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# The Prediction of ship's manoeuvring performance in initial design stage

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Most of fuel the economic hull forms, nowadays, have stern bulbs at their afterbodies. The adoption of stern bulb, even though good for the vessel's propulsion performance, has been known to deteriorate the course keeping stability of a vessel. The change of the concept of stern hull form requires the modification of the empirical formulae of various hull-oriented hydrodynamic derivatives used in the manoeuvring prediction programs.

In this study, PMM(Planar Motion Mechanism) tests and rudder open water tests were carried out for 19 models of low-speed blunt ship with stern bulb and horn type rudder. The MMG model has been used as a basic mathematical model for manoeuvring equation. Then the regression analyses were performed using selected principal parameters.

The results of present study have been compared with those of Kijima's formulae and PMM model tests. From those, It is found that the present prediction give improvement of prediction for ship's directional stability.

## 1. INTRODUCTION

International Maritime Organization adopted the interim standard A.751(18)[1] for ship manoeuvrability in November 1993. In order to cope with the manoeuvring standard well, it is required for a ship designer to have tools to accurately predict the ship manoeuvrability at the preliminary design stage of a vessel. In general, low-speed blunt-ships with stern bulb are known to have bad manoeuvring characteristics because of the full hull form with large block coefficient and small length to beam ratio.

The captive model test is seen to give correct solution about ship's manoeuvring performance but designer can not entrust to towing tank test at initial design stage because of the limitation of time and cost.

Resultly, the numerical simulation with the principal parameters derived from PMM database is taken a measure for ship's manouevrability prediction at initial design stage.

Kijima et al.[2] proposed the approximate formulae for hydrodynamic forces on a ship with closed stern. These formulae are obtained semi-empirically by the results of model test and of numerical calculation by lifting surface theory. Whereas the Kijima's formulae are limited for a ship with closed stern, those could not be adopted manoeuvring prediction for a ship with stern bulb.

In previous study, Lee et al.[3] derived regression equations for ships with stern bulb tested at Hyundai Maritime Research Institute by nondimensionalized principal parameters which Kijima used to predict hydrodynamic derivatives for ships with closed stern and simulated ship's manoeuvring performance by making use of formulae derived by regression analysis.

At the present paper, we studied to improve Kijima's model used to predict ship's manoeuvrability at initial design stage. The mathematical model is adopted as Kijima's model and the regression analyses are carried out for hydrodynamic derivatives and hull-propeller-rudder interaction coefficients. Finally, we simulate ship's manoeuvrabillity to validate the present MMG model and compare those with results of PMM test and Kijima's method.

## 2. MATHEMATICAL MODEL

By reference to the ship-fixed coordinate system shown in Fig.1, O-XYZ is space fixed coordinate and G-xyz is the body fixed coordinate.

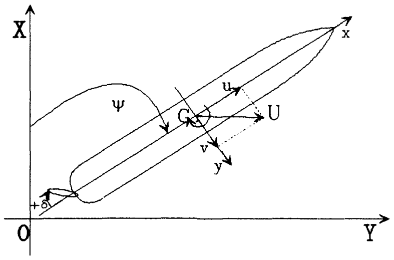



Fig.1 Coordinate systems

Referring the body fixed coordinate system, G-xyz, the basic equations of the ship's manoeuvring motion can be written in the following form.

$$\begin{aligned} m(\dot{u} - vr) &= X = X_H + X_P + X_R \\ m(\dot{v} + ur) &= Y = Y_{HP} + Y_R \\ I_{zz}\dot{r} &= N = N_{HP} + N_R \end{aligned} \tag{1}$$

where the terms with subscript H represent hull forces and the terms with subscripts P and R denote propeller forces and rudder forces respectively.

The mathematical model of hull forces in the paper was developed on the basis of the MMG model. Details of the model tests, their analyses and derivation of the mathematical model can be found in Lee et al.[4]. The forces acting on ship hull can be written as follows.

$$\begin{aligned} X_H + X_R &= -m_x\dot{u} + (m_y + X_{\beta r})\beta r + X_{uu}\cos^2\beta \\ Y_{HP} &= -m_y\dot{v} - m_x ur + Y_{HO}(\beta, r) \\ N_{HP} &= -J_{zz}\dot{r} + N_{HO}(\beta, r) \end{aligned} \tag{2}$$

The hull forces and moment are as follows.

$$\begin{aligned} Y_{HO} = \frac{1}{2}\rho LdU^2[&Y'_\beta\beta + Y'_r r' + Y'_{\beta\beta}\beta|\beta| + \\ &Y'_{rr}r'|r'| + (Y'_{\beta\beta r}\beta + Y'_{\beta rr}r')\beta r'] \end{aligned} \tag{3}$$

$$\begin{aligned} N_{HO} = \frac{1}{2}\rho L^2dU^2[&N'_\beta\beta + N'_r r' + N'_{\beta\beta}\beta|\beta| \\ &+ N'_{rr}r'|r'| + (N'_{\beta\beta r}\beta + N'_{\beta rr}r')\beta r'] \end{aligned}$$

According to regression analysis in this paper, hydrodynamic derivatives are obtain ed as follows.

$$\begin{aligned}
X'_{\beta r} + m' + m'_y &= 0.998 - 14.6991A'_p d/B - 1.0925k - 4.5865(A'_p d/B)^2 - 21.9443k^2 + 119.2277kA'_p d/B \\
Y'_{\beta rr} &= 1.8779 - 30.8615k + 153.6857k^2 \qquad (4) \\
Y'_\beta &= -9.5114 + 30.278C_b - 36.8419k - 22.1929C_b^2 + 20.3124k^2 + 40.3232C_b k \\
Y'_r - (m' + m'_x) &= 0.2443 - 0.1962C_b - 1.854B/L \\
Y'_{\beta\beta} &= -31.3506 + 3.622C_b + 318.2181B/L + 29.1844C_b^2 - 290.0526(B/L)^2 - 262.1299C_b B/L \\
Y'_{rr} &= 0.5578 - 8.3636A'_p d/B - 10.281(2lcb/L) + 11.8301(A'_p d/B)^2 + 30.8604(2lcb/L)^2 + 120.0584(2lcb/L)(A'_p d/B) \\
N'_\beta &= 0.0024 + 1.0272k + 0.2218kA'_p(1 - C_b) \\
Y'_{\beta\beta r} &= 7.9058 - 28.8732A'_p - 69.5545B/L - 4.431A'^2_p + 152.0147(B/L)^2 + 169.9388(A'_p B/L) \\
N'_r &= -0.0416 - 0.0006A'_p d/B + 0.29B/L - 2.29(A'_p d/B)^2 - 2.01(B/L)^2 + 2.22(A'_p d/B)(B/L) \\
N'_{\beta\beta} &= -0.2149 - 0.1991(A'_p d/B) + 4.6127k + 13.38(A'_p d/B)^2 - 22.53k^2 - 9.59k(A'_p d/B) \\
N'_{\beta rr} &= -1.5678 - 5.41A'_p + 23.16B/L + 2.38A'^2_p - 78.96(B/L)^2 + 25.33A'_p B/L \\
N'_{\beta\beta r} &= -1.5678 - 5.41A'_p + 23.16B/L + 2.38A'^2_p - 78.96(B/L)^2 + 25.33(A'_p B/L)
\end{aligned}$$

where k=2d/L. The variable of Ap'(=100 $A_p$/Ld) represents side area of stern bulb and the definition of that is shown in Fig.2

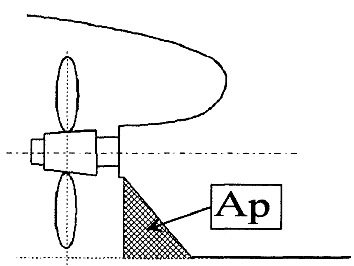



Fig.2 Configuration of $A_p$

The propeller thrust is as follows[2].

$$X'_P = (1-t)n^2D_P^4K_T(J)/\frac{1}{2}\rho LU^2d \quad (5)$$

The rudder force and moment including the hydrodynamic force and moment induced on ship hull by the rudder action can be written in the following forms[2].

$$\begin{aligned} X_R' &= -(1-t_R)F_N'\sin\delta \\ Y_R' &= (1+a_H)F_N'\cos\delta \\ N_R' &= (x_R' + a_H x_H')F_N'\cos\delta \end{aligned} \quad (6)$$

where

$$a_H = -11.4036 + 40.94C_b - 81.11k - 31.69C_b^2 + 90.76k^2 + 79.47C_bk$$

$$x'_H = -6.054 - 0.101A'_p + 58.18B/L + 3.4A'^2_p - 148.44(B/L)^2 - 8.73(A'_pB/L)$$

The rudder normal force is expressed as follows.

$$\begin{aligned} F_N' &= (U_R/U)^2(A_R/Ld)f_\wedge \sin\alpha_R \\ f_\wedge &= (5.5426\wedge)/(\wedge+2.4280) \\ U_R &= \sqrt{u_R^2+v_R^2} \end{aligned} \quad (7)$$

$A_R$ ; moveable rudder area
$\wedge$ ; rudder aspect ratio

where the rudder coefficient($f_\wedge$) can be estimated for horn type rudder. The effective inflow angle and velocity at a rudder can be described as follows.

$$\begin{aligned} \alpha_R &= \delta + \delta_0 - \gamma(\beta - l_R'r') \\ \delta_o &= -(\pi s_o/90) \\ s_0 &= 1 - u(1-w_p)/nP \\ u_R &= \varepsilon u_P\sqrt{\eta_H\left\{1+x\left(\sqrt{1+\frac{8K_T}{\pi J^2}}-1\right)\right\}^2 + (1-\eta_H)} \end{aligned} \quad (8)$$

$x = 0.6/\varepsilon$ where $\eta_H = D_P/H$

The $\varepsilon$ and $\gamma$ that represent the rudder normal force in Eqn.(8) can be described below.

$$\varepsilon = -2.3281 + 8.697C_b - 3.78k + 1.19C_b^2 + 292.k^2 - 82.51(kC_b) \quad (9)$$

$$\gamma_1 = 6.8736 - 16.77C_b + 3.5687k + 4.68C_b^2 - 253.14k^2 + 74.83kC_b \text{ , where } \beta \le 0$$

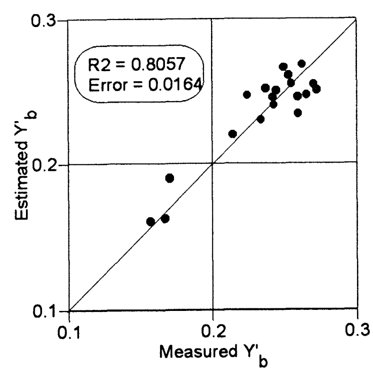
$$\gamma_2 = 23.708 - 83.84C_b + 173.72k + 71.64C_b^2 + 157.01k^2 - 261.11kC_b \text{ , where } \beta \ge 0$$

## 3. REGRESSION ANALYSIS AND SENSITIVITY STUDY

### 3.1 Regression analysis

The selection of regressive parameters must to be appropriated for the accurate prediction of hydrodynamic derivatives and hull-propeller-rudder interaction coefficients.

The coefficients of determination(R2) and regression errors checked by regression analyses are shown in Fig. 3 ~Fig. 4. For the purpose of reducing the error of regression analyses at the start, the regression analyses were carried out to selecting regressive parameters beyond five numbers. Owing to lack of experimental datas and mathematical uniqness due to the selection of many variables, the accuracy of manoeuvring analysis is decreased rather than regression analysis by Kijima's nondimensioal parameters[3]. Therefore, the parameters of principal dimensions and $A_p'$ that express side area ratio of stern bulb are introduced for regression analysis. The 1st and 2nd polynomial regression analyses are carrried out to selecting two nondimensional parameters that the accuracy of correlation is the highest, correlation coefficient is the largest and the regression error is the smallest. Fig.3 show the results of regression analysis for linear hydrodynamic derivatives in comparison with experimental datas. In these figures, the plotted symbols such as a circle show the measured results and the lines show the estimated results. The estimated values for linear hydrodynamic derivatives agree well with the measured results of PMM tests.



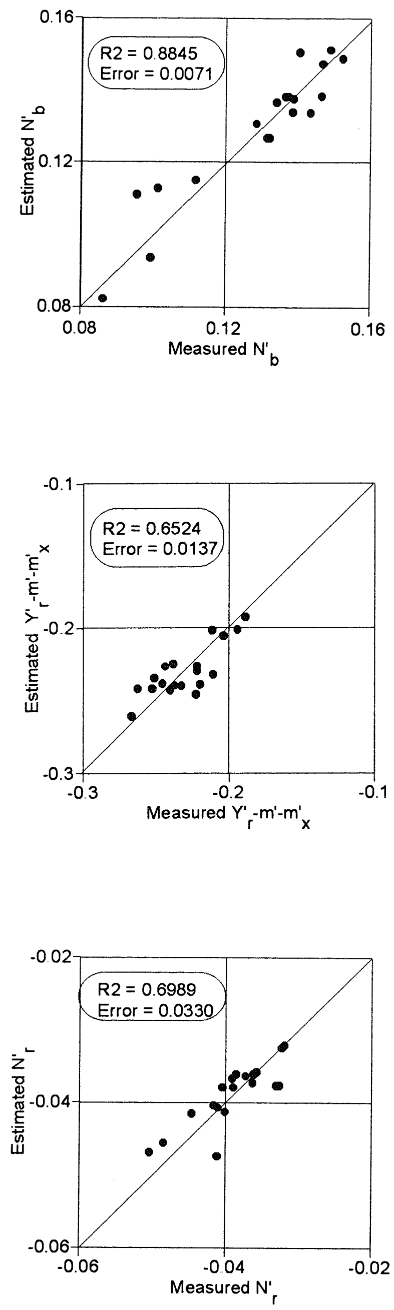
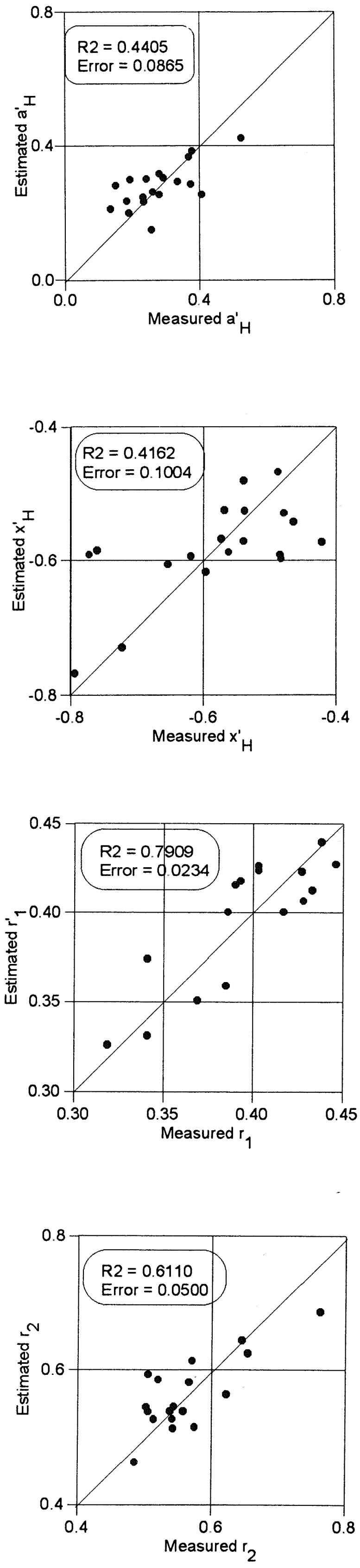
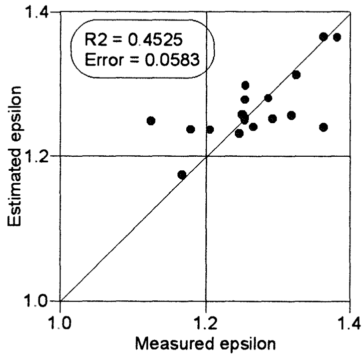



Fig.3 Comparison of measured and estimated coefficient( $Y'_\beta$, $Y'_r-m'-m'_x$, $N'_\beta$, $N'_r$)

Fig.4 show the results of regression anal ysis for $a_H, x'_H, \gamma_1, \gamma_2, \varepsilon$ and $f_\wedge$. In these figures, it can be seen that the errors of flow-straightening coefficients are smaller than those of other variables.





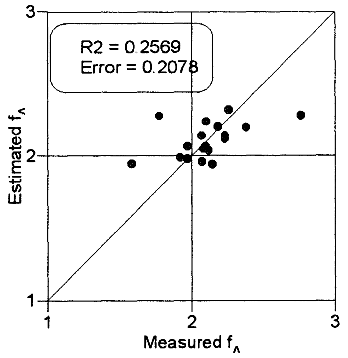




Fig.4 Comparison of measured and estimated coefficient( $a_H$, $x'_H$, $\gamma_1$, $\gamma_2$ and $\varepsilon$ )

### 3.2 Sensitivity study on simulation parameters

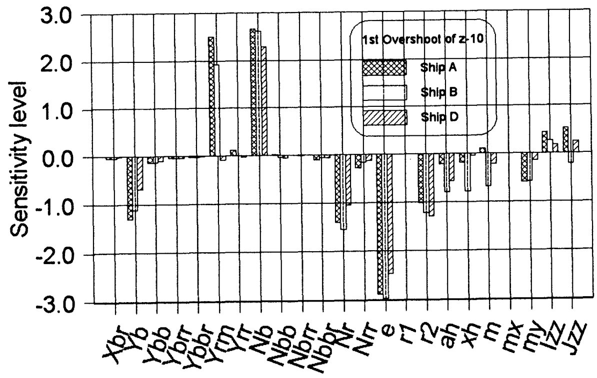
For the purpose of improving the predicti on accuracy, the most technique is to conce ntrate the improvement on such parameters that more strongly affect the predicted valu es. The sensitivity study has been perform ed with the three ships as used in the pre sent study. The full scale ships used for the sensitivity study are a chemical carrier (Ship A), oil tankers(Ship B and D) shown in Table 3.

Table 3. Dimension ratios of ships

| | Ship A | Ship B | Ship C | Ship D |
|---|---|---|---|---|
| L/B | 5.6 | 5.57 | 6.52 | 5.52 |
| B/T | 2.88 | 2.82 | 2.90 | 2.56 |
| L/T | 16.15 | 15.70 | 18.92 | 14.09 |
| $C_B$ | 0.7855 | 0.8166 | 0.8152 | 0.8149 |
| $A_R$/Ld(%) | 1.84 | 1.92 | 1.47 | 1.75 |

The items to be evaluated are those specified in the 1st and 2nd overshoot angle of 10°/10° zig-zag manoeuvre. The relative sensitivity here represents the ratio of change in estimated results when each parameter is individually increased 10%[5].

Fig.5 show the results of sensitivity study on the 1st and 2nd overshoot angle of 10°/10° zig-zig manoeuvre. It is found that $\varepsilon$ and $N'_\beta$ are paticularly dominant in the prediction of the overshoot angle of 10°/10° zig-zig manoeuvre.



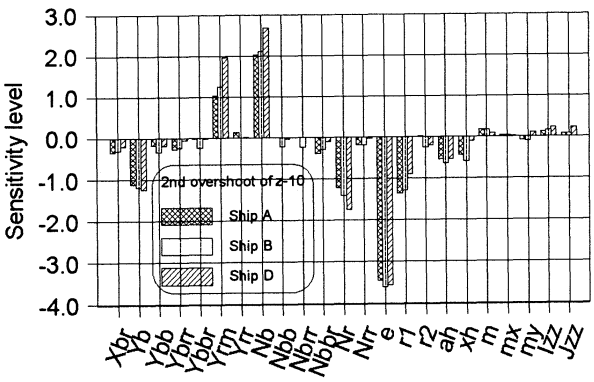




Fig.5 Relative sensitivity of parameters on 1st and 2nd overshoot angle of 10°/10° zig-zig manoeuvre

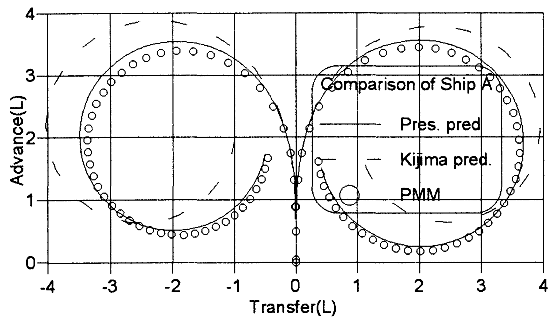
## 4. MANOEUVRING SIMULATION

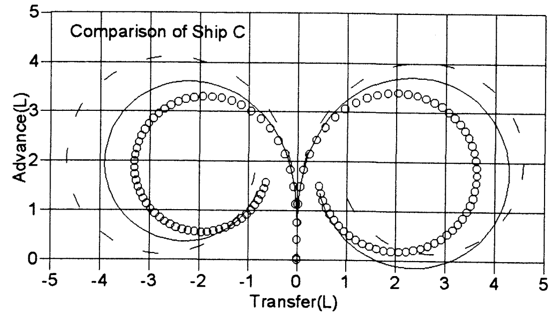
The manoeuvring simulation has been carried out with MMG mathematical modelling program developed in this paper for the case of three ships. The full scale ships used for the manoeuvring simulation study are a chemical carrier(Ship A), a chip carrier(Ship C) and a oil tanker(Ship D) shown Table 3.

The results of numerical simulation on manoeuvring motion by using regressed hydrodynamic forces are shown in the following figures, which the plotted symbols such as circle show the measured results, solid line show the present predicted results and dotted line show the Kijima's predicted results. Fig.6 show the trajectories of turning motion with rudder angle of 35° to starboard and port. They are nondimensionalized by LBP. It is clearly shown that turning performance of present prediction definitely agree well with the results of Kijima's and PMM model tests. Additionally, the case of ship A is better agreement with other results. Fig.7 show comparative plots of the time histories of heading angle for the 10°/10° zig-zag manoeuvres, respectively. It is found that the present prediction of 1st and 2nd overshoot angle is better correct than any other methods in case of ships with stern bulb. Fig.8 show comparative plots of the time histories of heading angle for the 20°/20° zig-zag manoeuvres.

The trends are similar to those of the 1st and 2nd overshoot angles 10°/10° zig-zag manoeuvres.

In case of unstable ship, the improve ment is definitely proved by overshoot angle appeared in the present prediction.



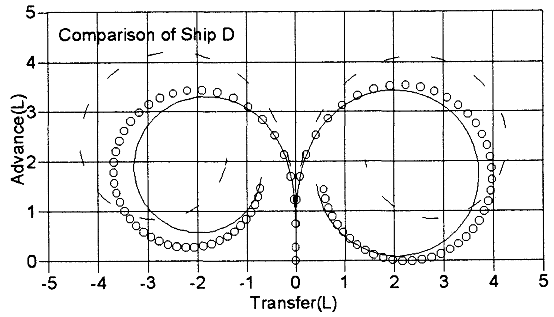
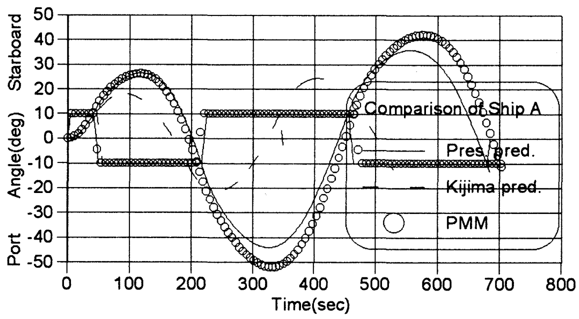
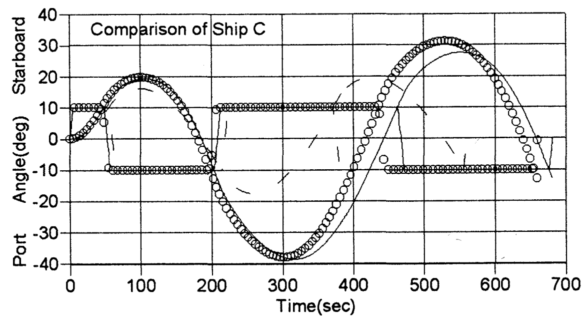




Fig.6 Comparison of turning trajectories by present prediction, Kijima's results and PMM results



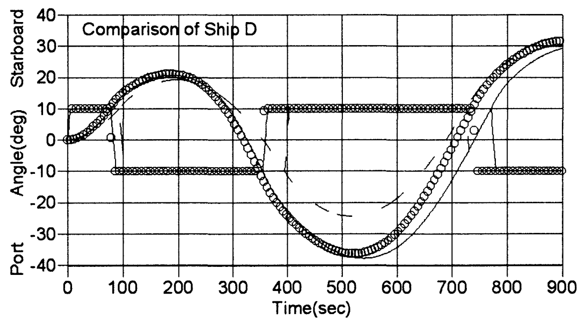




Fig.7 Comparison of 10°/10° zig-zag manoeuvre by present prediction, Kijima's results and PMM results

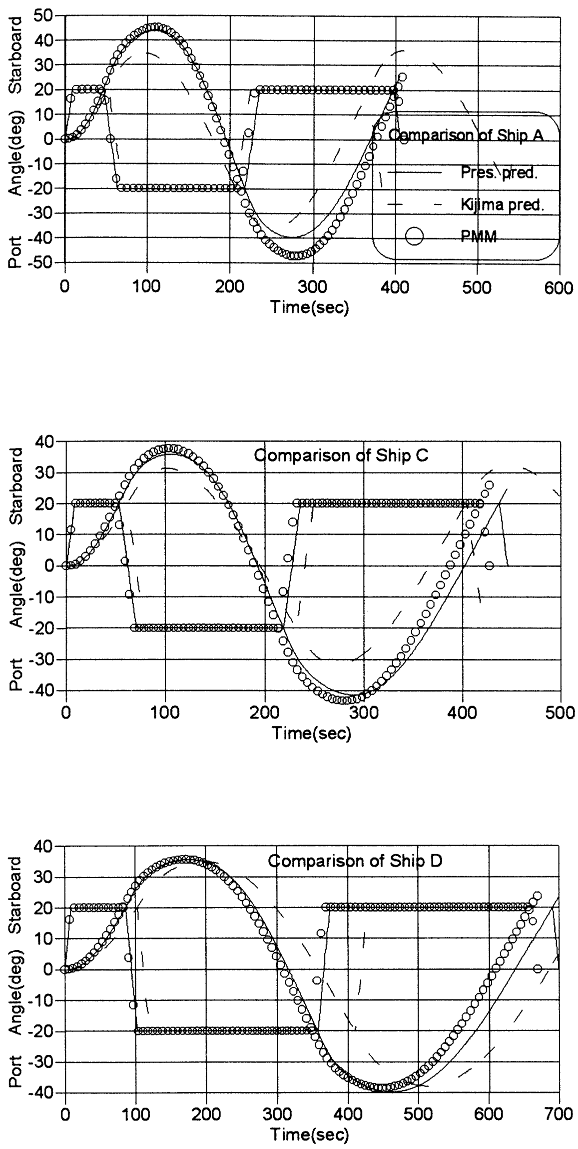



Fig.8 Comparison of 20°/20° zig-zag manoeuvre by present prediction, Kijima's results and PMM results

## 5. CONCLUSION

To predict ship's manoeuvrability at early design stage, the prediction method by semi emperical technique based on model tests is developed and the capability of present technique is validated by Kijima's method and PMM test.

The present study is applied to Kijima's mathematical model, and is proposed the approximate formulae to estimate the hydrodynamic derivatives acting on a ship and hull-propeller-rudder interaction coefficients. The approximate formulae proposed in this paper are obtained by the data on PMM model tests at HMRI. From the simulation results, the prediction method gives satisfied results for ships with stern bulb of bad course keeping stability and we partially consider hull form parameters such as side area of stern bulb in database system.

Additionally, it must be to accumulate the data for more correct prediction of ship's manoeuvrability, and the formulae for prediction of high speed vessels equal to container must be also obtained by accumulation of model test datas.

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