MANOEUVRING PREDICTION OF FISHING VESSELS

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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.

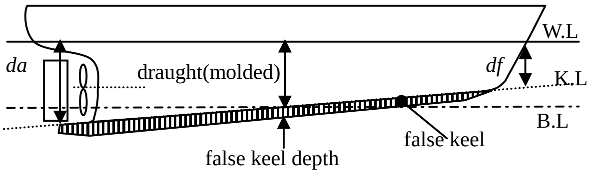


Fig.1 Initial trim and false keel of a fishing boat

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.

$$\left.\begin{aligned} m(\dot{u}_G - v_G r) &= X \\ m(\dot{v}_G + u_G r) &= Y \\ I_{zz}\dot{r} &= N - x_G Y \end{aligned}\right\} \qquad (1)$$

where, m : mass of ship
I_{ZZ} : moment of inertia of ship in yaw motion

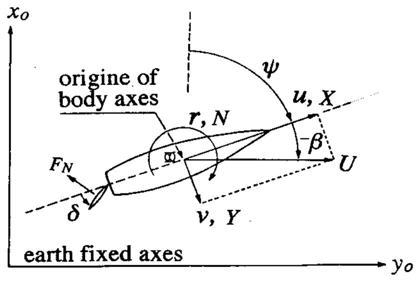


Fig.2 Co-ordinate system

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.

$$\left.\begin{aligned} X &= X_H + X_R + X_P \\ Y &= Y_H + Y_R + Y_P \\ N &= N_H + N_R + N_P \end{aligned}\right\} \quad (2)$$

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

X_H, Y_H and N_H are approximated by the following polynomials of β and r'. The coefficients of the polynomials are called hydrodynamic derivatives.

$$\left.\begin{aligned} X_H &= -m_x\dot{u} + (\rho/2)LdU^2 \\ &\times\left\{X'_0 + X'_{\beta\beta}\beta^2 + (X'_{\beta r} - m'_y)\beta r' + X'_{rr}r'^2 + X'_{\beta\beta\beta\beta}\beta^4\right\} \\ Y_H &= -m_y\dot{v} + (\rho/2)LdU^2 \\ &\times\left\{Y'_\beta\beta + (Y'_r - m'_x)r' + Y'_{\beta\beta\beta}\beta^3 + Y'_{\beta\beta r}\beta^2 r' + Y'_{\beta rr}\beta r'^2 + Y'_{rrr}r'^3\right\} \\ N_H &= -J_{ZZ}\dot{r} + (\rho/2)L^2dU^2 \\ &\times\left\{N'_\beta\beta + N'_r r' + N'_{\beta\beta\beta}\beta^3 + N'_{\beta\beta r}\beta^2 r' + N'_{\beta rr}\beta r'^2 + N'_{rrr}r'^3\right\} \end{aligned}\right\} \quad (3)$$

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

X_P , Y_P , N_P and X_R , Y_R , N_R are expressed as the following formulas.

$$\left.\begin{aligned} X_P &= (1-t_P)\rho K_T D_P^4 n^2 \\ Y_P &= 0 \\ N_P &= 0 \end{aligned}\right\} \quad (4)$$

$$\left.\begin{aligned} X_R &= -(1-t_R)F_N\sin\delta \\ Y_R &= -(1+a_H)F_N\cos\delta \\ N_R &= -(x_R + a_H x_H)F_N\cos\delta \end{aligned}\right\} \quad (5)$$

where, δ is rudder angle, x_R represents the location of rudder (=-L/2), and t_P, t_R, a_H, and x_H are the interactive force coefficients among hull, propeller and rudder. K_T 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.

$$F_N = \frac{\rho}{2}A_R f_\alpha U_R{}^2\sin\alpha_R \quad (6)$$

where, A_R is rudder area. f_α is the graduent of the lift coefficient of ruder, and can be approximated as the function of rudder aspect ratio Λ.

$$f_\alpha = 6.13\Lambda/(2.25+\Lambda) \quad (7)$$

U_R and α_R represent the rudder inflow velocity and angle respectively, they can be described as the followings.

$$\left.\begin{aligned} U_R &= \sqrt{u_R{}^2 + v_R{}^2} \\ \alpha_R &= \delta - \tan^{-1}\left(\frac{-v_R}{u_R}\right) \end{aligned}\right\} \quad (8)$$

where,

$$\left.\begin{aligned} u_R &= \varepsilon(1-w)u\sqrt{\eta\left\{1+\kappa\left(\sqrt{1+8K_T/\pi J^2}-1\right)\right\}^2 + (1-\eta)} \\ v_R &= \gamma_R(v - rl_R) \end{aligned}\right\} \quad (9)$$

Table 1 Principal particulars of ship models (Full-scale expression)

Ship Model	A	B	C	D	E	F
scale	1/14.6	1/14.6	1/14.6	1/12.2	1/15.0	1/16.4
Lpp (=*L*, m)	27.50	33.74	33.74	26.85	31.00	26.16
B (m)	6.50	6.50	7.80	5.90	7.40	10.00
d (m, molded)	2.60	2.60	2.60	2.184	2.515	4.071
Keel depth (m)	0.30	0.30	0.30	0.50	0.44	0.50
d_{em} (m)	2.90	2.90	2.90	2.684	2.955	4.571
Baseline trim (m)	0	0	0	1.724	2.37	1.000
Initial trim (m)	0.80	0.80	0.80	0.70	0.80	0.80
Keel trim (m)	0.20	0.20	0.20	0	0	0
Total trim (m)	1.00	1.00	1.00	2.424	3.170	1.800
$\bigtriangledown$ (m^3)	313.3	419.2	435.3	274.4	414.3	681.9
Dp (m)	1.9	1.9	1.9	2.07	2.7	2.04
L/B	4.231	5.191	4.326	4.551	4.189	2.616
d_{em}/B	0.446	0.446	0.372	0.455	0.399	0.457
Cb (by d_{em})	0.604	0.659	0.570	0.645	0.611	0.655
Cb/(*L/B*)	0.143	0.127	0.132	0.142	0.146	0.250
Total trim/d_{em}	0.345	0.345	0.345	0.940	1.073	0.383
x_G /*Lpp* (%*L*)	-2.15	-1.48	-1.60	-10.24	-8.71	-2.19
A_R/Ld_{em}	1/28.6	1/35.0	1/37.9	1/24.1	1/24.6	1/27.3(F)
Dp/H	0.904	0.904	0.904	0.955	0.971	0.838

ε, κ, γ_R 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.

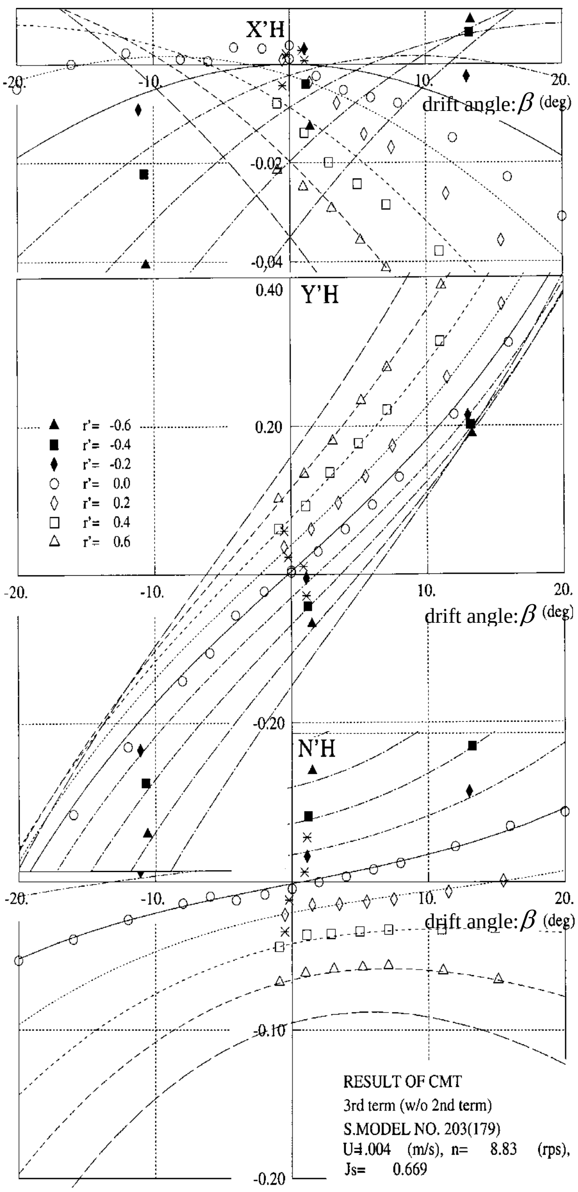


Fig.3 Hull force and moment coefficients measured by CMT (Ship model E).

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 $(\rho/2)LdU^2$ and $(\rho/2)L^2dU^2$ 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.

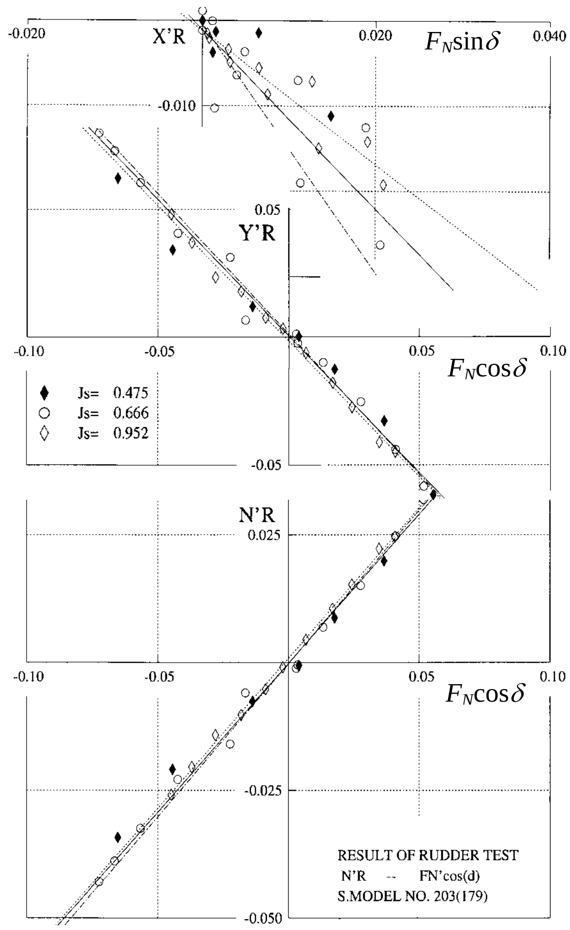


Fig.4 Rudder force and moment coefficients measured by rudder tests (Ship model E).

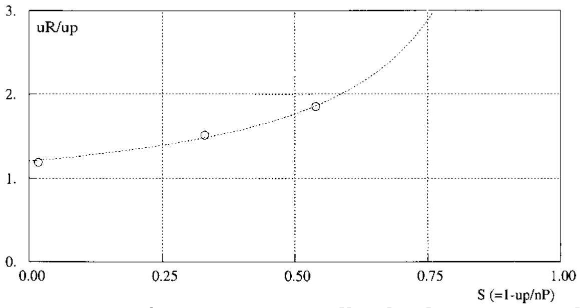


Fig.5 u'_R for various propeller loading measured by rudder tests (Ship model E).

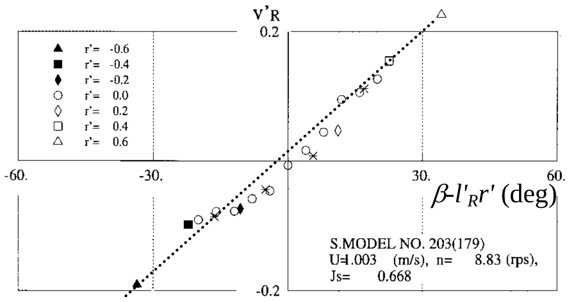


Fig.6 v'_R measured by CMT or oblique towing test with rudder angle (Ship model E)

The identified characteristic of longitudinal rudder inflow velocity: u_R is shown in Fig.5 as the ratio of u_R (=(1-w)u) and analyzed parameter ε, κ are listed in Table 2.
From the measurement of rudder force during CMT or oblique towing test with rudder angle, the parameters of lateral rudder inflow velocity in eq.(9): γ_R and l_R can be obtained. The identified characteristic of lateral inflow velocity is shown in Fig.6, and parameter γ_R and l_R 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 2 Measured hydrodynamic derivatives and coefficients
(derivatives are made non-dimensional by $(\rho/2)Ld_{em}U^2$ or $(\rho/2)L^2d_{em}U^2$)

Ship Model	A	B	C	D	E	F
Hull derivatives						
$X'_{\beta\beta}$	-0.0078	-	-0.1095	-0.1388	0.0091	0.0973
$X'_{\beta r}-m'_y$	-0.2363	-	-0.1626	-0.2086	-0.1341	-0.4126
X'_{rr}	-0.0123	-	-0.0054	-0.0444	-0.0771	0.0000
$X'_{\beta\beta\beta\beta}$	-0.1503	-	0.5880	0.1098	0.2300	0.0000
Y'_{β}	0.5477	0.4763	0.4809	0.7699	0.8801	0.8116
$Y'_r-m'_x$	0.0480	-	0.0276	0.1430	0.1712	0.0705
$Y'_{\beta\beta\beta}$	1.3792	-	1.1348	1.8850	0.5308	0.9625
$Y'_{\beta\beta r}$	0.1938	-	0.0808	0.4890	1.1373	-0.1078
$Y'_{\beta rr}$	0.2886	-	0.5188	0.6723	0.4966	0.4756
Y'_{rrr}	-0.0384	-	-0.0023	0.0223	0.0099	-0.0226
N'_{β}	0.1140	0.1226	0.1070	0.0833	-0.0016	0.1805
N'_r	-0.0574	-	-0.0601	-0.0781	-0.0506	-0.0649
$N'_{\beta\beta\beta}$	0.2830	-	0.3380	0.2902	0.3020	0.3227
$N'_{\beta\beta r}$	-0.4586	-	-0.5209	-0.7940	-0.5335	-0.2941
$N'_{\beta rr}$	0.0567	-	0.0008	0.0575	-0.0150	0.0018
N'_{rrr}	0.0005	-	-0.0016	-0.0271	-0.0152	0.0000
Interactions						
$1-t_R$	0.883			0.800	0.856	0.820
a_H	0.027			0.067	0.000	0.437
ε	0.885			1.164	0.966	1.179
κ	0.565			0.452	0.664	0.385
$l'_R\,(=l_R/L)$	-0.976			-1.023	-0.948	-0.774
γ_R	0.490			0.330	0.416	0.615

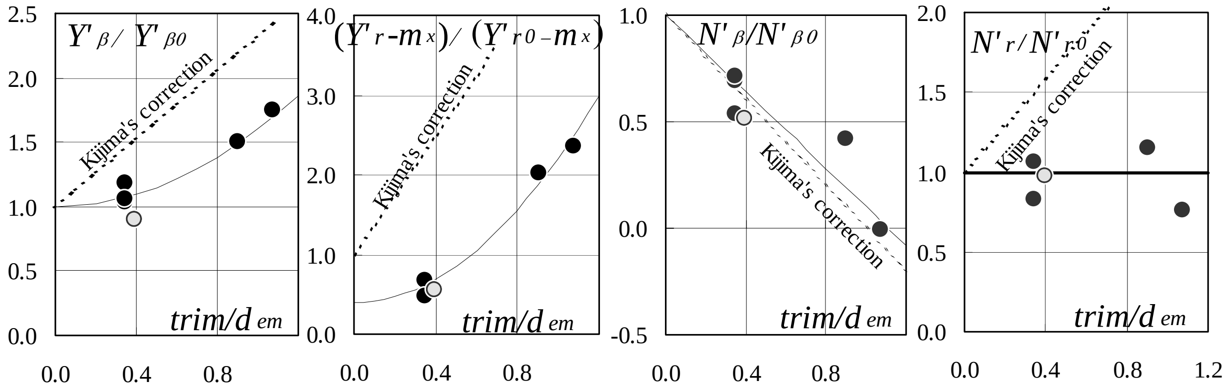


Fig.7 Comparisons of effects of trim on linear hydrodynamic derivatives
(bases are Kijima's formula without trim)

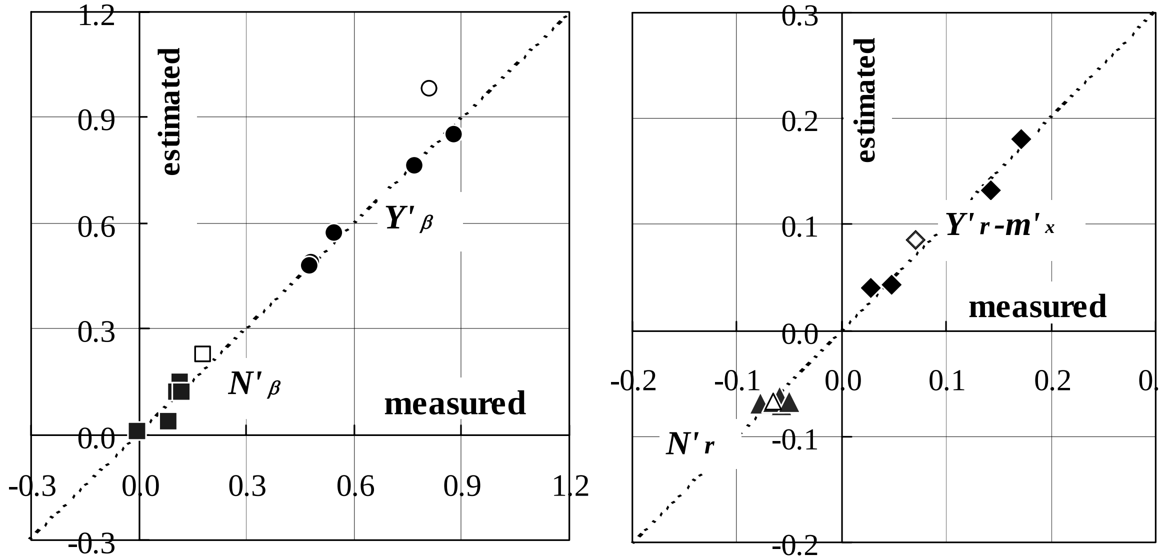


Fig.8 Relation of linear hydrodynamic derivatives between measured and estimated

$$
\left.\begin{aligned}
Y'_\beta &= Y'_{\beta 0}\left(1+0.6\tau'^2\right)\\
Y'_r - m'_x &= \left(Y'_r - m'_x\right)_0\left(0.4+1.8\tau'^2\right)\\
N'_\beta &= N'_\beta\left(1-0.9\tau'\right)\\
N'_r &= N'_{r0}
\end{aligned}\right\} \qquad (10)
$$

where, τ'=trim/d_{em}

$$
\left.\begin{aligned}
Y'_{\beta 0} &= 0.5\pi k + 1.4Cb/(L/B)\\
\left(Y'_r - m'_x\right)_0 &= 0.5Cb/(L/B)\\
N'_{\beta 0} &= k\\
N'_{r0} &= -0.54k + k^2
\end{aligned}\right\} \qquad (11)
$$

where, k is the lateral aspect ratio of ship (k=2d_{em}/L).

The trim in the above equations represents the total amount of trim including baseline trim, initial trim and false keel trim, and d_{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 τ' 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.

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_{em}/B for fishing vessels.
The derivatives of X'_H can be as expressed as the following simple formulas even though the data size is limited.

$$
\left.\begin{aligned}
X'_{\beta\beta} &= -0.35 + 0.8\left(d_{em}/B\right)\\
X'_{\beta r} - m'_y &= \left\{-0.46 + 2.5\left(d_{em}/B\right)\right\}m'\\
X'_{rr} &= 0.03 - 0.09\tau'\\
X'_{\beta\beta\beta\beta} &= 2.7 - 6.0\left(d_{em}/B\right)
\end{aligned}\right\} \qquad (12)
$$

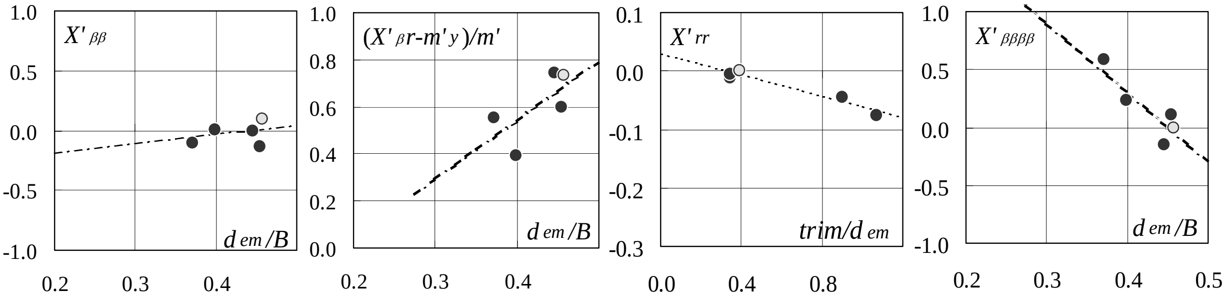


Fig.9 Effect of trim or d_{me}/B on non-linear hydrodynamic derivatives of X'_H

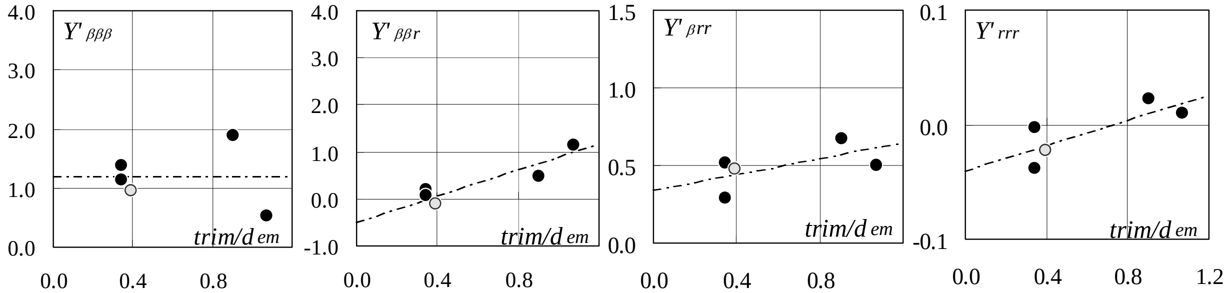


Fig.10 Effect of trim on non-linear hydrodynamic derivatives of Y'_H

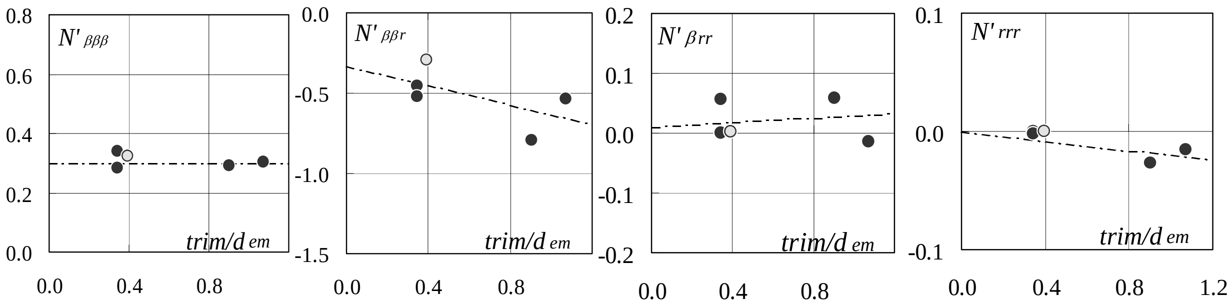


Fig.11 Effect of trim on non-linear hydrodynamic derivatives of N'_H

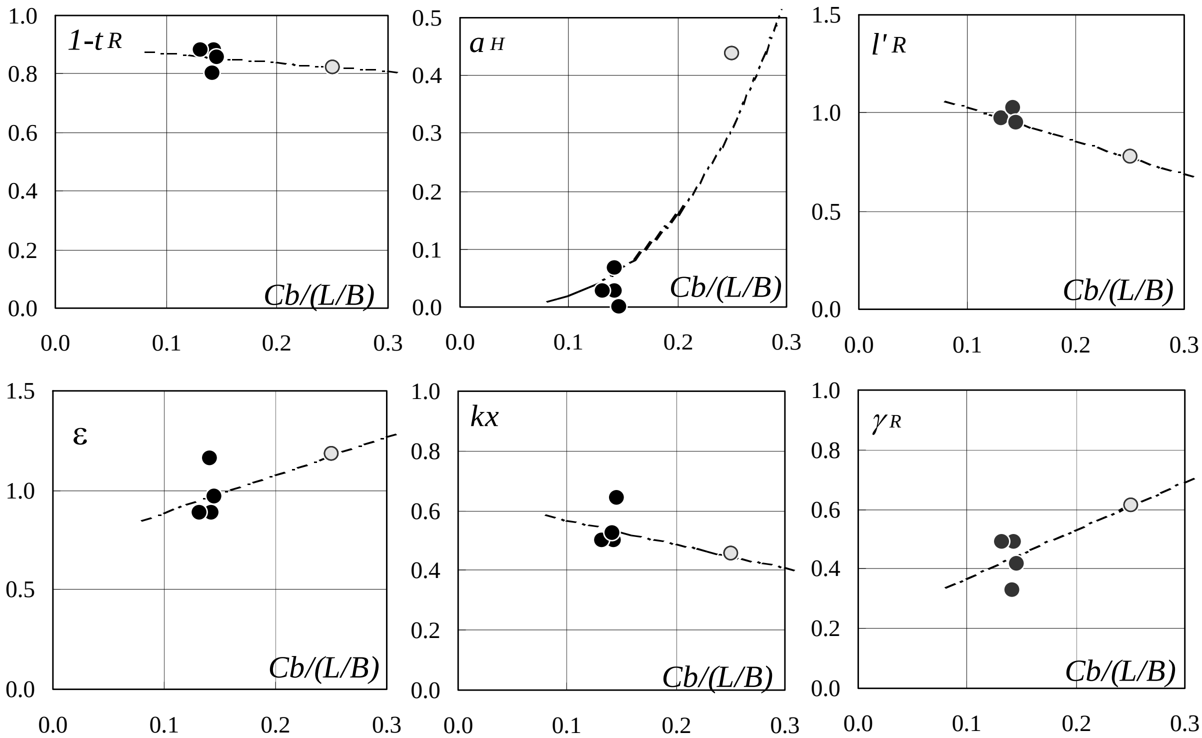


Fig.12 Effect of $Cb/(L/B)$ on interactive force coefficients hull, propeller and rudder

As for the derivatives of Y'_H and N'_H , 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.

$$\left.\begin{aligned} Y'_{\beta\beta\beta} &= 1.2 \\ Y'_{\beta\beta r} &= -0.5 + 1.4\tau' \\ Y'_{\beta rr} &= 0.34 + 0.26\tau' \\ Y'_{rrr} &= -0.04 + 0.055\tau' \end{aligned}\right\} \quad (13)$$

$$\left.\begin{aligned} N'_{\beta\beta\beta} &= 0.3 \\ N'_{\beta\beta r} &= -0.33 - 0.3\tau' \\ N'_{\beta rr} &= 0.01 + 0.02\tau' \\ N'_{rrr} &= -0.02\tau' \end{aligned}\right\} \quad (14)$$

4.3 Interactive force coefficients among Hull, Propeller and Rudder

The interactive force coefficients: $(1\text{-}t_R)$, a_H, l'_R $(=l_R/L)$, γ_R and ε are mainly expressed by $Cb/(L/B)$ as shown in Fig.12, and described eq.(15) and eq.(16).

$$\left.\begin{aligned} 1 - t_R &= 0.9 - 0.3Cb/(L/B) \\ a_H &= 2.0(Cb/(L/B))^2 \\ x'_H &= -0.45 \end{aligned}\right\} \quad (15)$$

$$\left.\begin{aligned} l'_R &= 1.2 - 1.7Cb/(L/B) \\ \gamma'_R &= 0.21 + 1.6Cb/(L/B) \\ \varepsilon &= 0.7 + 1.9Cb/(L/B) \\ k_x &= \varepsilon\kappa = 0.55 - 0.8Cb/(L/B) \end{aligned}\right\} \quad (16)$$

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.

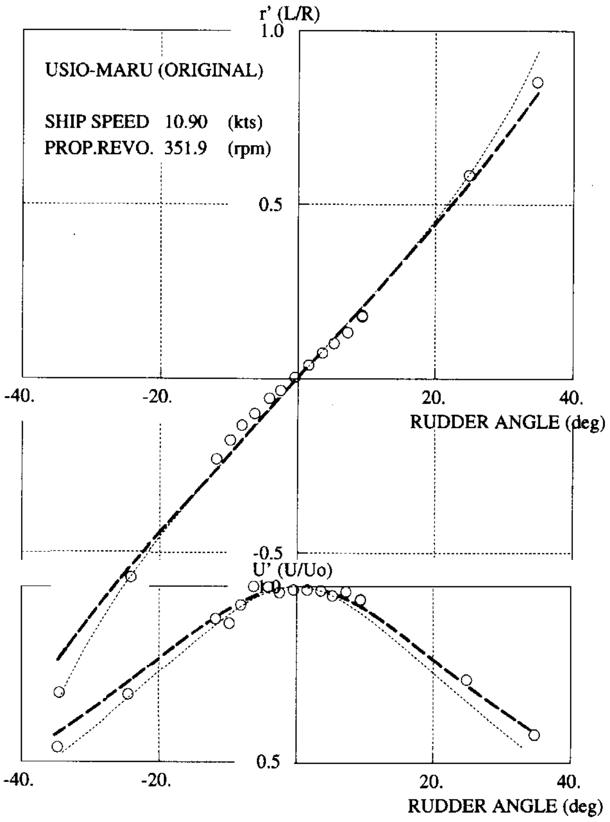
$$\left.\begin{aligned} 2.6 &< L/B < 5.2 \\ 0.37 &< d_{em}/B < 0.46 \\ 0.57 &< Cb < 0.66 \\ 0 &< \tau' = trim/d_{em} < 1.1 \end{aligned}\right\} \quad (17)$$

5. PREDICTED MANOEUVRING MOTION

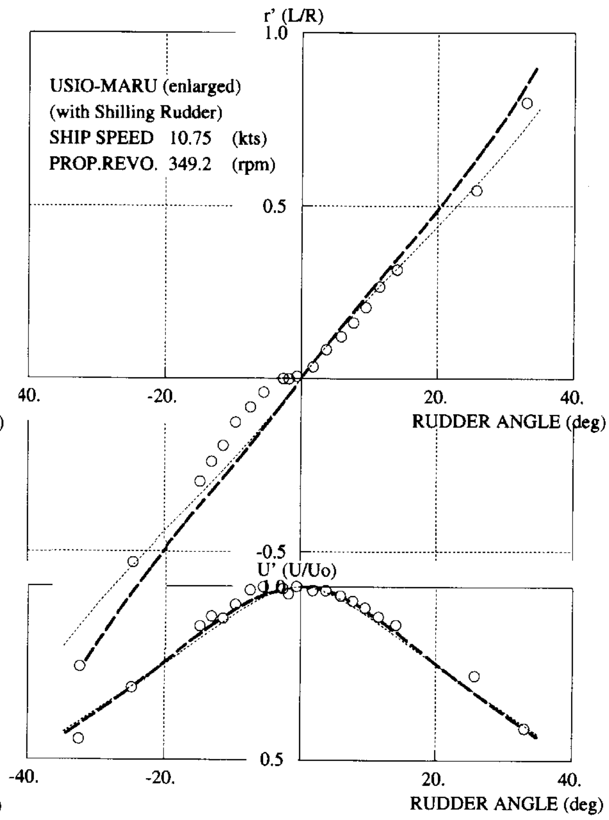
Using the above-mentioned formulas to estimate hydrodynamic derivatives and coefficients, manoeuvring ship motions are predicted by the computer simulation. The mathematical model is from eq.(1) to (9) in principle. For the flapped rudder, the mathematical model of rudder normal force eq.(7) is replaced 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 3 Estimated hydrodynamic derivatives and coefficients

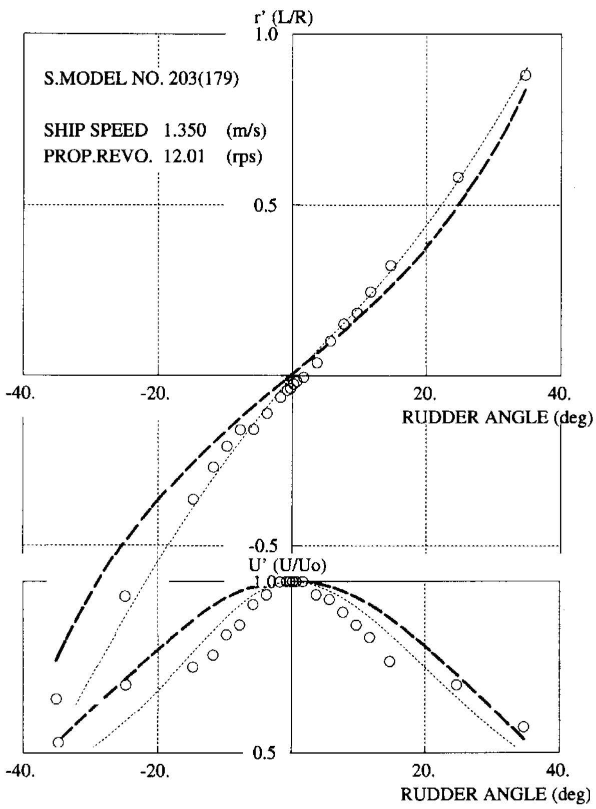
Ship Model	A	B	C	D	E	F
Hull derivatives						
$X'_{\beta\beta}$	0.0069	-0.0526	0.0069	0.0139	-0.0305	0.0157
$X'_{\beta r}-m'_y$	-0.1872	-0.1238	-0.1665	-0.1921	-0.1571	-0.3418
X'_{rr}	-0.0010	-0.0010	-0.0010	-0.0513	-0.0666	-0.0054
$X'_{\beta\beta\beta\beta}$	0.0231	0.4692	0.0231	-0.0295	0.3041	-0.0426
Y'_{β}	0.5692	0.5433	0.4797	0.7634	0.8515	0.9830
$Y'_r-m'_x$	0.0439	0.0452	0.0390	0.1325	0.1803	0.0850
$Y'_{\beta\beta\beta}$	1.2000	1.2000	1.2000	1.2000	1.2000	1.2000
$Y'_{\beta\beta r}$	-0.0172	-0.0172	-0.0172	0.7644	1.0019	0.0513
$Y'_{\beta rr}$	0.4297	0.4297	0.4297	0.5748	0.6189	0.4424
Y'_{rrr}	-0.0210	-0.0210	-0.0210	0.0097	0.0190	-0.0183
N'_{β}	0.1455	0.1322	0.1186	0.0374	0.0066	0.2256
N'_r	-0.0697	-0.0706	-0.0633	-0.0680	-0.0666	-0.0666
$N'_{\beta\beta\beta}$	0.3000	0.3000	0.3000	0.3000	0.3000	0.3000
$N'_{\beta\beta r}$	-0.4334	-0.4334	-0.4334	-0.6009	-0.6518	-0.4481
$N'_{\beta rr}$	0.0169	0.0169	0.0169	0.0281	0.0315	0.0179
N'_{rrr}	-0.0069	-0.0069	-0.0069	-0.0181	-0.0215	-0.0079
Interactions						
$1\text{-}t_R$	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
ε	0.971	0.951	0.941	0.969	0.977	1.176
κ	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
γ_R	0.439	0.421	0.413	0.437	0.443	0.610



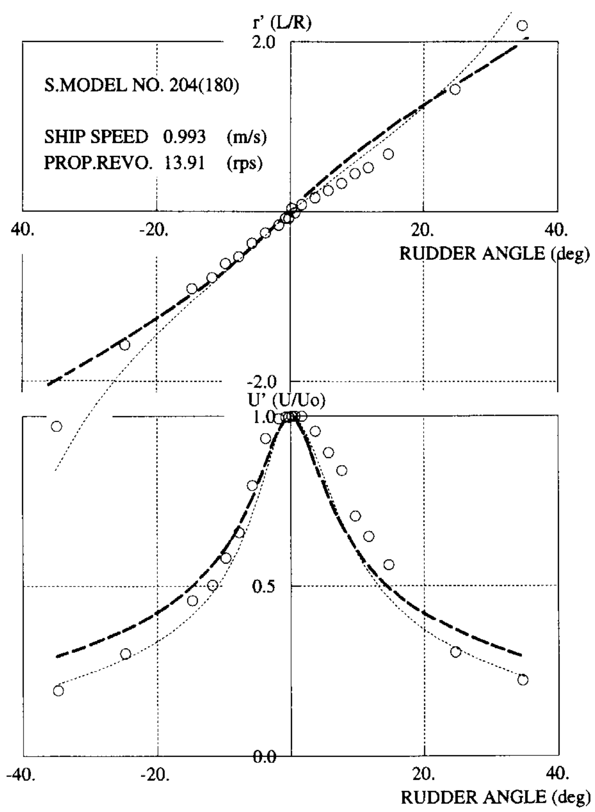
(Ship model A)



(Ship model C)

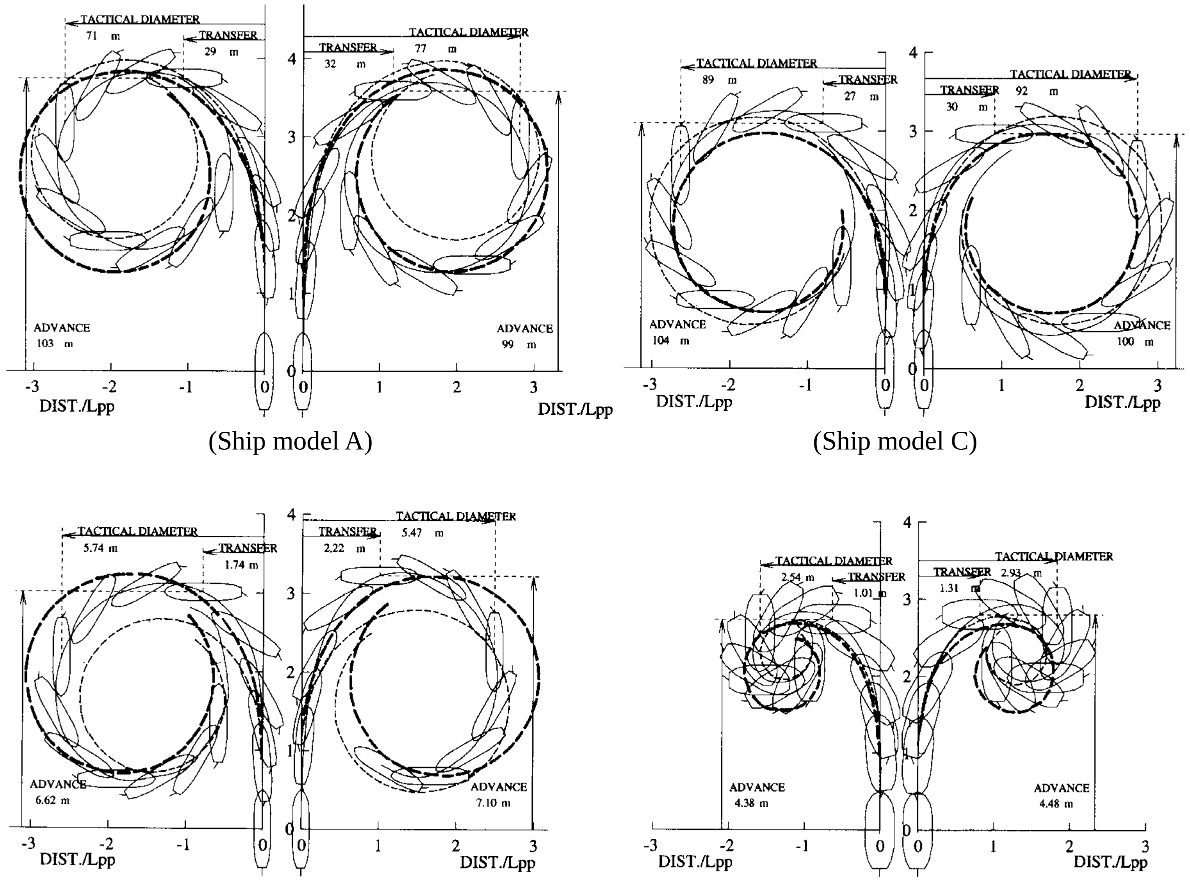


(Ship model D)



(Ship model F)

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)



(Ship model A) (Ship model C)

(Ship model D) (Ship model F)

Fig.14 Comparisons of turning trajectories of 35ºrudder angle, observed 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 35º rudder angle. These simulated results that are using the proposed formulas of hydrodynamic coefficients 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_{em}/B 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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