Sixth International Symposium on Marine Propulsors
smp'19, Rome, Italy, May 2019

Scale Effect of Gate Rudder

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ABSTRACT

This paper introduces a new power prediction method for an innovative propulsion system which may not be categorized as a conventional energy saving device and it has not been even fully explored so far. Yet this system, which is called "GATE RUDDER", has been already applied for the first time on a 2400 GT container ship and full-scale sea trials were conducted successfully in November 2017 in Japan. The recent full-scale trials with this domestic container vessel have confirmed the superior performance of the gate rudder system (Sasaki 2018). However, the big discrepancy between the model test and the sea speed trial results was found when those are compared with the data of her sister ship equipped with a conventional flap rudder. After 12 month from her delivery, the voyage data revealed the fact that the difference observed in the speed trial was not negligible and surprisingly much larger difference was found based on the voyage data (Fukazawa 2018).

This paper investigates the scale effect of the Gate Rudder system and concludes that the main reason of the discrepancy between the model test and full scale data can be related the scale effect associated with the drag and lift characteristics at low Reynolds numbers for both rudder blades.

Keywords

Gate Rudder, Energy Saving Device, Ducted Propeller, Scale Effect.

Fig.1 Flap rudder (left) and Gate Rudder (right)

1 INTRODUCTION

The power prediction of ships based on model tests is one of the main tasks for a towing tank. Within this context, the conduct of tank tests and their analysis procedures have been historically developed by taking into account not only theoretical approaches but also empirical model ship correlation factors in order to achieve the accurate full scale power predictions at sea trial, In fact the introduction of the turbulence stimulators is the most well-known practice artificially to trip the flow to be turbulent on the model ship surface. However it is also well-known fact that the laminar flow can be found for appendages in the stern region even within the thick boundary layers which can be stimulated by the above mentioned procedure using turbulence stimulator. It is also true that the turbulence stimulator is not applied to the models of the conventional rudders because they operate in the propeller slip stream with accelerated flow which can suppress the presence of a laminar flow and its separation. In this paper, a new powering procedure for a ship with the gate rudder system is presented by introducing two corrections for the model test data related to the rudder drag and rudder lift. By applying these two corrections to the existing model test data of the ship with the gate rudder, the discrepancy between the model test and the sea trial result can be minimized as studied and discussed in the remaining parts of the paper.

Table 1 Principal dimensions of Shigenobu & Sakura

	Sakura	**Shigenobu**
Loa (m)	111.4	111.4
B (m)	17.8	17.8
d (m)	5.24	5.24
Main Engine	3309kW x 220rpm	3309kW x 220rpm
Rudder	Flap Rudder	Gate Rudder
Delivery	August 2016	December 2017

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2. SCALE EFFECT

2.1 Effect of Rudder Position

As shown in Fig.1, Gate Rudder is located each side of a propeller with large clearances. Therefore the flow field surrounding the Gate Rudder is quite different from that of a conventional rudder case. The features of the flow field of the Gate Rudder can be summarized as follows;

(1) The flow field surrounding Gate Rudder is rather uniform without strong disturbance from the propeller slip stream

(2) The average flow speed at the rudder blades is close to the ship speed while the flow has a component in the transverse direction toward to the ship center plane

(3) The propeller accelerates the flow in the vicinity of the rudder blades and the top position of the propeller where the high wake zone is observed in the case of a conventional rudder.

(4) Larger transverse flow and hence lift on the rudder blades can be generated by the propeller contraction which will increase the gate rudder thrust

The difference of flow fields between the model and full scale depends on the model size. If the model length (L_M) is not large enough ($L_M < 12$m), the flow around the Gate Rudder has a possibility of being laminar or developing laminar separation because of its location and that of the large thickness to chord ratio for the rudder.

The scale effect of the rudder drag should be considered not only for the Gate Rudder but also for the conventional rudder. However we will know its difference clearly if we compared those flow characteristics based on the real case. (Sasaki et.al. 2017)

2.2 Drag Coefficients for Model and Full Scale

The resistance of the rudder F_{RX} and the side force of the rudder F_{RY} can be represented by equation (1) and (2).

$$F_{RX} = F_{RD}\cos(\alpha) - F_{RL}\sin(\alpha) \quad (1)$$

$$F_{RY} = F_{RD}\sin(\alpha) + F_{RL}\cos(\alpha) \quad (2)$$

where, F_{RD} and F_{RL} is contribution from the rudder drag and rudder lift, respectively and α is flow angle to the wing section. F_{RL} is negligibly small for the conventional rudder case except the condition behind a turning propeller F_{RD} can be predicted by the empirical formula when the flow velocity and rudder geometry is given.

$$F_{RD} = \frac{1}{2}\rho\int_0^H V_o(z)^2 C_F(z) * \left(1 + \frac{t(z)}{c(z)} + (\frac{t(z)}{c(z)})^2\right) \quad (3)$$

where V_0 and C_F is the local flow velocity and frictional resistance coefficient respectively corresponding to flow direction and flow characteristics (laminar or turbulent etc.) at z position. t/c is thickness-chord ratio at the same position.

Here, the drag coefficient of a rudder can be represented by equation (4) using ship speed V_S and rudder area S_R.

$$C_{RD} = \frac{F_{RD}}{\frac{1}{2}\rho V_S{}^2 S_R} \quad (4)$$

It should be also noted that each of the resistance components obeys a different set of scaling laws and the problem of scaling is made more complex because of interaction between these components.

We will explore the scale effect of the rudder drag by using data belongs to the first Gate Rudder system driven ship Shigenobu (Figure 2 on the right) as discussed in the following.

Fig. 2, Table 2 and Table 3 show the calculated rudder drag based on equation (3). for the Gate Rudder and conventional rudder in comparison. The values in this figure and tables are non-dimensionalised by the measured ship resistance.

In order to avoid confusion, we should remind that the resultant rudder drag is different from these figures for the Gate Rudder because of the lift force acting on the rudder surfaces.

It is quite often to see the thrust (negative resistance) of Gate Rudder even in the towing condition.

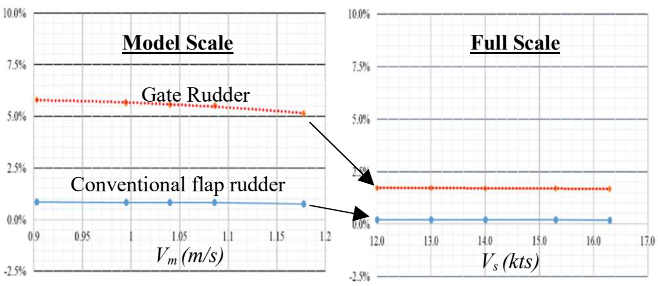

Fig.2 Rudder drag pct. to ship resistance for model and full scale

Table 2 Rudder Drag Calculations (model scale)

	Flap Rudder	Gate Rudder
S_R	100%	157%
V_X(model)	0.40	0.98
C_F(model)	0.00944	0.00700
C_{RD}(model)	0.0095	0.0405
% of Ship Resistance	0.8	5.3

Table 3 Rudder Drag Calculations (full scale)

	Flap Rudder	Gate Rudder
S_R	100%	157%
V_X(ship)	0.40	1.00
C_F(ship)	0.00281	0.0026
C_{RD}(ship)	0.0080	0.0068
% of Ship Resistance	0.2	1.7

As shown in Figure 3 and Table 2 & 3 it is very clear that the drag components of the two rudder cases are very contrasting as such. The model scale rudder drag of the Gate Rudder is 6-8 times higher than that of the conventional rudder and both rudder drag components will be decreased in full scale by 1/3 to 1/4.

Therefore, the scale effect of the Gate Rudder is relatively large compared with that of the conventional rudder and the difference between the model scale and full scale in the drag component of the Gate Rudder is 3.6% (5.3%-1.7%) of ship resistance while it is only 0.6% (0.8%-0.2%) for the conventional rudder case. It is marvelous that the difference is 6 times thanks to the flow speed difference around the rudder blades at each towing conditions.

2.3 Rudder Drag Correction

As mentioned section 2.2, the rudder drag explained in the previous section cannot be measured directly during the resistance test of the hull with the Gate Rudder. This is because the blades of the Gate Rudder are producing the lift force and hence compensating the rudder drag while a conventional rudder is simply a drag source contributing to the ship resistance. However, if we measured two rudder force components such as F_{RX} and F_{RY} according to the ship fixed coordinate, we can configure these drag and lift components using several assumptions according to the wing theory.

$$C_L = \kappa(\alpha + \alpha_g) \quad (5)$$

where, C_L is lift coefficient. α and α_g are attack angle and zero lift angle respectively.

The rudder drag coefficient C_{RD} and αcan be estimated by the following manner;

$$C_{RD} = \frac{F_Y' - C_L(1-(\alpha+\alpha_g)^2)^{0.5})}{\alpha+\alpha_g} \quad (6)$$

$$\alpha = \frac{(\kappa + F_X') - \sqrt{(\kappa + F_X')^2 + 2F_Y'^2}}{-F_Y'} - \alpha_g \quad (7)$$

F_X' and F_Y' is non-dimensional rudder force of F_{RX} and $F_{RY,}$ respectively and given by equations (8) and (9).

$$F_X' = \frac{F_{RX}}{\frac{1}{2}\rho V_S{}^2 S_R} \quad (8)$$

$$F_Y' = \frac{F_{RY}}{\frac{1}{2}\rho V_S{}^2 S_R} \quad (9)$$

We can observe positive flow angle α for every kind of vessel when the rudder blades are off centered.

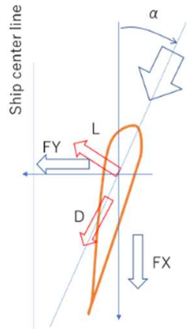

Fig.3 Rudder forces originated from lift and drag

By assuming the lift slope correction factor κ can be expressed by the following equation,

$$\kappa = \varepsilon \frac{6.13\lambda}{2.25+\lambda} \quad (10)$$

where λ is the aspect of ratio, ε is effect of low Reynolds number on lift slope which will be explained in section 2.4.

C_L and C_D can be obtained from the measured F_X and F_Y during the resistance test directly.

If we can express the rudder drag coefficient using Eq (11) by combining with the drag coefficient C_{RD0} explained in the previous section,

$$C_{RD} = C_{RD0} + \delta C_{RD} \quad (11)$$

where δC_{RD} may represent the additional resistance due to the rudder stock. For the sake of being conservative, we can use this additional resistance component without correction (no scale effect) such as wave resistance.

$$\delta F_{RX} = \frac{1}{2}\rho V_S{}^2 \delta C_{RD0} S_R cos\alpha \quad (12)$$

$$\delta C_{RD0} = C_{RD0S} - C_{RD0M} \quad (13)$$

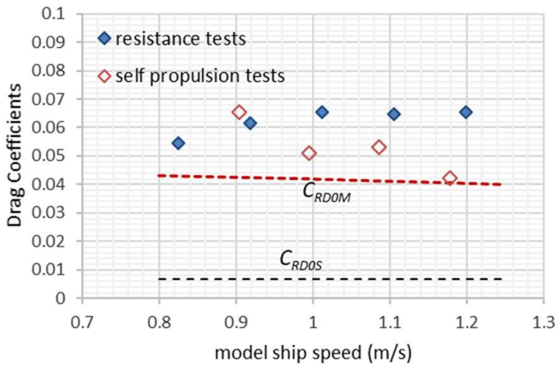

Fig.4 Obtained rudder drag coefficients

Fig. 4 shows the difference of obtained C_{RD} and calculated C_{RD0} (model). δC_{RD0} is less than 1% of the total hull resistance and the effect of this additional uncertain resistance on the full scale performance may not so serious from this figure.

2.4 Rudder Lift Correction

The lift coefficient of the Gate Rudder is also influenced by the model scale and the correction for it should be applied to the model test results. According to the wind tunnel test with a NACA0012 section for low Reynolds numbers, the nonlinear lift slope of Fig.5 is shown in the book written by McCormick (1995).

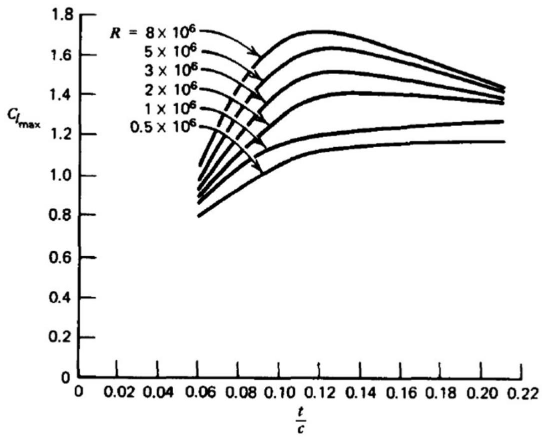

Fig.5 Effect of low Reynolds number on lift coefficients of typical wing section [3] (NACA24xx Series)

From the Fig.5, lift coefficient of the full scale rudder (C_{LS}) can be estimated by following equations;

$$\varepsilon = \frac{1.470X_M{}^3 - 3.109X_M{}^2 + 2.376X_M + 1.036}{1.470X_S{}^3 - 3.10 \quad {}_S{}^2 + 2.376X_S + 1.036} \quad (14)$$

if $R_{NS} > 8*10^6$ $XS=8*10^6$

where

$X_M = R_{NM} * 10^{-7}$

$X_S = R_{NS} * 10^{-7}$

In order to view the whole forces appeared in the previous sections, Fig.7 is prepared. It is obvious that the above mentioned two corrections are so important to evaluate the actual performance of Gate Rudder.

The effect of the ruder drag and lift correction on the Gate Rudder performance is significantly large and hence the discrepancy between the model test and full scale results can be explained by this phenomena. In the Shigenobu case, two rudder blades seem generating thrust almost more than 10%.

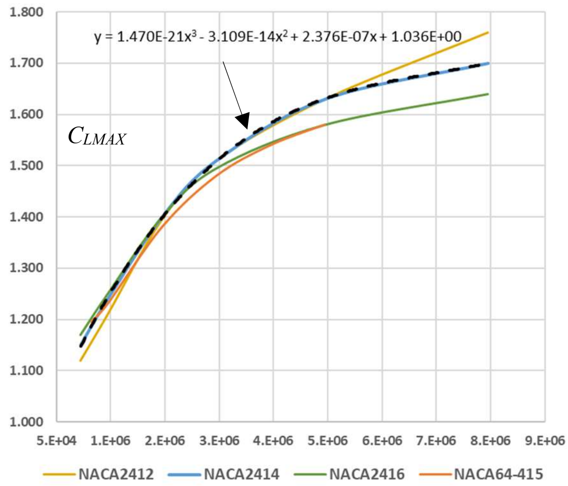

Fig.6 Reynolds effect on lift coefficients of typical NACA wing sections

3. POWERING PROCEDURE OF A SHIP

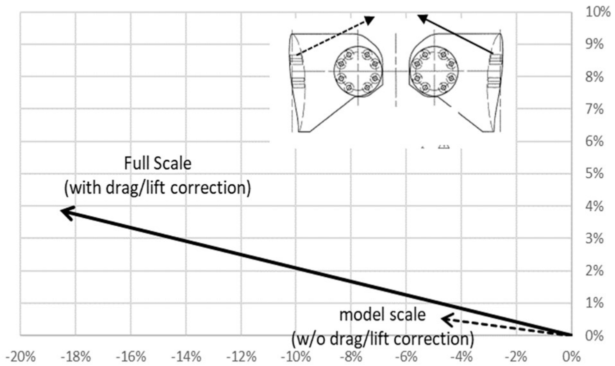

Fig.7 Effect of rudder drag/lift correction on rudder resultant force (model point case) to ship resistance

WITH A GATE RUDDER PROPULSION SYSTEM

Rudder drag correction and rudder lift correction can be applied to the results of both resistance and self-propulsion test. The difference of the procedure from the (original one) will be explained in the following sections.

3.1 Effective Horse Power

The effective horse power can be calculated based on a corrected total model resistance taking the corrected rudder drag and rudder lift coefficients into account.

$$EHP = R_{TS} * V_S \quad (15)$$

$$R_{TS} = C_{TS} 0.5 \rho V_S{}^2 S \quad (16)$$

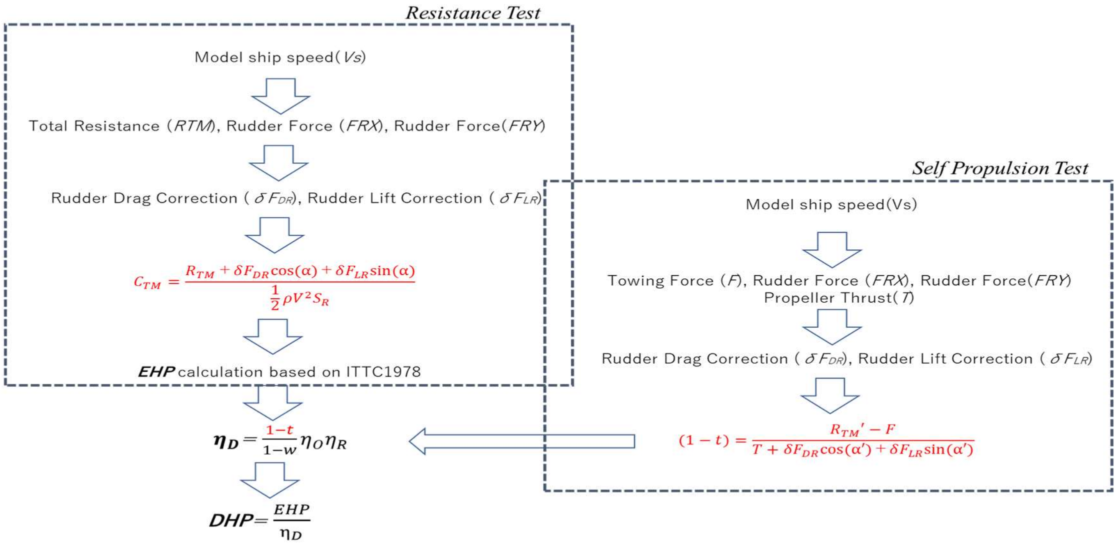

Fig.8 Modification of powering procedure for a ship with Gate Rudder Propulsion System

where, C_{TS} is the total resistance coefficient of the ship and estimated by the obtained total model ship resistance coefficient according to the standard procedure such as a recommended ITTC standard procedure.

The total model resistance coefficient can be represented as

$$C_{TM} = \frac{R_{TM} + \delta F_{RD}\cos\alpha + \delta F_{RL} sin\alpha}{0.5\rho V^{2} S_R} \quad (17)$$

Fig.8 shows the flow chart of the proposed new powering procedure for a ship with the Gate Rudder system by taking into account the scale effect on the drag and lift characteristics of the Gate Rudder.

3.2 Thrust Deduction Factor

We can apply thrust deduction factor correction to the self-propulsion test results by introducing the drag and lift correction explained in Sections 2.3 and 2.4 as follows:

$$1 - t = \frac{R_{TM} - F}{T + \delta F_{RD}\cos\alpha + \delta F_{RL} sin\alpha} \quad (18)$$

3.4 Effective Wake

The effective wake of the gate rudder propulsion system is the most difficult item to analyze because the propeller advance speed is accelerated by the gate rudder blades and this is not the component of the effective wake.

The effective wake is originated from the boundary deformation due to a propeller suction force and the magnitude of the deformation is proportional to the propeller thrust. Therefore actual effective wake of the gate rudder propulsion system is less than that of a conventional rudder system because the propeller thrust is smaller than the original configuration.

The non dimensional mean flow speed v_P at the propeller plane of the gate rudder propulsion system can be represented as follows;

$$v_P = C_1 v_{A0} + v_{inP} + v_{inR} \quad (19)$$

where, $\boldsymbol{v_{A0}}, \boldsymbol{v_{inP}}$ and, $\boldsymbol{v_{inR}}$ are **the** propeller advance speed of the conventional rudder case, propeller self-induced velocity and rudder induced velocity respectively.

C_1 is a correction factor of the wake variation for difference of the propeller diameter and the position. $C_1 < 1.0$ can be assumed because of the smaller propeller thrust and smaller propeller diameter of the gate rudder propeller.

Eq(19) can be represented by wake fraction as below;

$$w_{GR} = C_1 * (w_0 - 0.04) + w_{inR}$$

where, w_{inR} is rudder induced wake and the mean value can be estimated by following formula;

$$\boldsymbol{w_{inR}} = \boldsymbol{C_2} * \boldsymbol{C_T} + \boldsymbol{w_{0R}}$$

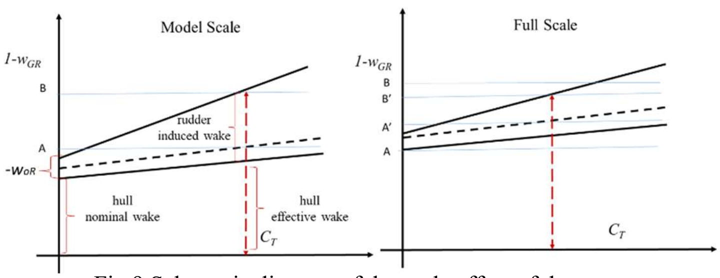

Fig.9 Schematic diagram of the scale effect of the wake of a gate rudder propulsion system

In Fig.9, dotted line and solid line show the scale effect of a conventional rudder case and a gate rudder propulsion system respectively. The point A' can be predicted from the point A according to the ITTC recommended procedure, while the point B' is not ruled by the same principal and B' can be smaller than the point B sometimes as shown in Fig.9.

Fig.10 shows the obtained effective wake from speed trial results based on torque identity method.

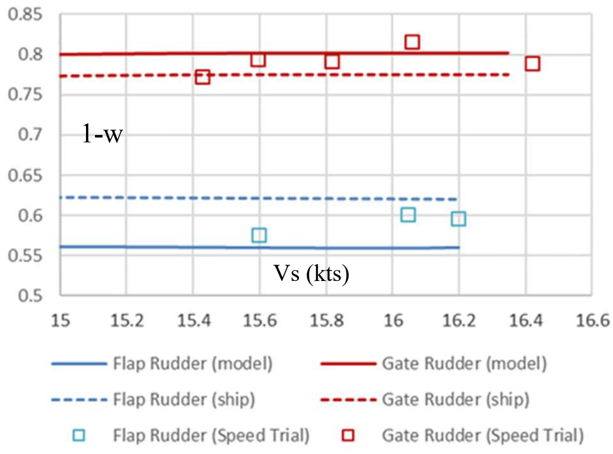

Fig.10 Effect of drag/lift correction on predicted and measured (speed trials) effective wake

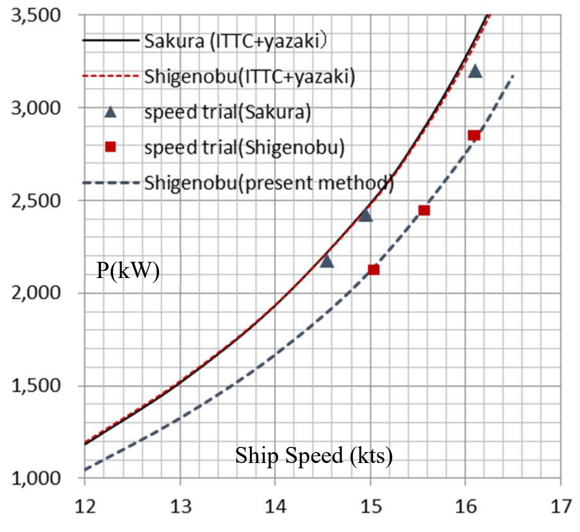

Fig.11 Effect of drag/lift correction on predicted power curves and speed trial results

Finally, Figure 11 shows the comparison of the trial power data for the two sister ships, one of which is fitted with the Gate Rudder system (Shigenobu) while the other with the conventional rudder (Sakura). The predicted power for Shigenobu, which is based on the proposed method, is also plotted on the same figure. As shown in this figure the proposed method is in very good agreement with the measured data justifying the scale effect corrections applied on the Gate Rudder drag and lift characteristics

4. CONCLUSIONS

This paper presented a new and practical powering prediction method suitable for a ship fitted with a Gate Rudder system. The method is based on the classical scaling procedure from model tests to full-scale ship with specific corrections on the drag and lift of the Gate Rudder system. The proposed new procedure has been developed based on the trial performance analysis of the two sister ships which demonstrated a 14% difference in power for the benefits of the gate rudder while the model tests did not support this finding

The conclusions found from this development work can be summarized as follows:

(1) The scale effect of a Gate Rudder can be considerably larger than that of the conventional rudder because of the special arrangement of the Gate Rudder behind the stern.

(2) The flow characteristics around a model Gate Rudder can be laminar due to the low Reynolds Number in model scale and hence the drag and lift coefficients of the Gate Rudder may be strongly affected by the associated scale effect.

(3) By applying the proposed drag and lift correction, the discrepancy in the speed trials of the subject sister vessels can be explained clearly, as demonstrated in this paper.

(4) The scale effect of the wake of a ship with a gate rudder is not the same as that of a ship with a conventional rudder. The measured propeller advanced speed based on the thrust identity should be divided into two components and the different scaling methods should be applied to each components.

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