta = 90^\circ$. The limits of the design particulars of the 21 different blunt-body ships that were analyzed for developing this regression model are shown in Table 4.

### Table 4. Applicable parameter ranges of blunt-body ships used for the regression model

<table>
<thead>
<tr>
<th>Ship parameter</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B / L$</td>
<td>0.163</td>
<td>0.2</td>
</tr>
<tr>
<td>$d / L$</td>
<td>0.055</td>
<td>0.073</td>
</tr>
<tr>
<td>$d / B$</td>
<td>0.302</td>
<td>0.411</td>
</tr>
<tr>
<td>$C_d$</td>
<td>0.777</td>
<td>0.833</td>
</tr>
</tbody>
</table>

### Validation with simulation

Several simulations were also carried out and compared with free-running experiments to validate the proposed method and regression model. A 4-m model VLCC
tanker, which was also used for the berthing experiments mentioned earlier, was used for the simulations and the experiment.

It may be observed that the initial conditions for some of the free-running experiments were not ideal. Maximum effort was made to keep the initial conditions of the experiments, such as the sway speed and yaw rate, equal to zero. However, some of the experiments commenced with a small deviation. It may be noted that since the experiments were carried out outdoors, it was difficult to start with the desired initial conditions. Another reason for the deviation is the real-time kinematic global positioning system (RTK-GPS) system that was used for calculating the surge and sway speeds. The RTK-GPS system had an accuracy level of ±0.03 m. The initial conditions for the simulations were set considering the above factors.

Simulation model

For the simulations, the proposed method and regression model were used for calculating the hull forces, while the other forces and moments were taken from Hasegawa. Additional experiments were carried out to increase the accuracy of the mathematical rudder model. The experimental conditions are shown in Table 5.

Hamamoto’s expression is used to express the hydrodynamic forces and moment resulting from the VecTwin rudder, and is written as:

\[
\begin{align*}
X_R &= -(1-t_p)(F_{H_R} \sin \delta_g + F_{NP} \sin \delta_p) \\
Y_R &= -(1+a_{H})(F_{NP} \cos \delta_g + F_{NP} \cos \delta_p) \\
N_R &= -(x_R + a_{H}x_H)(F_{NP} \cos \delta_g + F_{NP} \cos \delta_p)
\end{align*}
\]

The interaction coefficients of the hull and rudder \((t, a_{H}, x_{H})\) were determined from towing tank experiments. Figure 14 shows the interaction between the hull, propeller, and rudder in the surge direction. The gradient of the graph is \(1-t\), because the vertical axis is the sum of the rudder forces and the horizontal axis is the rudder forces acting on the hull. The gradient of this graph for each set of experimental data does not vary significantly with the ship’s velocity and the propeller revolutions. Therefore, \(t\) was considered to be a constant value in the simulations. The interaction coefficients between the hull and the rudders in the sway and yaw directions \((a_{H}, x_{H})\) were similarly analyzed. The coefficients were different as per the experimental conditions. The plot of \(a_{H}\) versus \(J_s\) is shown in Fig. 15. The values of \(a_{H}\) were obtained by fitting a second-order polynomial through the experimental data with the additional assumption that \(a_{H} = 0\) when \(J_s = 0\). The plot of \(x_{H}\) versus \(J_s\) is shown in Fig. 16. The values of \(x_{H}\) were obtained by fitting a straight line through the experimental data.

To express the normal forces of the VecTwin rudder, Hasegawa’s proposal was used:

\[F_{NP} \sin(\delta_p) + F_{NP} \sin(\delta_g) (N)\]

![Fig. 14. Interaction between the hull, propeller, and rudder in the surge direction. The cases are explained in Table 5](image1)

![Fig. 15. Interaction coefficient \(a_{H}\)](image2)

![Fig. 16. Interaction coefficient \(x_{H}\)](image3)

### Table 5. Experimental conditions for model validation

<table>
<thead>
<tr>
<th>Case</th>
<th>Speed (m/s)</th>
<th>rps</th>
<th>(J_s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>0.2</td>
<td>7</td>
<td>0.237</td>
</tr>
<tr>
<td>Case 2</td>
<td>0.4</td>
<td>7</td>
<td>0.474</td>
</tr>
<tr>
<td>Case 3</td>
<td>0.4</td>
<td>13.7</td>
<td>0.342</td>
</tr>
<tr>
<td>Case 4</td>
<td>0.8</td>
<td>13.7</td>
<td>0.484</td>
</tr>
</tbody>
</table>
\[ F_{NS} = \frac{F_{NS}}{dA \cdot U_{RS}^2} \cdot C_{Rs} \cdot \tan^{-1}(C_{Rs} \alpha_{RS}) \]
\[ F_{NP} = \frac{F_{NP}}{dA \cdot U_{RP}^2} \cdot C_{Rs} \cdot \tan^{-1}(C_{Rs} \alpha_{RP}) \]
\[ U_{RS} = \frac{1}{U} \sqrt{\eta_{RS}^2 + \eta_{RP}^2} \]
\[ U_{RP} = \frac{1}{U} \sqrt{\eta_{RS}^2 + \eta_{RP}^2} \]
\[ u_{RS} = C_{Rs} \left( \delta_s \right) \times \frac{\epsilon u_p}{1 - s^2} \times \sqrt{1 - 2(1 - \eta \kappa) s + (1 - \eta \kappa (2 - \kappa)) s^2} \]
\[ u_{RP} = C_{Rs} \left( \delta_s \right) \times \frac{\epsilon u_p}{1 - s^2} \times \sqrt{1 - 2(1 - \eta \kappa) s + (1 - \eta \kappa (2 - \kappa)) s^2} \]
\[ u_p = (1 - \omega_p) \mu \]
\[ \kappa = k \xi e \]
\[ \eta = D_p / h_p \]
\[ s = 1 - u_p / nP \]
\[ \eta_{RP} = -\gamma_{RP} (v + L_e \cdot u) \]
\[ \gamma_{RS} = -\gamma_{RS} (v + L_e \cdot u) \]

Figure 17 shows the rudder normal forces measured during the towing tank experiments. \( C_{Rs} \left( \delta_s \right) \) and \( C_{Rs} \left( \delta_s \right) \) in Eq. 11 were calculated from the experimental data and were used in the simulation utilizing interpolation. It is noted that the rudder forces were only measured for the parallel rudder condition with zero lateral speed and yaw rate of the ship. However, it is assumed that \( C_{Rs} \left( \delta_s \right) \) and \( C_{Rs} \left( \delta_s \right) \) in the straight running condition and the turning condition are not significantly different.

In the current work, simulations were carried out to validate the proposed method and regression model, and the experimental results were used for developing the simulation model. The proposed method can also be used with different rudder and propeller models based on the MMG model; this is because the method here follows the concept of the MMG model.

Cruising speed simulation

Simulations and free-running experiments for cruising speed were carried out at full speed, which is 0.8 m/s for the model ship and 13.5 knots for the full-scale ship. Figure 18 shows the time histories of the yaw and rudder angles and Fig. 19 shows time histories of the velocity parameters for the -20° zigzag test. The results of the simulation show a small deviation from the experiment at the first overshoot angle, but show good agreement with rest of the experimental data. Figure 20 shows the trajectory of the ship and Fig. 21 shows the time histories of the velocity parameters for a -30° turning test. It may be noted that the turning circle of the simulation is slightly smaller than that of the experiment; however, the time histories of the surge, sway, and yaw rate match well with the experiment results. From the above results, it can be concluded that the proposed method and regression model are suitable for expressing the hull forces of a ship at its cruising speed.

Low-speed simulation

The zigzag test for low speed was carried out at Dead Slow, which is 0.36 m/s for the model ship and 6 knots

![Fig. 17. Measured rudder forces in the parallel rudder condition](image)

![Fig. 18. Heading (H) and rudder (R) angles for the -20° zigzag test at Full Speed](image)
for the full-scale ship; however, the initial speed of the experiment was 0.54 m/s. This means that the experiment was started at the commencement of deceleration from Slow to Dead Slow. The initial conditions of the simulation were set as per the above observation. Figures 22 and 23 show the time histories of the parameters during the slow zigzag test. Although the simulation deviates slightly from the experiment during the first overshoot angle, generally, the simulation matches well the experimental data.

Figure 24 shows the trajectory of a ship that starts turning at zero speed. This type of movement can often be observed during a ship’s departure from harbor. The propeller revolutions for this experiment and simulation were set to 11 rps, which corresponds to a model ship speed of about 0.6 m/s. Figure 25 shows the time histo-
(1) A practical method for predicting hull forces is proposed. The ability to predict hull forces for maneuvers carried out from low speed to cruising speed was validated with experimental data for the *Esso Osaka*.

(2) A regression model for predicting the hydrodynamic coefficients for the current method is also proposed based on analysis of 21 different blunt-body ships at even keel.

(3) Simulations with the proposed method and regression model were carried out and the results compared with the free-running experimental data at various speeds. The results of the simulations show reasonable agreement with the experimental data.

References


Fig. 24. Ship trajectories for the 30° turning test starting from zero speed

Fig. 25. Velocity parameters for the 30° turning test starting from zero speed

Fig. 26. Ship trajectories for the 20° turning test at Dead Slow

Fig. 27. Velocity parameters for the 20° turning test at Dead Slow

ries of the velocity parameters. From the above results, it can be concluded that the proposed method and regression model are suitable for expressing the hull forces of a ship at low speeds.

Simulation in wind

A ship maneuvering at low speed is easily affected by wind. Prediction of a ship's motion in windy condition is important from the point of view of safety, especially at low speeds. Figure 26 shows a 20° turning test started at Dead Slow in windy conditions. It can be observed from the time histories of the velocity parameters in Fig. 27 that the ship was influenced by wind. Unfortunately, the wind conditions were not measured during the experiment. The wind condition was predicted from the time histories of the velocity parameters and used as a constant wind during the simulation. The predicted wind condition was a wind angle of 140° at 1.7 m/s. Fujiwara's equation was used for calculating wind forces during the simulation. Even though a constant wind condition was used during the simulation, the simulated values matched well the experiment results. From the above results, it can be concluded that the proposed method and regression model are suitable for expressing the hull forces of a ship at low speed even under windy conditions.

Conclusions

This work proposes a practical method of predicting hull forces and also suggests a regression model to predict hydrodynamic coefficients for a blunt-body ship under even keel conditions. The proposed model was validated by comparing the results with experimental data for the Esso Osaka. Simulations of a 4-m VLCC ship model with the proposed regression model were carried out and compared with the equivalent free-running experiments to validate the proposed model.