A Numerical Study on Maneuverability under Steady Equilibrium Condition in Waves for Free-running Model Ship

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Abstract: Authors developed a method; rudder effectiveness and speed correction (RSC), which makes both speed response in waves and rudder response of free-running model ships similar to those of full scale ships by using an auxiliary thruster.

In this paper, the speed and the maneuvering responses of free-running model ships applied RSC in waves on steady straight-running equilibrium condition and those of full scale ships are compared by numerical simulations. As the result, authors revealed that the speed decrease in waves as well as the maneuvering response of free-running model ships applied RSC are able to be precisely similar to those of actual full scale ships. In addition, they also revealed the applicability of RSC in extreme severe seas and showed possibility to evaluate speed decrease and maneuverability for full scale ships in these seas experimentally.

Key words: Speed response and rudder effectiveness similarity, Scale effect, Speed decrease in waves, Maneuverability in adverse conditions, Maneuverability Auxiliary thruster.

1. Introduction

Because of the introduction of EEDI regulations for new built ships, it is said that ships which have a small engine compared with their size are built to pass regulations easily. Therefore, determining minimum propulsion power to maintain the maneuverability in severe seas is encouraged. In order to determine them, evaluation of speed decrease in severe heading waves for full scale ship is necessary as International Maritime Organization (IMO) proposes [1]. Those evaluation depends on only numerical calculations, since speed response in waves on free-running model experiments can’t be similar to that of full scale ships because of the large difference of Reynolds number between model ships and full scale ships.

Although methods to estimate the speed decrease in waves for full scale ships near designated speed are in adequate level thanks to many successful researches regarding added resistance in waves, for example Tsujimoto et al. [2], it is required to estimate added resistance at not designated speed but low ship speed in order to evaluate speed decrease in severe heading waves by numerical calculations. In addition, wave drift sway forces and yaw moments are also needed to be formulated for the evaluation of maneuverability not only in heading seas but also in the other wave direction like oblique heading waves. However, methods to estimate them have not been developed enough yet because of the difficulty in model experiments to measure them [3]. Moreover, large different phenomena between in clam water and in severe seas, for example change of wake coefficient in waves, should be revealed enough for reliable sophisticated numerical tools. For these reasons, it is obvious that alternative more accurate methods to evaluate maneuverability in adverse conditions are necessary instead of numerical simulations.

Authors have proposed RSC [4][5] which is the method to make both speed response and rudder response of free-running model ships in clam seas and waves similar to those of full scale ships by using a

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duct fun type auxiliary thruster which can generate time varying longitudinal force for free-running model tests [6]. They have showed by numerical simulation that RSC can estimate maneuvering response of full scale ships by free-running maneuvering model tests.

In this report, the speed and the maneuvering responses of free-running model ships applied RSC in waves on steady straight-running equilibrium condition and those of full scale ships are estimated by numerical simulations for the aim of evaluating maneuverability in adverse conditions experimentally. As the results, authors disclosed that RSC can evaluate the speed decrease and the maneuvering responses in waves for full scale ships on straight-running conditions by free-running model tests and it can be applied in extreme rough seas in which ship speed decrease largely and drift angle and rudder angle become quite large. Since not only wave drift forces and moments but also all of actual phenomena in rough seas which are difficult to consider are reflected in the model experiment, these results imply they are not needed to be formulated thanks to RSC.

2. Methods of the Numerical Simulation

2.1 Algorithm and governing equations

Equations of surge and sway, yaw motions on steady straight-running equilibrium condition (1) according to the concept of MMG [7] are solved for ship speed V and drift angle β, rudder angle δ by Newton's method. Coordinate system in the simulation is body fixed axis system showed in Fig.1.

$$\begin{aligned} X &= X_0 + X_P + X_D + X_R + X_W + X_A + T_A = 0 \\ Y &= Y_D + Y_R + Y_W + Y_A = 0 \\ N &= N_D + N_R + N_W + N_A = 0 \end{aligned} \tag{1}$$

where, an item of subscript *0* means resistance in clam seas and an item of subscript *P* is thrust by propeller, items of subscript *D* and *R, W, A* are maneuvering forces and moment and those by rudder, and waves (wave drift forces and moments), wind respectively. T_A is longitudinal force by auxiliary thruster.

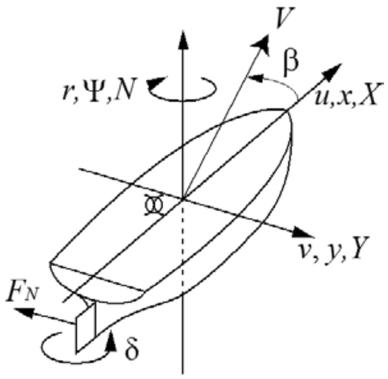


Fig. 1 – Coordinate system in the simulations

2.2 formulations of each items in governing equations

Resistance in clam water X_0 is calculated by (2).

$$X_0 = -\frac{\rho}{2} S_w u^2 \{C_W(Fn) + (1+k)C_{F0}(Rn) + \Delta C_F\} \tag{2}$$

where, ρ is density of fluid, S_W is wetted surface area, u is longitudinal ship speed, C_W is wave resistance coefficient, $1+k$ is form factor, C_{F0} is frictional resistance coefficient of a corresponding plate, ΔC_F is roughness allowance coefficient and zero in model scale. C_{F0} is calculated by ITTC procedures [8].

Thrust by propeller is calculated by (3).

$$X_P = (1-t)\rho K_T D_p{}^4 N_p{}^2 \tag{3}$$

where, t is thrust deduction fraction and constant value at self propulsion point, D_P is diameter of a propeller, N_P is propeller race of revolution, K_T is thrust coefficient and can be described by (4).

$$\begin{aligned} K_T &= a_0 + a_1 J + a_2 J^2 \\ J &= u(1-w)/nD_P \end{aligned} \tag{4}$$

where, 1-w is wake coefficient and this is a function of drift angle, J is propeller advance ratio.

Maneuvering forces and moments are calculated by Kang's method [9] which is applicable in large drift angle (-90deg$\leqq\beta\leqq$90deg). Derivatives for Kang's Method are estimated by Kang's regression model for a blunt-body ship [9].

Forces and moments by rudder are described as (5).

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

where, x_R is the location of a rudder (=-L/2), a_H and x_H are interactive force coefficients among hull, propeller and rudder, t_R is coefficient of additional drag force. These coefficients were assumed constant. F_N is rudder normal force and can be described as the following (6).

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

where, A_R is rudder area, f_α is the gradient of the lift coefficient of rudder, U_R and α_R represent rudder inflow velocity and angle respectively.

Longitudinal wave drift force X_W is estimated by Tsujimoto's proposal [2]. Y_W and N_W at any ship speed are estimated by interpolating the database whose wave drift forces and moments at zero ship speed are calculated by three-dimensional panel method [10], and they are interpolated by using ship type and principals. Y_W and N_W in all ship speed are assumed not to change from values at zero ship speed.

Wind forces and moments are calculated Fujiwara's method [11] and coefficients for the method are estimated by statistical equations (Ueno et al. [12]).

Auxiliary thruster force for models is described by (7) [13] and it is zero in case of full scale ships.

$$T_A = f_{TA} T_{SFC} = f_{TA} (X_{0m} - X_{0S}|_{us'=um'}) \tag{7}$$

where, T_{SFC} is the force required for skin friction correction (SFC), f_{TA} is defined auxiliary thruster coefficient and it depends on the way to use the auxiliary thruster, for example f_{TA}=1 in SFC. f_{TA} in the simulations are showed in section 3.2.

3. A Ship and Conditions in the Simulation

3.1 A ship for simulations

Principal dimensions of tanker for simulations, KVLCC1 [14], whose model length and scale ratio are 2.909m and 1/110.0 respectively are listed in Table 1. *1+k* and C_W for models are from model tests by Kim et al. [15]. *1-w* and *1-t*, K_T of a model, coefficients for forces and moments by rudder are from Yoshimura et al. [16]. Scale effects for full scale ships are considered in *1-w* and K_T, ΔC_F and they are estimated in accordance with the ITTC procedures [8]. The other coefficients are assumed to have no scale effects.

A full scale ship condition and four model conditions of KVLCC1: model point and ship point applied SFC, rudder effectiveness correction (REC) [13], RSC, were simulated.

Table 1 Principal dimensions of tanker, KVLCC1

item	Full scale	Model
Scale ratio	1	1/110.0
Length b.p.s. L [m]	320.0	2.909
Breadth [m]	58.0	0.527
Draft, d [m]	20.8	0.189
Wetted surface area [m^2]	27320	2.258
Propeller diameter, D_P [m]	9.86	0.090
Propeller pitch ratio	0.721	0.721
The number of a propeller blade	4	4
Rudder type	Horn rudder	
Movable rudder area[m^2]	112.26	0.00928
Rudder height[m]	15.8	0.144

3.2 conditions of propellers and auxiliary thrusters

The full scale ship was considered maneuvering with constant propeller rate of revolution corresponding to the designated ship Froude number, 0.142. Therefore, those for models at model point and ship point, REC are also given as constant values corresponding to the designated ship Froude number and they are listed in Table2. That for RSC is given as a function of Froude number in waves by following RSC definitions [4][5] to make speed and maneuvering response of models similar to those of full scale ships and showed in Fig.2, though the revolution for full scale ships is considered to be constant.

Auxiliary thruster coefficient f_{TA} of RSC is also given as a function of Froude number in waves and showed in Fig.2. This value also determined by following the definitions of RSC [4][5]. On the other hands, f_{TA} in the other cases are constant value listed in Table2. Although *1-w* was assumed a function of drift angle in the numerical simulation, f_{TA} and propeller rate of revolution for RSC were calculated by assuming that *1-w* was constant at self propulsion point for the simplification.

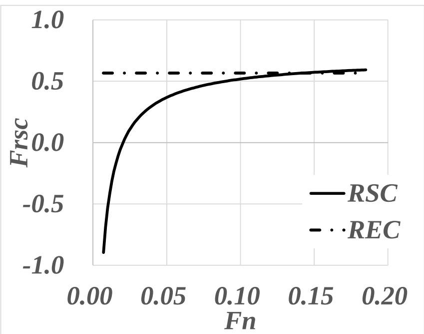
Table 2 Propeller rates of revolution and Auxiliary thruster coefficients f_{TA} in the simulation

	Scale	N_P[RPM]	f_{TA}
Full scale ship	Full	75.7	-
Model at model point	Model	1049.6	0.0
Model at ship point	Model	747.9	1.0
Model, REC [11]	Model	893.7	0.566
Model, RSC	Model	Function of Froude number (Fig. 2)	Function of Froude number (Fig. 2)

3.3 Wave and wind conditions

Waves in simulations were considered regular waves and short-crested irregular waves without swells. Ratio of wave height H_W to ship length L in regular waves is 1/72 and wave direction is 30 deg (oblique heading waves). Significant wave heights and mean wave periods in short-crested irregular waves correspond to the values of Beaufort scale of wind in state 8 ($H_{1/3}$=5.5m, T_W=9.1sec for full scale) and 11 ($H_{1/3}$=11.5m, T_W=13.1sec for full scale). Their frequency spectrums are ISSC spectrums and directional distributions are $\cos^2$.

Wind is not considered in regular waves and that in short-crested irregular waves is assumed uniform. The wind speed correspond with BF8 (U_A=19.0m/s) and BF11 (U_A=30.6m/s) respectively. Wind direction was assumed to correspond with principal wave direction.



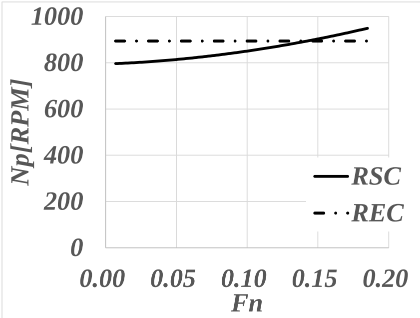


Fig. 2 – Propeller rate of revolution and Auxiliary thruster coefficient f_{TA} for RSC

4. Simulation Results

4.1 Results in regular waves

The simulation results; speed ratio V/V_0, drift angle β, rudder angle δ, on steady straight-running equilibrium condition in regular waves are showed in Fig.3-5. Simulation results at model point indicate that speed response in waves and maneuvering response of free-running models without corrections cannot be similar to those of full scale ships. It is caused that self propulsion points are different between models and full scale ships because of the large difference of Reynolds number between them.

According to the model, ship point (SFC) in Fig.4, although V/V_0 of SFC become closer to those of full scale ships than those of no correction, there is still difference. It is caused that propulsive thrust of model applied SFC cannot be similar to that of full scale ships when ship speed decrease in waves because of the difference of *1-w*. Rudder angle at ship point in Fig.5 indicates that it becomes larger than that of full scale ships.

Because forces of REC generated by auxiliary thruster are smaller than that of SFC, difference of speed response in waves between REC and full scale ships become larger than those between SFC and full scale ships as showed in Fig.4. Since rudder effectiveness by REC on straight-running condition in clam water is made similar to that of full scale ships, rudder response applied REC in waves is closer to that of full scale ships than that of model point and ship point. However, difference is still exist since speed response in waves is different between REC and full scale ships.

On the other hand, results applied RSC in Fig.3-5 indicate that both speed and maneuvering response in waves become similar to those of a full scale ship precisely regardless *λ/L*.

4.2 Results in short-crested irregular waves and winds

The simulation results in short-crested irregular waves BF8 with wind are showed in Fig.6-8. According to these figures, tendencies same as the results in regular waves were also obtained in irregular waves and RSC can satisfy both speed and maneuvering response similarity to those of full scale ships. These results indicate that RSC is applicable not only regular waves but also irregular waves with wind regardless the wave and wind direction.

The simulation results in short-crested irregular waves with wind BF11 are showed in Fig.9-11. In these environmental conditions, ship speed decrease up to about 20% of designated ship speed and absolute values of drift angle and rudder angle increase to about 40deg and 30deg respectively. Fig.9-11 indicate that RSC is applicable even in these extreme adverse condition. It is implied that RSC has the possibility to be able to estimate maneuverability or required minimum propulsive power for full scale ships in adverse condition experimentally.

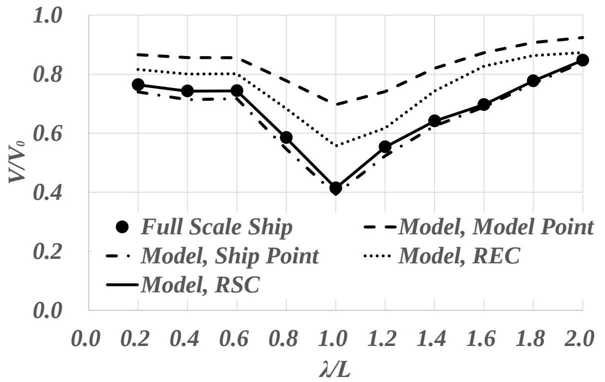


Fig. 3 – Speed ratio in regular waves (Oblique heading wave 30deg, H_W/L=1/72)

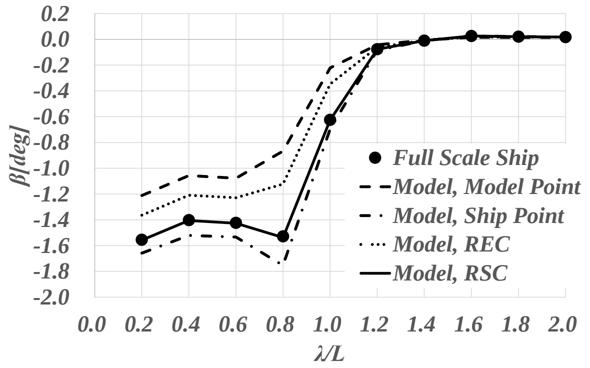


Fig. 4 – Drift angle in regular waves (Oblique heading wave 30deg, H_W/L=1/72)

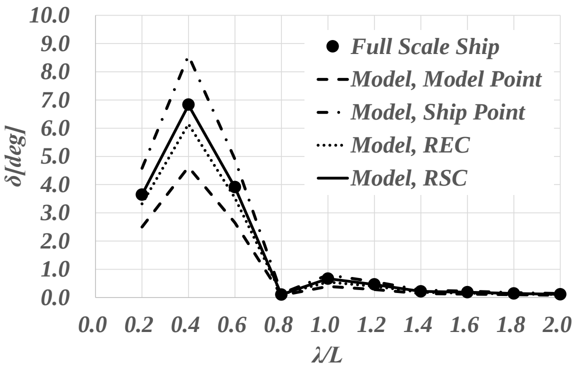


Fig. 5 – Rudder angle in regular waves (Oblique heading wave 30deg, H_W/L=1/72)

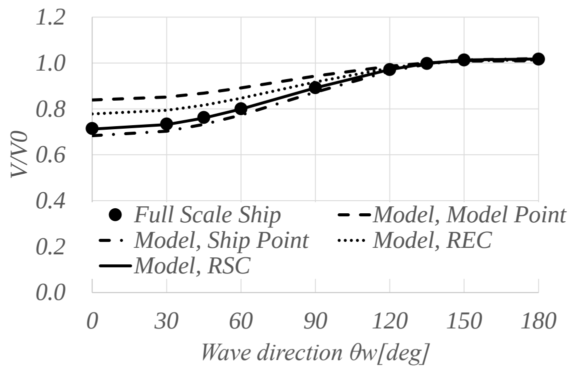


Fig. 6 – Speed ratio in irregular waves (BF8)

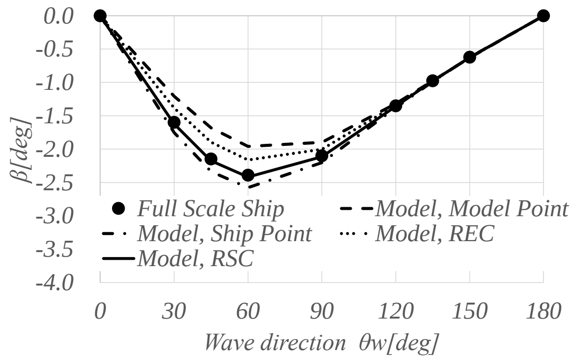


Fig. 7 – Drift angle in irregular waves (BF8)

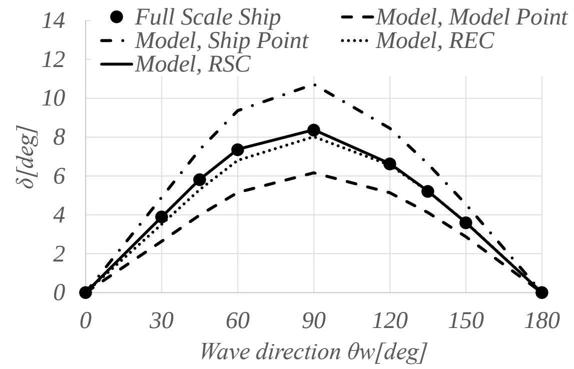


Fig. 8 – Rudder angle in irregular waves (BF8)

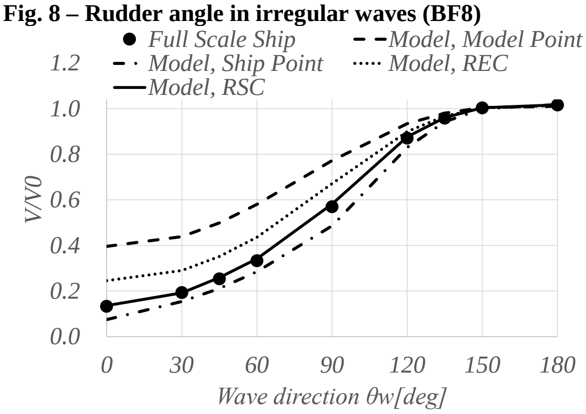


Fig. 9 – Speed ratio in irregular waves (BF11)

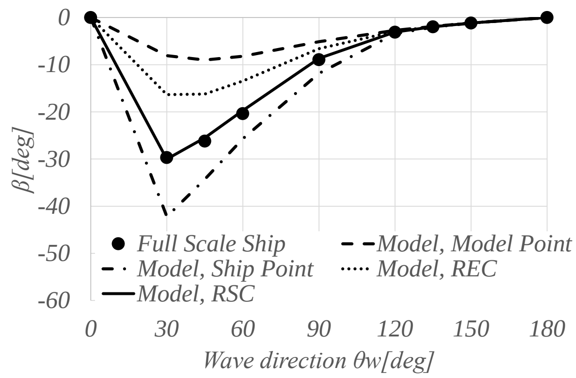


Fig. 10 – Drift angle in irregular waves (BF11)

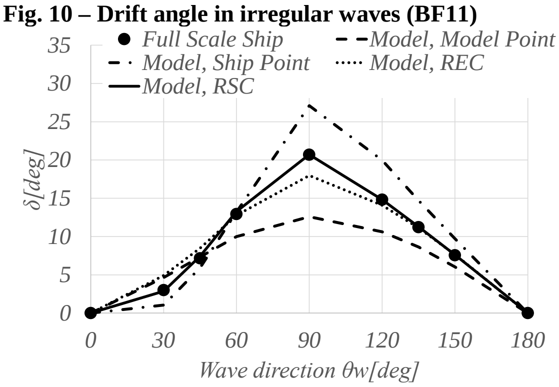


Fig. 11 – Rudder angle in irregular waves (BF11)

5. Conclusions

Authors have simulated speed and maneuvering response in waves for free-running model ships applied RSC and full scale ships on steady straight-running equilibrium condition. They have disclosed numerically that RSC is an experimental method which is able to make ship speed and drift angle, rudder angle on those condition similar to those of full scale ships regardless wave direction and whether regular or irregular waves, and the other kind of auxiliary thruster usage in free-running model test, for example SFC and REC, can't realize them.

In addition, Authors have conducted simulations in extreme adverse seas. As the result, they have also suggested that RSC is applicable in these conditions. Therefore, RSC may be able to estimate maneuverability for full scale ships in adverse conditions.

Important points of these conclusions are that speed decrease in waves or maneuverability and required minimum propulsive power in adverse conditions for full scale ships may be able to be measured directly by free-running model tests instead of estimation by numerical simulation. This implies that they can be evaluated without overcoming the difficulties in order to formulate wave drift forces and moments and all of difference between in clam water and in rough seas, changes of self propulsion factors etc., since all of those phenomena which are reflected in actual ships and seas are also included in free-running model tests.

Acknowledgments

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