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LOW SPEED SHIP MANOEUVRABILITY: MATHEMATICAL MODEL AND ITS SIMULATION

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ABSTRACT

In case of offshore support vessels, it is quite important for their behaviours in low speed manoeuvrability. It is not easy to operate offshore support vessels and it raises an importance to train crew by a ship handling simulator. Therefore it is quite hot issue for ship handling simulator vendors to provide mathematical model of support vessels, but from the users' point-of-view the model used for the simulator is not clear. Up to now some mathematical models are proposed in the literature, but the validation is not yet done carefully. For example, cross flow model is the main part for hydrodynamic force in low speed ship manoeuvring. From model ship experiments of various types of ships and from some comparison study, it is found that further discussion is necessary. In this paper, sway force and yaw moment as well as surge force will be treated in low speed condition with certain sway and yaw motions. There are many experiment results for such hydrodynamic forces and moment, especially for sway force and yaw moment, for sway motion, but those for yaw motion is quite limited.

In this paper, such hydrodynamic forces and moment for both sway and yaw motions are calculated and validated with experiment results. Some manoeuvring simulation will also demonstrate which terms and/or expressions in the mathematical model are affecting the motion.

INTRODUCTION

Ship manoeuvrability in low speed is becoming very important from the viewpoint of safety. ITTC manoeuvring committee reports about the necessity of standards for low speed (ITTC 2008 [1]), and in its latest report (ITTC 2011 [2]), the brief review of the mathematical models and expressions are introduced. According to the latter report, they are categorised into several models; cross-flow model (*e.g.* Oltman *et al.* [3]), polynomial model (*e.g.* Abkowitz [4], Norrbin [5], Kijima *et al.* [6], although they are not for low speed manoeuvring), Fourier expansion model (*e.g.* Yumuro [7], Takashina [8-9], Kang et al. [10]), tabular manoeuvring model and RANS-based CFD model (*e.g.* Toxopeus [11], Wang [12-13], Pinto-Heredero [14], Fathi [15]). Even though there are several proposals, yet discussions are diverged from the accuracy of the model compared with experiments except tabular manoeuvring model in which model is based on experimental data, to the availability to predict the hydrodynamic forces and moment for any appropriate ship type and particulars.

From the viewpoint of practical application of these models, predicting accuracy of hydrodynamic forces and moment of any given ship in low speed, *i.e.* relatively large drift angle with arbitrary rate of turn, is quite interesting and important.

In this paper, discussions are made in this point, using several experimental results and the proposed models.

PREDICTION METHODS OF HULL HYDRODYNAMIC FORCES AND MOMENT IN LOW SPEED

There are already several proposed prediction models for ship hull hydrodynamic forces and moment in low speed condition, as well as some of those described in the previous section. In this section, the authors will compare them.

Almost all models are considering the advanced velocity is from low speed range to normal seed range, but they cannot treat the condition at advanced speed is zero, because they use longitudinal velocity component for non-dimensionalisation. Kose *et al.* [16] (hereinafter referred as **Kose's model**) have proposed a polynomial model. In this model the unique feature is it can treat zero advanced speed condition applied by the following non-dimensionalisation denoted by (*).

$$\left.\begin{aligned}&\{X^*,Y^*\}=\{X,Y\}/\frac{\rho}{2}L^3g\\&N^*=N/\frac{\rho}{2}L^4g\\&m^*=m/\frac{\rho}{2}L^3\\&I_{zz}{}^*=I_{zz}/\frac{\rho}{2}L^5\\&\{u^*,v^*\}=\{u,v\}/\sqrt{Lg}\\&r^*=r\sqrt{L/g}\\&\{\dot{u}^*,\dot{v}^*\}=\{\dot{u},\dot{v}\}/g\\&\dot{r}^*=\dot{r}L/g\end{aligned}\right\}\qquad(1)$$

where g is gravity constant and other symbols are well-known conventional ones. Kose's model is the only unique model applying this non-dimensionalisation. Some applications were done using this model [*e.g.*17, 18]. However, it is still some difficult to apply this model in general, because due to the polynomial model it is necessary to get the coefficients by captive model test.

Karasuno *et al.* [19-23] (hereinafter **Karasuno's model**) have proposed component-type mathematical model for low speed model. They divided hydrodynamic forces and moment into several components as theoretically as possible such as ideal fluid force, viscous lift, cross flow lift/drag, induced drag and frictional resistance as shown in Figs. 1 and 2. Good aspect of this model is each coefficient is expressed in a regression form consisting of ship principal particulars. Besides, these regression models are derived from various types of ships from fishing vessels to box-type ships. Therefore it can be applicable to any ship without conducting captive model tests. On the other hand, a demerit is the structure of the model is quite sophisticated and some of ship particulars indicating aft-body bluntness are not always available. Therefore there is no paper, as far as the authors know, applying this model yet, except their works.

Kang *et al.* [10] (hereinafter **Kang's model**) therefore have proposed a way like explaining below.

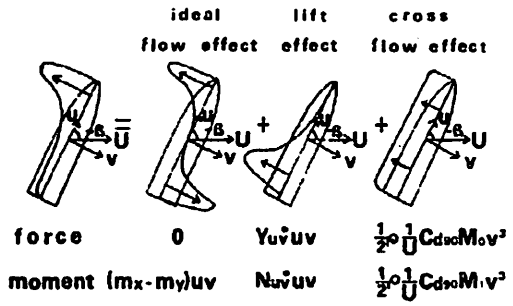


Fig. 1 Concept of component-type mathematical model (Karasuno *et al.* [19]).

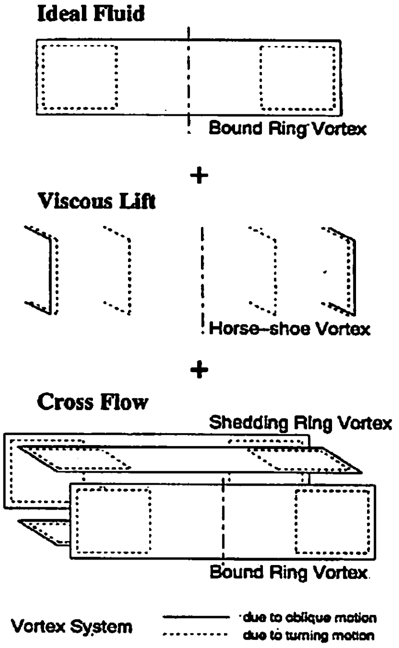


Fig. 2 Vortex systems in Karasuno's model [22].

- Generating hydrodynamic forces and moment using Karasuno's model for 21 blunt-body ships whose particulars data are published or known.
- Applying thus obtained forces and moment into the mathematical model proposed by Yumuro [7] (hereinafter **Yumuro's model**) and obtaining the coefficients.
- Building up new regression forms of each coefficient thus fit for Yumuro's model using principal particulars.
- Validating the simulation results compared with that of experiments.

This model estimates hydrodynamic forces and moment using Karasuno's model using as many ship as possible, whose particulars necessary for Karasuno's model are available and establishes new regression model using normal principal particulars fitting for Yumuro's model. Therefore in this model, ship type to be applied is restricted to blunt-body ship.

Yoshimura *et al.* [24, 25] (hereinafter **Yoshimura's model**) have proposed rather simpler model composed of linear lift forces and moment for small drift angle range by Kijima *et al.* [6] (hereinafter **Kijima's model**) and cross flow drag for large drift angle range basically by Oltman *et al.* [3] (hereinafter **Oltman's cross flow model**), although in the cross flow drag expression, correction factors related to apparent drift angle for yaw rate are introduced each for sway force and moment. Besides, not like others, astern hull resistance coefficient $X'_{O(A)}$ is considered and hull resistance component is expressed as follows:

$$X'_{Hresist}(u,\beta)=\{X'_{O(F)}+(X'_{O(A)}-X'_{O(F)})\}(|\beta|/\pi)u'\qquad(1)$$

where $X'_{Hresist}$ is hull resistance in longitudinal direction with or without drift angle β, and $X'_{O(F)}$ and $X'_{O(A)}$ are hull resistance coefficient for ahead condition ($\beta=0\,\text{deg}$) and astern condition ($\beta=\pi$) respectively. They provide C_{D90} the cross flow drag coefficient at $\beta = 90$ deg as a function of L/d, although in Karasuno's model, it is given in a function of $C_B \cdot L/d$.

Muto, Furukawa *et al.* [26] (hereinafter **Furukawa's model**) have proposed another simpler model. They have conducted experiments for wide range of the drift angle with certain combinations of yaw rate for four ships (bulk carrier, container and VLCC's) and took some representative points of the experimental data for sway force and yaw moment with the drift angle at 45, 90, 135 and 180 deg for making regression models for yaw rate using principle particulars respectively and connecting each point as well as Kijima's model used for less than 20 deg in absolute value of the drift angle. So this is a kind of the combination of a closed-fit model for the drift angle and a regression model for yaw rate.

EXPERIMENT RESULTS OF HULL HYDRODYNAMIC FORCES AND MOMENT IN LOW SPEED

Oh *et al.* have collected literatures treating model experiments of sway force and yaw moment in wide range of the drift angle, as well conducting their own experiments [27].

Figs. 3 and 4 show thus collected sway force and yaw moment, and principal particulars of the ship models are in Table 1. In case of sway force they are almost in line symmetry with respect to a vertical line at $\beta=90$ deg and it is understandable that it is mostly composed of lift force in smaller drift angle and cross-flow drag in rather larger range of drift angle. Some ships have small asymmetrical behaviour around its peak points and some models introduced in the previous section provide such features, but others not. On the other hand, in case of yaw moment, basically the dominant components are lift force component, and ideal flow component, well-known as Munk moment, point symmetry with respect to a point of $\beta=90$ deg and yaw moment is zero. However, in most cases, the asymmetrical feature around its peaks doesn't seem to be negligible.

Table 1. Principal particulars of model ships collected experiment results [27].

Ship type	L (m)	B (m)	d (m)	C_B
Self propulsion barge (B1) (Obokata *et al.* [28])	3.000	0.821	0.115	0.81
Tanker (T1) (Obokata *et al.* [28])	3.000	0.504	0.194	0.83
Tanker (T2) (Obokata *et al.* [28])	3.683	0.577	0.205	0.84
Cargo ship (C2) (Obokata *et al.* [28])	3.000	0.428	0.171	0.70
Slender Model (C3) (Obokata *et al.* [28])	3.000	0.300	0.180	0.58
LNGC (Takashina [8])	2.500	0.415	0.100	0.69
VLCC (Yumuro [7])	4.000	0.652	0.268	0.83
Tanker (Oh *et al.* [29])	3.940	0.580	0.220	0.83

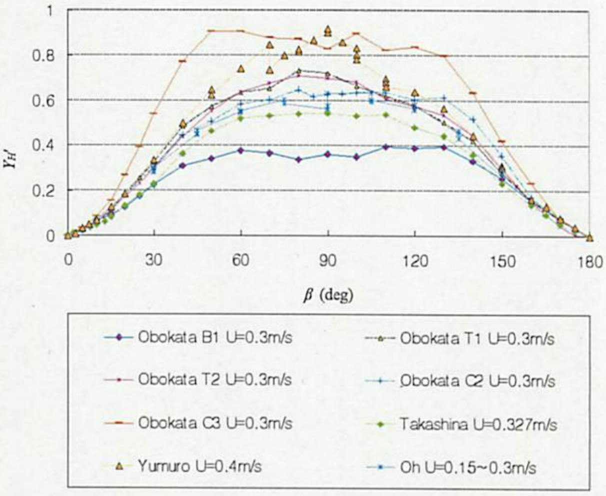


Fig. 3 Sway force of several ship models in low speed with wide range of drift angle [27].

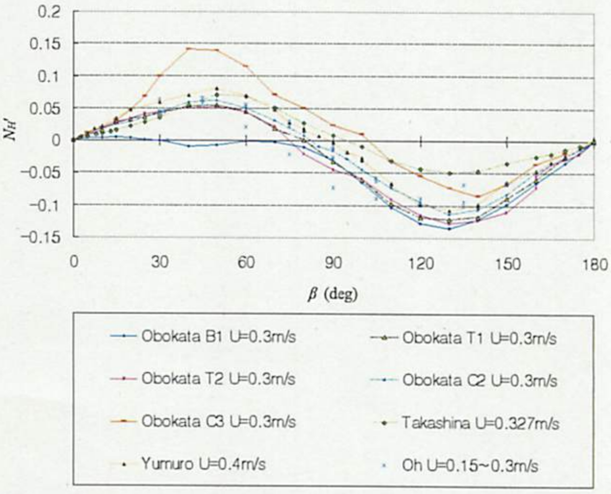
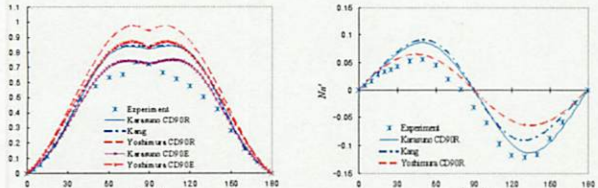


Fig. 4 Yaw moment of several ship models in low speed with wide range of drift angle [27].

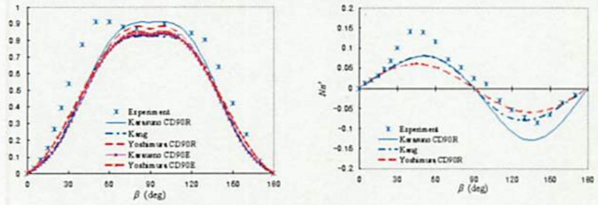
However, the problem is these features are quite dependent on ship type and/or frame lines, especially astern form, but most model neglect longitudinal ship shape asymmetry respect to midship or regard it in a simple way.

The discussion here is therefore how several models introduced in the previous section realise these features and how the differences between the experiment and the models, and amongst models play influence. Because these models are proposed to estimate ship motion in low speed, we need to check it by simulation.

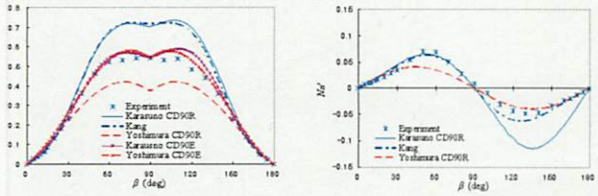
COMPARIZON BETWEEN EXPERIMENTS AND MODELS



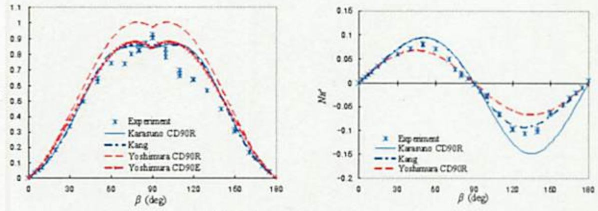
(1) Tanker (T1)



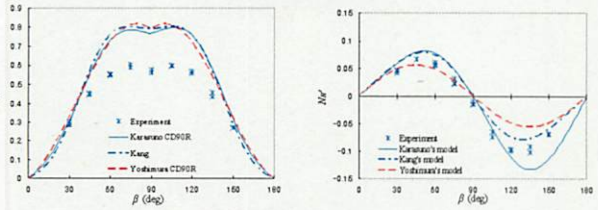
(2) Slender body ship (C3)



(3) LNGC



(4) Esso Osaka



(5) PANAMAX tanker

Fig. 5 Comparison results of sway force and yaw moment for sway motion [29].

Oh *et al.* [29] therefore, first, conducted comparison study to confirm how these models reproduce experiment results whose subject ships are not used when the models are proposed as shown in Fig. 5.

MATHEMATICAL MODEL

MMG coordinate system around midship as shown in Fig. 6 is used for the simulation, where x_G, x_t are coordinate of C.G. the subject ship and its added mass respectively. The right-hand is external forces and moment composing of terms due to hull (H), rudder (R) and propeller (P) respectively as shown in eqs. (3) and (4). Fig. 6 shows the case of single propeller twin-rudder system, but can treat single-propeller single-rudder or twin-propeller twin-rudder system can be also treated, and only definition of symbols and their positive directions are shown except v.

$$\left.\begin{aligned} (m+m_x)\dot{u}-m(vr+x_G r^2) &= X \\ (m+m_y)\dot{v}+(mx_G+m_y x_t)\dot{r} & \\ +mur &= Y \\ (I_{ZZ}+mx_G^2+J_{ZZ}+m_y x_t^2)\dot{r} & \\ +(mx_G+m_y x_t)\dot{v}+mx_G ur &= N \end{aligned}\right\} \tag{3}$$

$$\left.\begin{aligned} X &= X_H+X_P+X_R \\ Y &= Y_H+Y_R \\ N &= N_H+N_R \end{aligned}\right\} \tag{4}$$

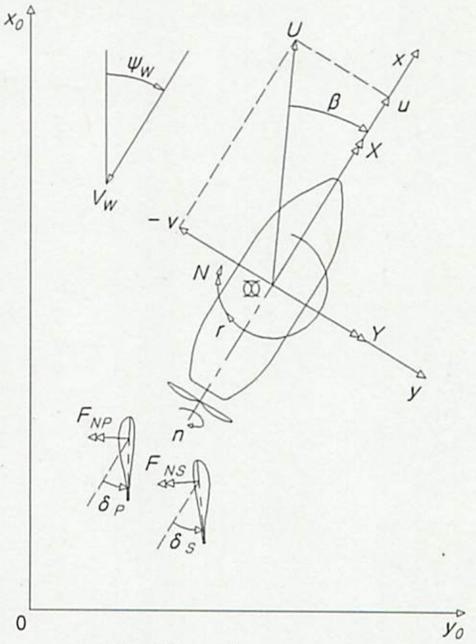


Fig. 6 Coordinate system.

SIMULATION OF SHIP MANOEUVRING

The main intention of the simulation is to confirm the influence of the difference between experiments and the models and amongst models, as described in the previous section.

The subject ship is not chosen from the ships listed in Table 1, but a new ship as listed in Table 2 whose experiments were conducted by Kang [30], although the experiment data treated in the present study is not published before. The thrust models are treated in normal way [*e.g.* 30], and the resistance is estimated in eq. (5) (hereinafter X_{uu} **model**).

$$X'_{Hresist}(u) = X'_{uu}\cdot u^2 \tag{5}$$

The model of rudder force and moment are separately analysed [31] and used for all models, because the subject ship is single-propeller twin-rudder ship and it is not, in general, easy to predict the model itself and the coefficients. Five models are chosen for the comparison, *i.e.* Kijima's model, Karasuno's model, Kang's model, Yoshimura's model and Furukawa's model. It is important to emphasise that these models except Kijima's model are aimed for low speed manoeuvring, so that it is necessary to choose appropriate ship motion containing relatively large drift angle against yaw rate to demonstrate the influence of these models, but in this study, as the first step, basic manoeuvring tests, *i.e.* turning test and zigzag test are chosen. Rudder is mariner type Super VecTwin® rudder [32] as shown in Fig. 7.

Table 2. Principal particulars of the simulation model ship.

Ship type	L (m)	B (m)	d (m)	C_B	X_G (m)	P/D_P
VLCC	4.000	0.666	0.240	0.817	0.123	0.669

Fig. 7 Super VecTwin® Rudder System [32].

In case of Yoshimura's model they propose different hull resistance component model as shown in eq. (2), so the authors have applied two models; one is **Yoshimura' resistance model** (eq. 2) and the other is replacing with same hull resistance component with X_{uu} model, but it didn't change in the following results, so original model is only shown. However, in case of low speed manoeuvring with relatively large drift angle, the authors should continuously check this point. Secondary, in Yoshimura's model [25, 33] $X'_{vr} + m'_y$ is estimated in eq. (6) or (7) as shown below, but it is not fit for the given ship, so the modified formula, shown in eq. (8), is used. This formula is base on Hasegawa's chart [34]. Kang made this regression form from the chart, for blunt-body ships, although there is no description in the thesis [30]

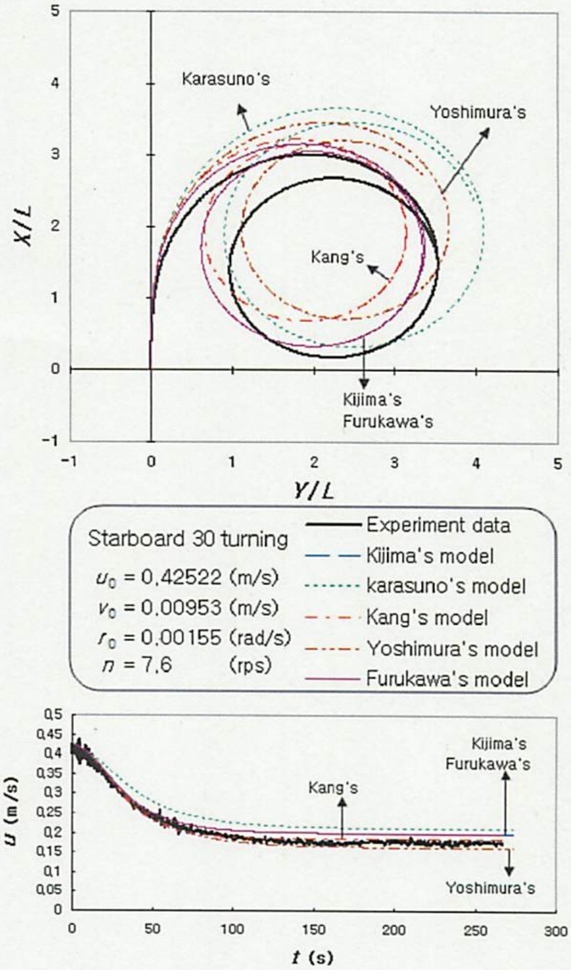
In case of Furukawa's model, they didn't provide the model for surge force, so X_{uu} model with eq. (8) is used.

$$X'_{vr} + m'_y = 2.86\cdot C_B/(L/B) - 0.21 \tag{6}$$

$$X'_{vr} + m'_y = -1.91\cdot C_B/(L/B) + 0.08 \tag{7}$$

$$X'_{vr} + m'_y = 1.67\cdot C_B - 0.5 \tag{8}$$

Figs. 8 and 11 are the simulation results of +/-30 deg turning tests and Figs. 12 and 13 are those of -10/+10 zigzag test. In the simulation, the initial conditions are set as same as each experiment as shown in each figure, and wind disturbance measured at experiments are shown in Figs. 9, 11 and 13.



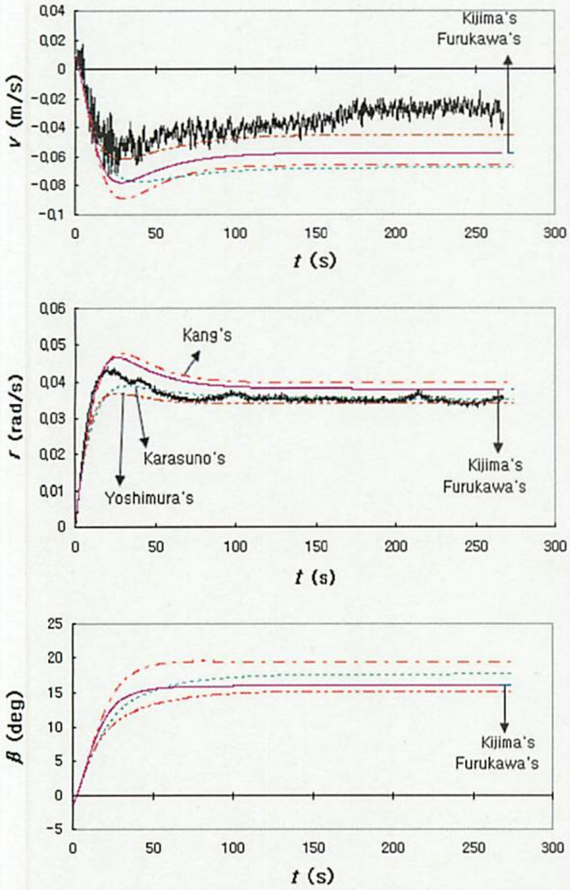


Fig. 8 Simulation and Experiment Comparison of Kijima, Karasuno, Kang, Yoshimura and Furukawa's models for starboard 30 deg turning test (From the top, trajectory, longitudinal speed component, transverse speed component, drift angle and yaw rate).

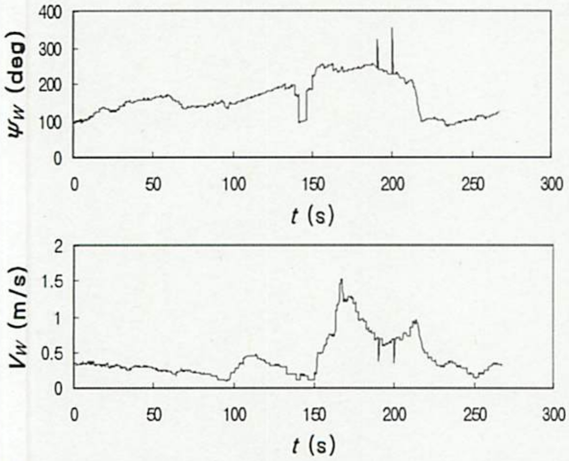
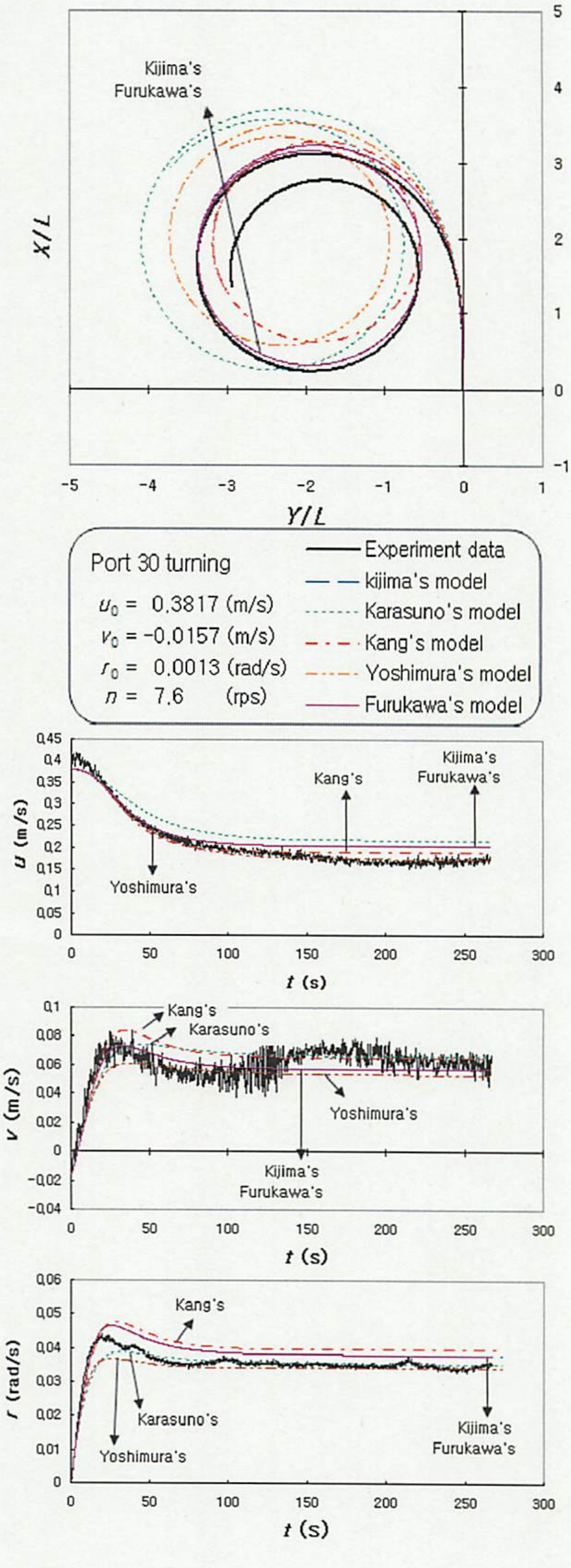


Fig. 9 Time history of relative wind direction and velocity during starboard 30 deg turning test of Fig. 8.



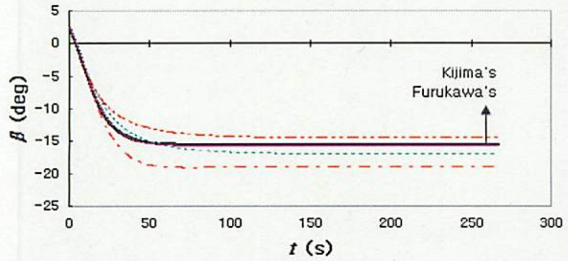


Fig. 10 Simulation and Experiment Comparison of Kijima, Karasuno, Kang, Yoshimura and Furukawa's models for port 30 deg turning test (From the top, trajectory, longitudinal speed component, transverse speed component, drift angle and yaw rate).

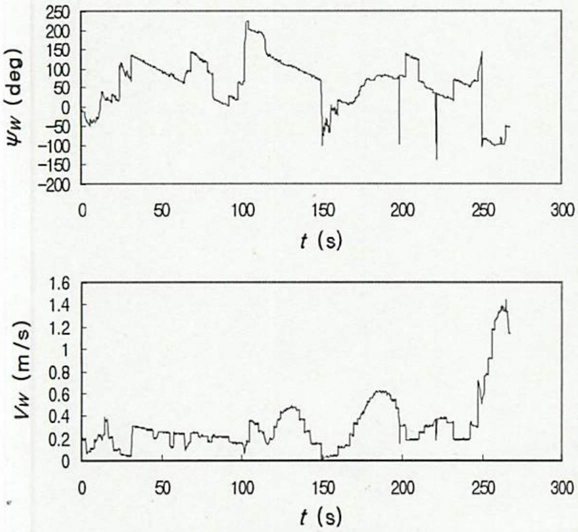
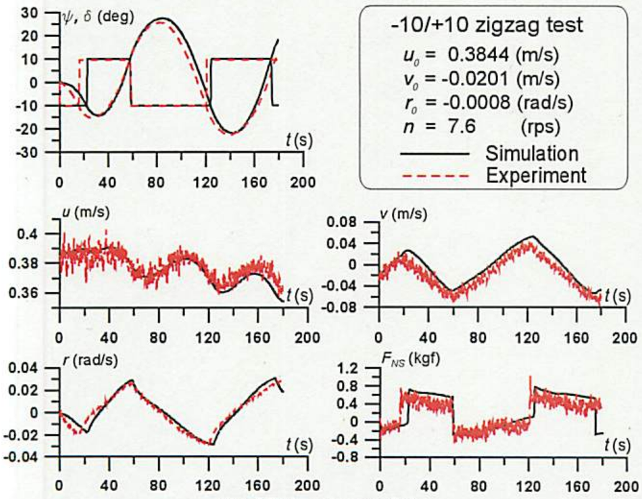
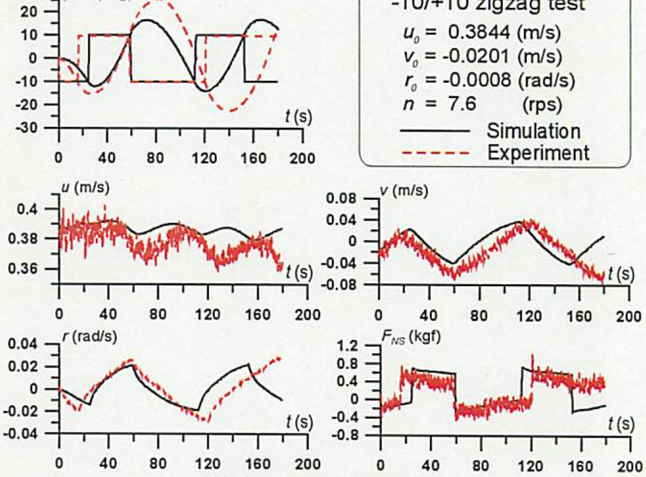


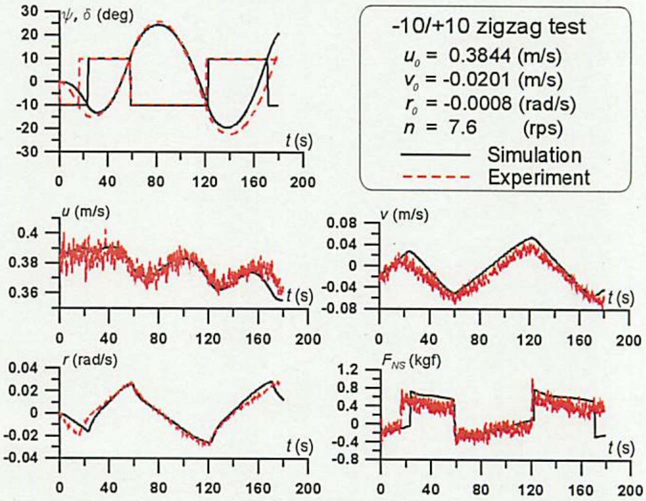
Fig. 11 Time history of relative wind direction and velocity during port 30 deg turning test of Fig. 10.



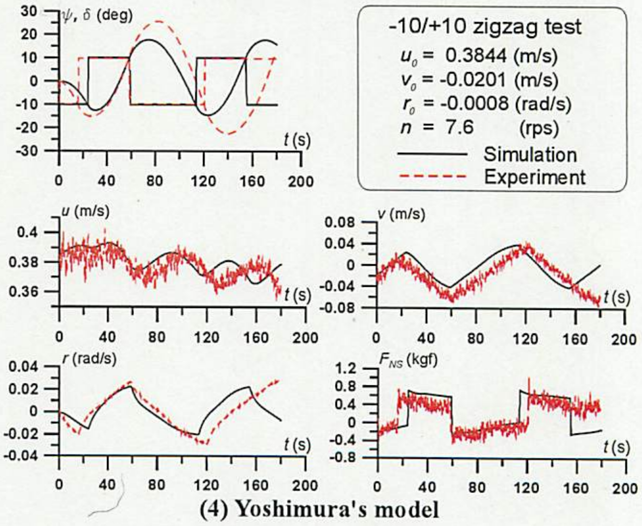
(1) Kijima's model



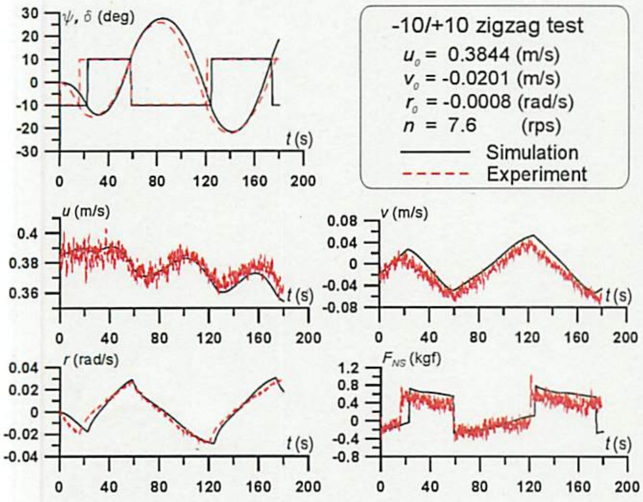
(2) Karasuno's model



(3) Kang's model



(4) Yoshimura's model



(5) Furukawa's model

Fig. 12 Simulation and Experiment Comparison of (1) Kijima, (2) Karasuno, (3) Kang, (4)Yoshimura and (5) Furukawa's models for -10/+10 zigzag test (From the left top to right bottom, heading and rudder angles, longitudinal speed component, transverse speed component, starboard-side rudder normal force).

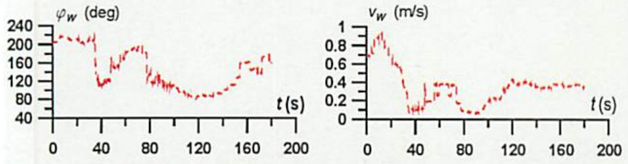


Fig. 13 Time history of relative wind direction and velocity during -10/+10 zigzag test of Fig. 12.

First of all, at a glance, both results diverge much, especially, in the trajectory, because of some discrepancy in steady state estimation error. However, it can be said, in other word, it is quite good guess without conducting any captive/free-running model test. Secondary, the motion range (in terms of drift angle and yaw rate), it is still relatively small drift angle range less than 20 deg, so that the most differences came from lift force estimation. Although there are big difference in the estimation of C_{D90} (cross-flow drag coefficient in β=90 deg) in Fig. 4 and the peak values and its asymmetry in Fig. 5, the motion range is less than this area.

The results of Fig. 9, 10 and 12 show these disturbance does not affect much and most models predict the experiment result quite well. Again, the motion here is relatively small, and Kijima's model is dominant at small drift angle.

However, on the other words, we can say that all models chosen in this paper can treat and simulate ship motion not only at low speed but also at normal speed where drift angle is less than 20 deg without changing the model itself. For this fact, these models will be more important, when we treat ship motions in wide range of speed.

CONCLUSIONS

In this paper, the authors first reviewed the existing research on low speed manoeuvrability. Four models are chosen for the difference of each proposed hydrodynamic forces and moment. Finally, the numerical simulation is conducted to check the influence of each model's feature. The main conclusions are summarised as follows:

(1) Mathematical models for ship motion in low speed are briefly reviewed.

(2) Models are compared in terms of hydrodynamic forces and moment in captive model test and motions in free-running tests.

(3) Some models can express asymmetry in hydrodynamic forces and moment, but the difference of the models is much dependent on lift force estimation in small drift angle for turning and zigzag test.

(4) Continuous efforts to investigate the mathematical model for low speed ship manoeuvrability is required and especially, simulation of ship behaviour in such case is requested.

(5) All models can treat ship motion not only at low speed condition, but also even at normal speed.

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