<table>
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<th>Title</th>
<th>Instructions for use of Fishing Vessels</th>
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<tbody>
<tr>
<td>Author(s)</td>
<td>Yoshimura, Yasuo; Ma, Ning</td>
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Abstract: Fishing vessels generally have good performance in ship manoeuvrability. The relatively large rudder and propeller assist to make such performance, so there has been little need to the manoeuvering prediction. However, the manoeuvring prediction has become very important because the strong rudder force sometimes causes the capsizing accident. As for the principal dimensions of fishing vessels, they are different from conventional merchant ships. The ship length is generally small. The length beam ratio: \( L/B \) becomes less than 3.0 particularly in Northern Europe. Besides, they large initial trim by the stern. Therefore, the hydrodynamic force becomes quite complicated. This makes a difficulty when predicting the manoeuvrability of these vessels.

In this paper, the authors show the database of hydrodynamic derivatives with several fishing vessels including the recent European wide beam vessel, and then introduce the empirical formulas to predict the hydrodynamic derivatives as well as other hydrodynamic coefficients based on the obtained database. Using these empirical methods, manoeuvring ship motions can be easily simulated and the manoeuvring prediction successfully done.

1. INTRODUCTION

Fishing vessels have a relatively large rudder, propeller and initial trim by the stern. These arrangements generally make good performance in ship manoeuvrability. However, the manoeuvring prediction becomes very important because the strong rudder force sometimes causes the capsizing accident [1]. Such kind of prediction is also necessary when calculating the broaching motion in following seas [2].

As for the principal dimensions of fishing vessels, the length beam ratio: \( L/B \) is rather smaller than the conventional merchant ships. Particularly in Northern Europe, ship length tends to be small. Some of them have less than 3 of \( L/B \). In addition, fishing vessels have a large initial trim by the stern and a false keel as shown in Fig.1. Initial trim becomes 30 or 40% of mean draught of ship. Some false keels also have a trim. Therefore, the hydrodynamic force during manoeuvring becomes more complicated in the manoeuvring prediction of fishing vessels.

2. MATHEMATICAL MODEL FOR MANOEUVRING PREDICTION

The mathematical model for manoeuvring motion can be described by the following equations of motion, using the coordinate system in Fig. 2.

\[
\begin{align*}
\mathbf{m} (\dot{u}_G - v_G r) &= X \\
\mathbf{m} (\dot{v}_G + u_G r) &= Y \\
I_{zz} \dot{r} &= N - x_G Y
\end{align*}
\]

where, \( \mathbf{m} \): mass of ship \( I_{zz} \): moment of inertia of ship in yaw motion

![Co-ordinate system](image)

Fig.2 Co-ordinate system

The notation of \( u_G, v_G \) and \( r \) are velocity components at center of gravity of ship (C.G), and \( x_G \) represents the location of the C.G in x-axis direction. \( X, Y \) and \( N \) represent the hydrodynamic forces and moment acting on the mid-ship of hull.

These forces can be described separating into the following components from the viewpoint of the physical meaning.
\[ \begin{aligned}
X &= X_H + X_R + X_P \\
Y &= Y_H + Y_R + Y_P \\
N &= N_H + N_R + N_P
\end{aligned} \]

where, the subscripts \( H \), \( P \) and \( R \) refer to hull, propeller and rudder respectively according to the concept of MMG [3],[4].

2.1 Forces and Moment Acting on Hull

\[ \begin{aligned}
X_H &= -m_u \dot{u} + \left( \rho / 2 \right) L_d U^2 \\
& \quad \times \left\{ X'_H + X'_H \beta^2 + \left( X'_{\rho u} - m'_u \right) \beta r' + X'_\rho r'^2 + X'_\rho \beta r' \right\} \\
Y_H &= -J_{zz} \ddot{r} + \left( \rho / 2 \right) L_d U^2 \\
& \quad \times \left\{ Y'_H + Y'_H \beta^2 + \left( Y'_{\rho u} - m'_u \right) \beta r' + Y'_\rho r'^2 + Y'_\rho \beta r' \right\} \\
N_H &= -J_{zz} \dot{r} + \left( \rho / 2 \right) L_d U^2 \\
& \quad \times \left\{ N'_H + N'_H \beta^2 + \left( N'_{\rho u} - m'_u \right) \beta r' + N'_\rho r'^2 + N'_\rho \beta r' \right\}
\end{aligned} \]

where, \( m, m' \), and \( J_{zz} \) are the added mass and moment of inertia. Drift angle: \( \beta \) and dimensionless turning rate: \( r' \) are expressed as \( \beta = -\sin^{-1}(v / U), r' = r (L / U) \).

The notations of \( u \) and \( v \) are velocity components and \( U \) is the resultant velocity at the mid-ship.

2.2 Force and Moment Induced by Propeller and Rudder

\[ \begin{aligned}
X_P &= (1 - t_p) \rho K_p D_p^2 \eta^2 \\
Y_P &= 0 \\
N_P &= 0
\end{aligned} \]

\[ \begin{aligned}
X_R &= -(1 - t_R) F_{\kappa} \sin \delta \\
Y_R &= -(1 + a_H) F_N \cos \delta \\
N_R &= -(x_R + a_H x_H) F_N \cos \delta
\end{aligned} \]

where, \( \delta \) is rudder angle, \( x_R \) represents the location of rudder (\( =-L / 2 \)), and \( t_p, t_R, a_H, x_H \) are the interactive force coefficients among hull, propeller and rudder. \( K_p \) is the thrust coefficient of a propeller force. These are the functions of the advance constant of propeller. \( F_N \) is rudder normal force and described as the following.

\[ F_N = \frac{1}{2} A_{f_R} f_{\alpha} U_R^2 \sin \alpha_R \]

where, \( A_{f_R} \) is rudder area, \( f_{\alpha} \) is the gradient of the lift coefficient of rudder, and can be approximated as the function of rudder aspect ratio \( \Lambda \).

\[ U_R = \sqrt{u_k^2 + v_k^2} \]

\[ \alpha_R = \delta - \tan^{-1}\left( \frac{-v_k}{u_k} \right) \]

\[ \begin{aligned}
\text{Table 1 Principal particulars of ship models (Full-scale expression)}
\end{aligned} \]
ε, κ, γ_ř and l_R in the above equations are the parameters with the ruder inflow velocity and angle. (1-w) and η are the effective propeller wake fraction and the ratio of propeller by rudder height (D_P/H).

3. MEASUREMENT OF HYDRODYNAMIC DERIVATIVES AND COEFFICIENTS

In order to make the database of the hydrodynamic derivatives and coefficients for fishing vessels, hydrodynamic forces and moments are measured with several fishing vessels. The principal particulars of these ship models are listed in Table 1.

Ship models A, B and C are the fisheries research vessels with stern trawl [5], and D and E [1] are the typical Japanese stern trawlers. Model F is the recent wide beam stern trawler in Northern Europe, and has a flapped rudder.

The hydrodynamic derivatives and coefficients in the mathematical model can be obtained by captive model tests such as CMT (Circular Motion Test), oblique towing tests and rudder tests. Measured hydrodynamic force coefficients are shown with ship model E from Fig. 3 to Fig. 6 as an example.

Hull force and moment coefficients: X_H, Y_H and N_H are measured by CMT. Forces and moment are made non-dimensional by \( \frac{\rho}{2} L dU^2 \) and \( \frac{\rho}{2} L^2 dU^2 \) respectively and plotted in Fig.3 against drift angle. The curves in these figures show the identified characteristics using eq.(3) with the parameter of \( r' \).

The hydrodynamic derivatives that are the coefficients in the equation are listed in Table 2.

Rudder force and moment coefficients: X_R, Y_R and N_R are measured by rudder test with some propeller loading conditions. Rudder normal force is also measured simultaneously in this test. These forces and moment are made non-dimensional and plotted in Fig.4 against longitudinal and lateral component of rudder normal force: \( F_N \sin \delta \) and \( F_N \cos \delta \). The interactive force coefficients \( t_R, a_H, \) and \( x_H \) in eq.(5) are obtained from the gradients of these coefficients, and listed in Table 2.

From the measurement of rudder normal forces for various propeller loading, the parameters with longitudinal rudder inflow velocity in eq.(9) can be obtained.
or oblique towing test with rudder angle, the parameters of lateral rudder inflow velocity in eq.(9): \( \gamma_R \) and \( \kappa \) can be obtained. The identified characteristic of lateral inflow velocity is shown in Fig.6, and parameter \( \gamma_R \) and \( \kappa \) are listed in Table 2. These measurements have been performed with ship model A,B,C,D and F. The obtained hydrodynamic derivatives and coefficients are listed in Table 2.

### 4. DATABASE OF HYDRODYNAMIC DERIVATIVES AND COEFFICIENTS FOR FISHING VESSELS

Obtained hydrodynamic derivatives and coefficients are expressed by simple formulas to get them easily for arbitral fishing vessels.

#### 4.1 Linear hydrodynamic derivatives

For the expression of linear derivatives, well-known Kijima’s formulas [6] are used in principle. However, the formulas are based on the conventional merchant ships, some modifications are required. The linear derivatives are generally affected by trim. The effects of trim on linear derivatives are plotted in Fig.7 on compared with Kijima’s trim corrections. From these figures, it is pointed out that the following trim corrections are more suitable for fishing vessels.

<table>
<thead>
<tr>
<th>Ship Model</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( X'_{\beta\beta} )</td>
<td>-0.0078</td>
<td>-</td>
<td>-0.1095</td>
<td>-0.1388</td>
<td>0.0091</td>
<td>0.0973</td>
</tr>
<tr>
<td>( X'_{\beta\beta\beta\beta} )</td>
<td>0.3527</td>
<td>0.4763</td>
<td>0.4809</td>
<td>0.7699</td>
<td>0.8801</td>
<td>0.8116</td>
</tr>
<tr>
<td>( X'_{\beta\beta\beta\beta} )</td>
<td>-0.2363</td>
<td>-</td>
<td>-0.1626</td>
<td>-0.2086</td>
<td>-0.1341</td>
<td>-0.4126</td>
</tr>
<tr>
<td>( X'_{\gamma\gamma} )</td>
<td>-0.0123</td>
<td>-</td>
<td>-0.0054</td>
<td>-0.0444</td>
<td>-0.0771</td>
<td>0.0000</td>
</tr>
<tr>
<td>( X'_{\gamma\gamma\gamma\gamma} )</td>
<td>-0.1503</td>
<td>-</td>
<td>0.5880</td>
<td>0.1098</td>
<td>0.2300</td>
<td>0.0000</td>
</tr>
<tr>
<td>( Y'_{\beta} )</td>
<td>0.5477</td>
<td>0.4763</td>
<td>0.4809</td>
<td>0.7699</td>
<td>0.8801</td>
<td>0.8116</td>
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<tr>
<td>( Y'_{\gamma\gamma} )</td>
<td>0.0480</td>
<td>-</td>
<td>0.0276</td>
<td>0.1430</td>
<td>0.1712</td>
<td>0.0705</td>
</tr>
<tr>
<td>( Y'_{\gamma\gamma\gamma\gamma} )</td>
<td>1.1792</td>
<td>-</td>
<td>1.1348</td>
<td>1.8850</td>
<td>0.5308</td>
<td>0.9625</td>
</tr>
<tr>
<td>( Y'_{\gamma\gamma\beta\beta} )</td>
<td>0.1938</td>
<td>-</td>
<td>0.0808</td>
<td>0.4890</td>
<td>1.1373</td>
<td>-0.1078</td>
</tr>
<tr>
<td>( Y'_{\gamma\gamma\beta\gamma} )</td>
<td>0.2886</td>
<td>-</td>
<td>0.5188</td>
<td>0.6723</td>
<td>0.4966</td>
<td>0.4756</td>
</tr>
<tr>
<td>( Y'_{\gamma\gamma\gamma\gamma} )</td>
<td>-0.0384</td>
<td>-</td>
<td>0.0023</td>
<td>0.0223</td>
<td>0.0099</td>
<td>-0.0226</td>
</tr>
<tr>
<td>( N'_{\beta} )</td>
<td>0.1140</td>
<td>0.1226</td>
<td>0.1070</td>
<td>0.0883</td>
<td>-0.0016</td>
<td>0.1805</td>
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<tr>
<td>( N'_{\gamma\gamma} )</td>
<td>-0.0574</td>
<td>-</td>
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<td>-0.0781</td>
<td>-0.0506</td>
<td>-0.0649</td>
</tr>
<tr>
<td>( N'_{\gamma\gamma\gamma\gamma} )</td>
<td>0.2830</td>
<td>-</td>
<td>0.3380</td>
<td>0.2902</td>
<td>0.3020</td>
<td>0.3227</td>
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<tr>
<td>( N'_{\gamma\gamma\beta\beta} )</td>
<td>-0.4586</td>
<td>-</td>
<td>-0.5209</td>
<td>-0.7940</td>
<td>-0.5335</td>
<td>-0.2941</td>
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<tr>
<td>( N'_{\gamma\gamma\beta\gamma} )</td>
<td>0.0567</td>
<td>-</td>
<td>0.0008</td>
<td>0.0575</td>
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<td>0.0018</td>
</tr>
<tr>
<td>( N'_{\gamma\gamma\gamma\gamma} )</td>
<td>0.0005</td>
<td>-</td>
<td>0.0016</td>
<td>-0.0271</td>
<td>-0.0152</td>
<td>0.0000</td>
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<td>Interactions</td>
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<td></td>
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<tr>
<td>( 1-l'_{R} )</td>
<td>0.883</td>
<td>0.800</td>
<td>0.856</td>
<td>0.820</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( a_H )</td>
<td>0.027</td>
<td>0.067</td>
<td>0.000</td>
<td>0.437</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \varepsilon )</td>
<td>0.885</td>
<td>1.164</td>
<td>0.966</td>
<td>1.179</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \kappa )</td>
<td>0.565</td>
<td>0.452</td>
<td>0.664</td>
<td>0.385</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( l'<em>{R}(=l</em>{R}/L) )</td>
<td>-0.976</td>
<td>-1.023</td>
<td>-0.948</td>
<td>-0.774</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \gamma_R )</td>
<td>0.490</td>
<td>0.330</td>
<td>0.416</td>
<td>0.615</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Fig. 7 Comparisons of effects of trim on linear hydrodynamic derivatives
(bases are Kijima’s formula without trim)

\[
\begin{align*}
Y'_\beta &= Y'_{\beta 0} \left( 1 + 0.6r'^2 \right) \\
Y'_r - m'_x &= (Y'_r - m'_{x0}) \left( 0.4 + 1.8r'^2 \right) \\
N'_{r0} &= N'_{r0} \left( 1 - 0.9r' \right) \\
N'_r &= N'_{r0} \\
\text{where, } \tau' &= \text{trim/d}_\text{em}
\end{align*}
\]

The trim in the above equations represents the total amount of trim including baseline trim, initial trim and false keel trim, and \(d_{\text{em}}\) the effective mean draught including false keel depth at mid-ship. The correction of \(N'_r\) is not found in this analysis. Kijima’s trim-correction model includes \(Cb/(L/B)\), this parameter, however, has no contribution to the correction of such fishing vessels and expressed only by \(\tau'\) as shown eq.(10), though the \(Cb/(L/B)\) of tested ships are quite different from each other. The subscripts "0" in eq.(10) represents linear hydrodynamic derivatives without trim. In this expression, Kijima’s empirical formulas written by eq.(11) are used. The relation of linear derivatives between measured and estimated are shown in Fig.8, where it is found that the linear derivatives well agree with the measured one.

\[
\begin{align*}
Y'_{\beta 0} &= 0.5\pi\kappa + 1.4Cb/(L/B) \\
(Y'_r - m'_{x0}) &= 0.5Cb/(L/B) \\
N'_{r0} &= k \\
N'_{r0} &= -0.54k + k^2 \\
\text{where, } k &= \text{the lateral aspect ratio of ship (} k = 2d_{\text{em}}/L).\n\end{align*}
\]

4.2 Non-linear hydrodynamic derivatives

Measured non-linear derivatives of hull are plotted in Fig.9 - Fig.11. Although these derivatives have not been proposed yet as a function, they are described by trim or \(d_{\text{em}}/B\) for fishing vessels. The derivatives of \(X'_{a_{yy}}\) can be as expressed as the following simple formulas even though the data size is limited.

\[
\begin{align*}
X'_{\beta 0} &= -0.35 + 0.8(d_{\text{em}}/B) \\
X'_r - m'_{x} &= [-0.46 + 2.5(d_{\text{em}}/B)]m' \\
X'_r &= 0.03 - 0.09r' \\
X'_{\beta 0pc} &= 2.7 - 6.0(d_{\text{em}}/B)
\end{align*}
\]
Fig. 9 Effect of trim or $d_{cm}/B$ on non-linear hydrodynamic derivatives of $X'_{H}$

Fig. 10 Effect of trim on non-linear hydrodynamic derivatives of $Y'_{H}$

Fig. 11 Effect of trim on non-linear hydrodynamic derivatives of $N'_{H}$

Fig. 12 Effect of $Cb/(L/B)$ on interactive force coefficients hull, propeller and rudder
As for the derivatives of \( Y' \) and \( N' \), they may be the function of \( Cb \), \( L/B \), \( d_{em}/B \) trim and so on. However, as plotted in Fig.10 and Fig.11, the database shows the contributions except trim are so small, that they can be expressed as the following simple formulas of trim.

\[
\begin{align*}
Y'_{pp0} &= 1.2 \\
Y'_{pp} &= -0.5 + 1.4r' \\
Y'_{pv} &= 0.34 + 0.26r' \\
Y'_{rv} &= -0.04 + 0.055r' \\
N'_{pp0} &= 0.3 \\
N'_{pp} &= -0.33 - 0.3r' \\
N'_{pv} &= 0.01 + 0.02r' \\
N'_{rv} &= -0.02r' \\
\end{align*}
\]

These regression formulas, however, fully depend on the database. Therefore, the available ship dimensions must be clarified. In this analysis, the following limitations may be provided from the database.

\[
\begin{align*}
2.6 < L/B < 5.2 \\
0.37 < d_{em}/B < 0.46 \\
0.57 < Cb < 0.66 \\
0 < r' = trim / d_{em} < 1.1 \\
\end{align*}
\]

4.3 Interactive force coefficients among Hull, Propeller and Rudder

The interactive force coefficients: \((1-t_R)a_H, l'_R \) (=\( I_2/L \)), \( \gamma_R \) and \( \varepsilon \) are mainly expressed by \( Cb/(L/B) \) as shown in Fig.12, and described eq.(15) and eq.(16).

\[
\begin{align*}
1-t_R &= 0.9 - 0.3Cb/(L/B) \\
a_H &= 2.0(Cb/(L/B))^2 \\
x'_{st} &= -0.45 \\
\end{align*}
\]

5. PREDICTED MANOEUVRING MOTION

Using the above-mentioned formulas to estimate hydrodynamic derivatives and coefficients, manoeuvring ship motions are predicted by the computer simulation. The mathematical model is from eq.(1) to (9) in principle. For the flapped rudder, the mathematical model of rudder normal force eq.(7) is replaced to the Yoshimura’s formula [7]. The estimated derivatives and coefficients are listed in Table 3. Simulated ship motions are shown in Fig.13 and Fig.14 with ship model A, C, D and F.

<table>
<thead>
<tr>
<th>Ship Model</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
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<td>Hull derivatives</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>( X'_{pp0} )</td>
<td>0.0069</td>
<td>-0.0526</td>
<td>0.0069</td>
<td>0.0139</td>
<td>-0.0305</td>
<td>0.0157</td>
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<tr>
<td>( X'_{pp} )</td>
<td>-0.1872</td>
<td>-0.1238</td>
<td>-0.1665</td>
<td>-0.1921</td>
<td>-0.1571</td>
<td>-0.3418</td>
</tr>
<tr>
<td>( X'_{pv} )</td>
<td>0.0010</td>
<td>-0.0010</td>
<td>-0.0010</td>
<td>-0.0513</td>
<td>-0.0666</td>
<td>-0.0054</td>
</tr>
<tr>
<td>( X'_{rv} )</td>
<td>0.0231</td>
<td>0.4692</td>
<td>0.0231</td>
<td>-0.0295</td>
<td>0.3041</td>
<td>-0.0426</td>
</tr>
<tr>
<td>( Y'_{pv} )</td>
<td>0.5692</td>
<td>0.533</td>
<td>0.4797</td>
<td>0.7634</td>
<td>0.8515</td>
<td>0.9830</td>
</tr>
<tr>
<td>( Y'_{pv} )</td>
<td>-0.0479</td>
<td>0.0452</td>
<td>0.0390</td>
<td>0.1325</td>
<td>0.1803</td>
<td>0.0850</td>
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<tr>
<td>( Y'_{rr} )</td>
<td>-0.0012</td>
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<td>( Y'_{rv} )</td>
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<td>( Y'_{rv} )</td>
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<td>( N'_{pv} )</td>
<td>0.1455</td>
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<td>0.0374</td>
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<tr>
<td>( N'_{pv} )</td>
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<tr>
<td>( N'_{pp0} )</td>
<td>0.3000</td>
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<td>0.3000</td>
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<tr>
<td>( N'_{pp} )</td>
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<td>-0.6009</td>
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<tr>
<td>( N'_{pv} )</td>
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<td>0.0281</td>
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<td>( N'_{rv} )</td>
<td>-0.0069</td>
<td>-0.0069</td>
<td>-0.0069</td>
<td>-0.0181</td>
<td>-0.0215</td>
<td>-0.0079</td>
</tr>
</tbody>
</table>

Interactions

| 1-t_R | 0.857 | 0.860 | 0.862 | 0.857 | 0.856 | 0.825 |
| a_H | 0.058 | 0.046 | 0.041 | 0.057 | 0.062 | 0.314 |
| \( \varepsilon \) | 0.971 | 0.951 | 0.941 | 0.969 | 0.977 | 1.176 |
| \( \kappa \) | 0.551 | 0.573 | 0.583 | 0.553 | 0.546 | 0.383 |
| \( l'_R \) | -0.957 | -0.976 | -0.984 | -0.959 | -0.952 | -0.774 |
| \( \gamma_R \) | 0.439 | 0.421 | 0.413 | 0.437 | 0.443 | 0.610 |
Fig. 13 Comparisons of spiral characteristic measured and predicted.
(dotted bold line: prediction by the proposed hydrodynamic coefficients,
dotted thin line: prediction by the originally measured coefficients)
In each figures, dotted bold lines represent the simulated results using the estimated derivatives and coefficients, and dotted thin lines using the measured original data in references. Fig.13 shows the comparisons of simulated spiral characteristics compared with the measured ship motions, and Fig.14 shows the comparisons of turning trajectories of 35° rudder angle. These simulated results that are using the proposed formulas of hydrodynamic derivatives are well coincident with measured ship motions for the wide range of ship dimensions. As the results, the manoeuvring prediction method proposed here becomes a practical tool for the design, research and investigation of fishing vessels, though the size of database is not enough.

6. CONCLUSION

The authors have shown the hydrodynamic derivatives and the other coefficients, and proposed the manoeuvring prediction method for fishing vessels. The concluding remarks are summarized as the followings.

1) Linear hydrodynamic derivatives without trim can be estimated by Kijima’s model. However, the Kijima’s trim-corrections are not available for fishing vessels. For this correction, eq.(10) proposed here are suitable.

2) Non-linear derivatives can be estimated by the simple formulas as shown in eq.(12) - eq.(14). They can be expressed by \( d_{\phi}/dA \) or trim.

3) Interactive force coefficients among hull, propeller and rudder can be estimated by \( Cb/L/B \) as in eq.(15) and eq.(16).

4) Predicted manoeuvring ship motions that are using the above mentioned formulas of hydrodynamic derivatives and coefficients are well coincident with measured one for a wide range of ship dimensions of fishing vessels.

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