Ship Manoeuvring Hydrodynamic Forces and Moment in Low Speed

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Abstract

MMG model is well-known as an established mathematical model as well as so-called Abkowitz model for ship manoeuvrability in moderate speed, but the model for low speed is not yet established. There are already several proposed models for low speed, but most of them are based on Inoue-Kijima's empirical formula for small drift angle or yaw rate and extend it for large angle experimentally. Karasuno has proposed it with summation of several theoretical components and whose coefficients are identified and modeled with regression analysis for various types of ships. The model can express physical characteristics very well. However, the model needs many ship parameters and some of them are not easy to be provided. The model is designed for applying for various ships and contrary, the accuracy goes down. Kang improves this point by making the model applicable for blunt body ships. On the other hand, Yoshimura has proposed another model based on the continuity from small drift angle model to large drift angle model. The model is much simpler than Karasuno's model and looks similar accuracy. In the present study, these three models are particularly chosen for the comparison and some future direction is also suggested.

Keywords: Ship manoeuvrability, mathematical model, low speed, hydrodynamic forces and moment, cross flow model

1 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), and in its latest report (ITTC 2011), 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, polynomial model, Fourier expansion model, tabular manoeuvring model and RANS-based CFD model. 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.

2 Brief introduction of several models

The mathematical models, which are used to predict low speed motion of hulls, are largely based on cross flow drag model (Oltman and Sharma 1984). In this model the forces are assumed to compose of kinematic forces, *i.e.* ideal fluid forces, viscous lift, induced drag, cross flow drag, cross flow lift and frictional resistance. Each component of these hydrodynamic forces is calculated according to the slender body theory. Since for the large drift angle the sway force becomes quite susceptible to the cross flow drag induced by the flow separation, the slender body theory fails in those large drift angle region. For this purpose, Karasuno *et al.* (2003) have proposed almost similar segmented mathematical model, where the components of forces are being calculated on the basis of physical phenomena that are occurring during vortex shedding from hull. To take account of viscosity effect, the bound horse-shoe vortices at the fore end are considered to be shedding out weakly while at the aft end the vice versa is considered. The strength of those vortices are being empirically derived using static coefficients, whose empirical forms show reasonable approximations of the above mentioned forces for turning motion of the ships. Although for induced drag some discrepancies exist.

2.1 Cross flow model

For designing of mooring system, several model experimental studies were done mostly in 1980s. Obokata (1981) has carried out experimental study using various 7 types of ships including a self-propulsion barge and proposed a model to express hydrodynamic forces and moment. Oltman and Sharma (1984) have also used the cross flow model for simulation of various ship manoeuvring, including engine and rudder. The cross flow drag is expressed in general in the following form and it is explained the integration of lateral drag in longitudinal direction as shown in Fig. 1.

$$\left.\begin{aligned} Y_{HNL} &= -(\frac{\rho}{2})\int_{-\frac{L}{2}}^{\frac{L}{2}} C_D(x)d(x)\left|v+rx\right|(v+rx)dx \\ N_{HNL} &- -(\frac{\rho}{2})\int_{-\frac{L}{2}}^{\frac{L}{2}} C_D(x)d(x)\left|v+rx\right|(v+rx)xdx \end{aligned}\right] \quad (1)$$

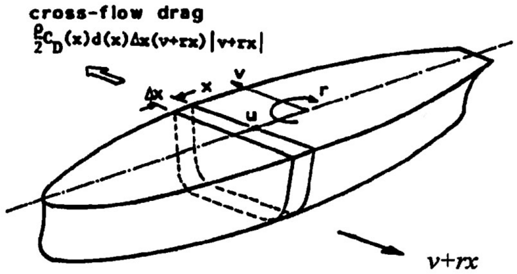

Fig. 1 Concept of cross flow drag (Yoshimura *et al.* 2009)

The important parameter when we use the cross flow model is cross flow drag coefficient *CD*. It, in general, depends on the section, so that is a function of *x*, *the position in longitudinal coordinate of the ship*. They consider it as the 7, 8 and 9th polynomial function as shown in Fig. 2 (Oltman and Sharma 1984), where they call it C_{CFD}.

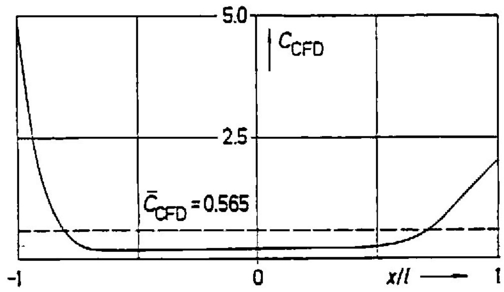

Fig. 2 Cross flow drag coefficient C_{CFD} of a tanker model (Oltman and Sharma 1984)

Actually there are not enough data to express *CD*(*x*), and it is inconvenient to calculate eq. (1) most researchers after regard it as a constant *CD* alongside ship length. If the ship is even keel condition, *d*(*x*) is also considered as a constant *d*. Yoshimura *et al.* (2009) has introduced additional correction factors C_{rY} and C_{rN} for the expression of apparent sway velocity in eq. (1) as below.

$$\begin{aligned} v_{xY} &= v + C_{rY}rx \\ v_{xN} &= v + C_{rN}rx \end{aligned} \quad (2)$$

where

v_{xY} , v_{xN} : apparent sway velocities at a coordinate *x* apart from the mid-ship in longitudinal direction in sway force and yaw moment expressions respectively

C_{rY} , C_{rN} : coefficients to evaluate apparent sway velocities v_{aY}, v_{aN} respectively, and they are determined to coincide the experiment results of various *r* at $\beta = 0$.

Obokata (1981) treats the model to pivoting point expressing the relation between sway force and yawing moment for wide range of drift angle and stall angle for lift force, too.

Karasuno *et al.* (1988) has extent Obokata's model into more physically constructed and sophisticated component type model and proposed each coefficient into regression model using principal particulars *etc.* based on the model experiments. As for the cross flow component, he expresses it in the following form.

$$C_D = C_{D90} \left|\sin\beta\right| \cdot (1 + p\cos^2\beta) \quad (2)$$

where

C_{D90} : cross flow drag coefficient at β = 90 deg.

p : correction factor taking account of stall influence as shown in Fig. 3

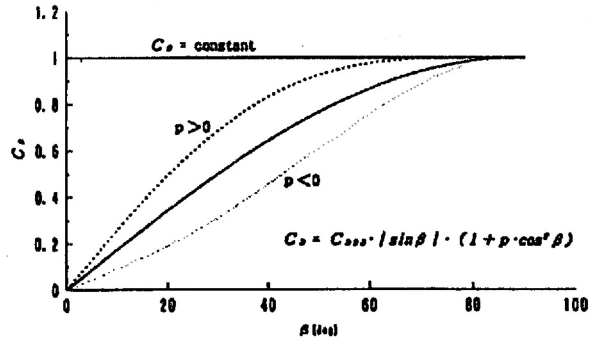

Fig. 3 Correction factor p in Karasuno's cross flow model (Karasuno *et al.* 1991)

2.2 Polynomial model

Abkowitz (1964) has employed polynomial type mathematical model for ship manoeuvrability using Taylor expansion for moderate ship speed. Since then, many researchers such as Norrbin (1971) have used this type of model. So-called MMG model is also a kind of polynomial model, although it treats interaction components between hull, propeller and rudder. These models are commonly used before MMG model appears.

For low speed mathematical model, Takashina and Hirano (1990) have used this type model using 2nd order (for surge), 5th order (for sway) and 3rd order (for yaw) polynomials respectively. However, it is somewhat difficult to treat this type in general, because we need experiment data to get the coefficients.

For moderate speed, Kijima ***et al.*** (1999) have established well-known regression model, sometimes called as Inoue or Inoue-Kijima empirical formula based on the slender body theory and model experiments of various ships. To establish similar regression model for low speed, we need many experiments of various ships and some theoretical consideration.

2.3 Fourier expansion model

Yumuro (1988) and Takashina (1990) have employed this type of model for low speed manoeuvring, because the general form of sway force and yaw moment in wide range of drift angle look like sinusoidal function. It is quite natural to apply sine and cosine functions for modelling this kind of data than applying polynomial models. We don't need to have higher order terms nor worry the extremely deformed value outside the fitted area. Kang and Hasegawa (2007) have applied this type of model by improving Yumuro's model (1988), specially targeted for blunt body ships. In case of polynomial and Fourier expansion models, we need many experiment data to get certain regression models, when we apply for an arbitrary ship. Instead of conducting many ship model experiments, Kang and Hasegawa (2007) provide hull hydrodynamic forces and moment estimated by Kijima's empirical formula (1999) for small drift angle and Krasuno model (2003) for large drift angle. They regard them as given experiment data and applied Yumuro's Fourier expansion model. Based on thus obtained coefficients regression analysis is done to propose general Fourier expansion model for an arbitrary blunt body ship.

2.4 RANS-based CFD model

Numerical calculation for the prediction of hull forces and moments are getting popular very recently. Significant developments in the parallel computing and memory management have instigated many researchers to apply many of the CFD techniques in the ship manoeuvring field. Among those, implementation of RANS (Reynolds Averaged Navier-Stokes) equation based simulations has been found to be quite practical in terms of cost effectiveness against the amount of effort needed (ITTC Manoeuvring Committee 2008). In most of the literature on RANS simulations the concentration has been mostly put on the flow field determination around the manoeuvring ships. For those cases, most of the analyses are confined to the low drift angle motion. Since, flow separation becomes quite significant during large drift motion, the viscous effect in large drift angle are mostly dictated by the pressure gradients at the leeward side of the ships. Therefore, the effectiveness of the RANS methods largely depend upon the capabilities to predict the adverse pressure gradients correctly at the side where vortex shedding is significant. In this context, DES (detached eddy simulation) and URANS (Unsteady RANS) simulations are being carried out by Pinto-Heredero (2010) for Wigley hulls. The vortical structures and shear layer instabilities are being analyzed qualitatively to show the capability of RANS methods to predict the unsteady phenomena quite reasonably in the flow field. Although no comparisons were made between experiment and calculation, the unsteadiness related to the vortical structures shed from fore and aft end show reasonable prediction of Karman like vortices. For extensive range of drift angle the force and moment coefficients were calculated by Fathi (2010) for a proprietary tanker model. The calculated values show reasonable approximation for sway force and yaw moments except for the 70-110 degree range as compared to the experiment data. Discrepancies in surge force calculations suggest a significant lack in the prediction of frictional resistances. For unsteady motion of ships numerical calculations were carried out for a Wigley hull (Wang 2009a, 2009b), where a berthing manoeuvre was simulated and compared to the experimental results. The velocities at different stages of the manoeuvre were calculated by user defined functions. The lateral hydrodynamic forces were reasonably calculated using a commercial CFD code (FLUENT). On the basis of these simulations, similar kinds of simulations are needed to be carried out for blunt body ships to confirm the predictability of unsteady ship manoeuvres using RANS codes.

3 Comparison of three models

In this chapter, Karasuno (2003) and Yoshimura (2009) from cross flow model and Kang (2007) from Fourier expansion model are chosen for the comparison for applying for general commercial ships. Even though Kang's model (2007) is limited to apply for blunt body ships, it is tested.

3.1 Model ships used for comparison

Five model ships are used for the comparison study, whose principal particulars are tabulated in Table 1. The data are taken from the references as listed. Except Esso Osaka other ships are not used to determine regression models of each coefficient in Karasuno, Yoshimura and Kang's models. On the other hand Esso Osaka is used by all models. As described in **2.3**, Kang's model has some limitation for its applicable range in ship particulars, L/B, d/L, d/B and C_B and the slender body ship and the LNGC are outside the range. Other three ships are blunt body ships, but still at the almost edge of the limit in some parameter. In this paper these limitations are neglected. Yoshimura's model has also some regression forms in his proposal such as $CD90$, so it has also some limitations, but it permits almost all commercial ships. Karasuno's model, on the contrary, permits almost all types of ships including box type mathematical ships and fishery boats. It means that the expected prediction accuracy is in this order. Experiment data are digitized from the references except PANAMAX tanker, so some discrepancy may occur due to the resolution of the figure and digitized error.

3.2 Results of comparison

Comparison study was done for sway force and yaw moment due to sway motion. Due to the lack of experiment data, sway force and yaw moment due to yaw motion is carried out only for Esso Osaka and surge force is for two ships.

The results are shown in Figs. 4-6. In each figure, the graph legends and symbols denote as follows.

Marks→

Experiment: experiment data taken from individual reference

Karasuno: experiment data by Karasuno

Yoshimura: experiment data by Yoshimura

Others: experiment data by others

Lines→

Karasuno CD90R: Karasuno's model where $CD90$ is predicted using Karasuno's $CD90$ regression model

Kang: Kang's model

Yoshimura CD90R: Yoshimura's model where $CD90$ is predicted using Yoshimura's $CD90$ regression model

Table 1 Principal Particulars of model ships used for comparison study

Ship type	L [m]	B [m]	d [m]	C_B	Speed [m/s]	Reference
Tanker 1 (T1)	3.00	0.54	0.19	0.83	0.30	Obokata 1981
Slender body ship (C3)	3.00	0.30	0.18	0.58	0.30	Obokata 1981
LNGC	2.50	0.42	0.10	0.69	0.32	Takashina 1986
Esso Osaka	4.00	0.65	0.27	0.83	0.40	Yumuro 1988

PANAMAX tanker	3.94	0.58	0.22	0.83	0.25	Oh 2012

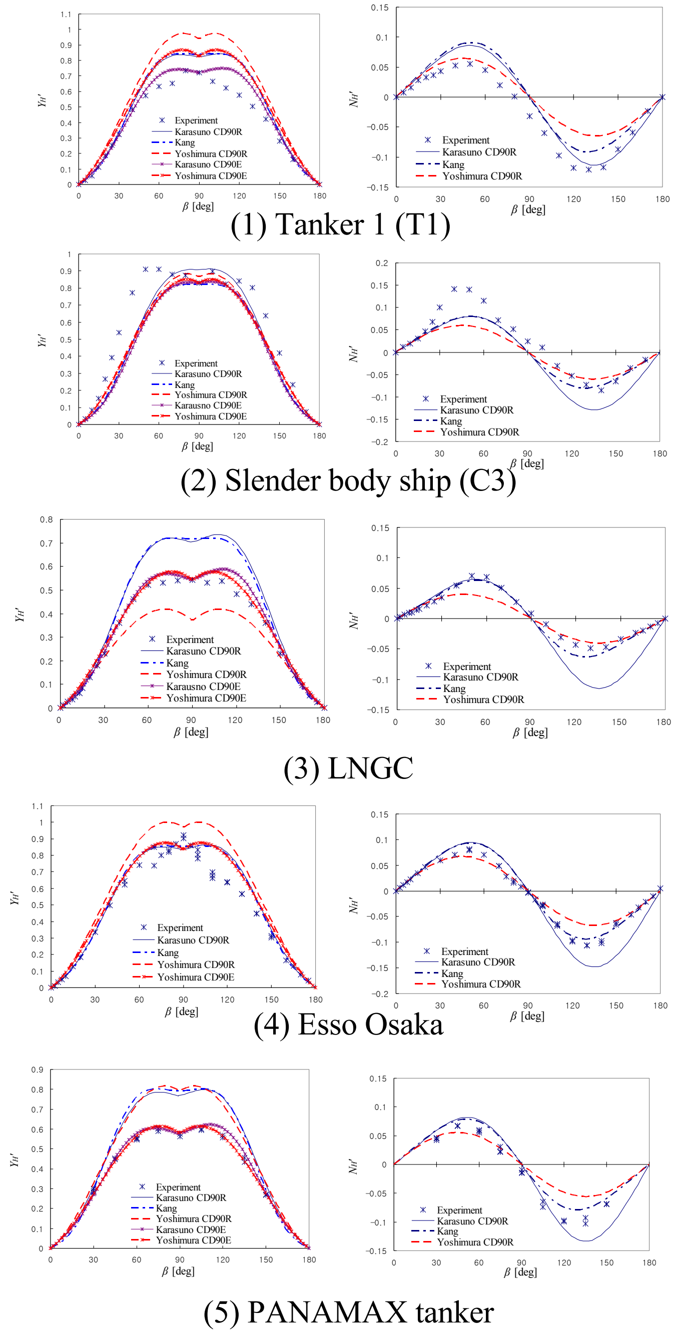

Fig. 4 Comparison results of sway force and yaw moment for sway motion

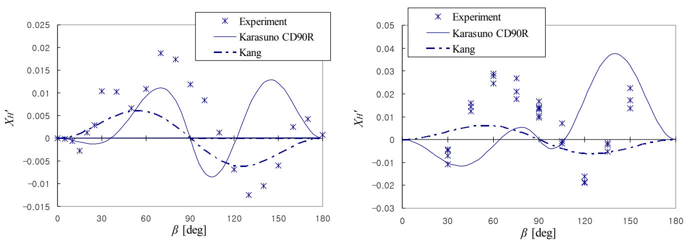

Fig. 5 Comparison results of surge force for sway motion (left: slender body ship, right: PANAMAX tanker)

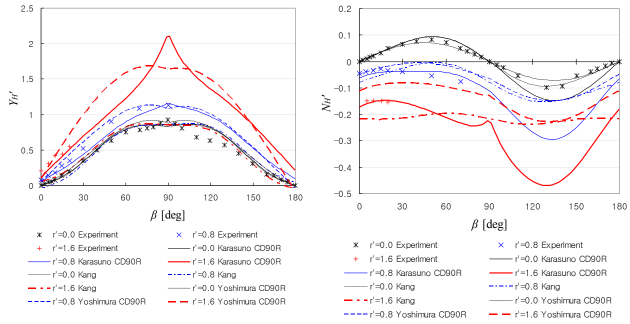

Fig. 6 Comparison results of sway force and yaw moment for yaw motion (Esso Osaka)

Karasuno CD90E: Karasuno's model where $CD90$ is predicted from experiment data at β = 90 deg.
Yoshimura CD90E: Yoshimura's model where $CD90$ is predicted from experiment data at β = 90 deg.

These comparison results are useful to check the availability of various models proposed and detail consideration will be done in the continuous study.

4 Conclusions

In this paper, ship hull hydrodynamic forces and moment in low speed are discussed reviewing previous researches and compared them with some existing experiment data.

Main conclusions will be summerised as follows.

(1) Karasuno, Yoshimura and Kang's models are compared and validated for other experiment data to some extent.

(2) In sway force due to sway motion cross flow drag coefficient at β = 90 deg. is most important parameter to express the total force. Precise estimation or using experiment data is recommended.

(3) In yaw moment due to sway motion the matching of each model is acceptable, but asymmetric behaviour of experiment is well expressed by Karasuno's model.

(4) In surge force due to sway motion and in sway force and yaw moment due to yaw motion behaviour of each model is somewhat different within models and due to lack of experiment data further investigation is necessary.

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Nomenclature

Any symbols and coordinate system not explained in this paper are based on conventions generally used in ship manoeuvrability.

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