Fifth International Symposium on Marine Propulsion
SMP'17, Espoo, Finland, June 2017

Full Scale Performance Prediction Method for a Ship with ContraRotating Propellers

Yasuhiko Inukai[1], Jun Ando[2]

[1] Japan Marine United Inc.,Tokyo, Japan
[2] Kyushu University,Fukuoka, Japan

ABSTRACT

This paper presents a new performance prediction method for a ship with Contra-Rotating Propellers (CRP). The main features are to treat CRP as a combination of two single propellers and consider the mutual interaction between the aft and forward propeller adequately. To verify a validity of the method, self-propulsion factors of propeller working in a simplified flow are analyzed at first. Then, full scale delivered power is estimated for a VLCC with various methods and the difference is discussed. Finally, we compare estimated speed-power curves with those obtained by sea trial and confirm the present method estimates them accurately.

Keywords

Conta-Rotating Propellers, Performance Prediction Method, Self-Propulsion Analysis

1 INTRODUCTION

Contra-Rotating Propellers (CRP) is known as one of the highest efficient propulsion system. The number of merchant ships with CRP is growing over the past 10 years under the strong demand on greenhouse gas reduction and over 30 ships with CRP are operated today. There is no full scale performance prediction method for CRP recognized as the standard one. However full scale data have been accumulated little by little and we have more opportunities to compare the estimated delivered power P_D with sea trial results than before. To enhance the number of ships with CRP, an establishment of the accurate performance prediction method is essential. In this paper, the authors deal with how to analyze self-propulsion factors and estimate full scale delivered power of a ship with CRP.

Main difference between a conventional single propeller and CRP is the number of equipped propellers. CRP is composed of two propellers rotating around the same axis in opposite directions. Thus, CRP can be regarded as the following propulsion systems.

1. CRP as a single propulsion unit
2. CRP as a combination of two single propellers with CRP setup
3. CRP as a combination of two single propellers

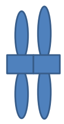
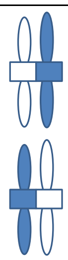
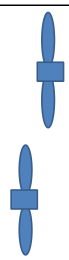
1.Single propulsion unit (CRP unit)	2.Combination of single propellers with CRP setup (SP with CRP unit)	3.Combination of two single propellers (SP)
		

Figure 1: Recognition ways of CRP

Figure 1 shows an illustration of the three different propulsion system.

Depending on which system is applied in the prediction method, propeller open water characteristics (POC) used in the procedure varies and estimation results on P_D also changes as a result. Oh et al (2014) carried out propeller open water and self-propulsion tests for a crude oil tanker and predicted full scale powering performance using the above three different kind of POCs. They showed that each method estimates different P_D with 2% discrepancy in maximum. Unlike a single propeller, propulsive coefficients (i.e. self-propulsion factors and propeller efficiency) of CRP include interference between two propellers, which influences on the powering prediction. Hence, how to consider the mutual interference is an important issue for a power prediction for ships with CRP. Especially an effective wake fraction w should be carefully treated because of having strong scale effect among self-propulsion factors. Sasaki et al (1996) proposed a method considering an influence by the rudder on the interference between two propellers. While Sasaki regarded CRP as a combination of two single propellers with CRP setup, Ishida et al (1998) proposed a method regarding CRP as a combination of two single propellers. To separate the interference component in the w, they derived a relationship between an induced velocity and a propeller loading factor of the other propeller by performing open water tests for CRP setup and each propeller separately.

In order to adequately comprehend working condition of each propeller, SP method can be thought to be preferable because it directly uses their individual POCs. Thus, we developed a new performance prediction method based on Ishida's method with modifying a treatment of the mutual interaction. The main modification is to separate an induced velocity from a forward propeller to an aft propeller into an axial and a tangential direction, by which we can consider the mutual interaction more reasonably.

First, we describe an outline of general self-propulsion analysis methods for a ship with CRP, followed by that of the present method. Then, we show comparisons of w and relative rotative efficiency η_R analyzed for a propeller working in a simplified flow and the differences between the methods are discussed. Next, full scale P_D is estimated for a VLCC with various methods and the differences are also discussed. Finally, we compare estimation on P_D for two ships with sea trial results and show the present method predicts them accurately.

2 SELF-PROPULSION ANALYSIS METHOD

2.1 Kind of Analysis Method

Self-propulsion analysis methods for a ship with CRP are classified by a kind of POC used in the analysis. The advance ratio J, the thrust coefficient K_T and the torque coefficient K_Q are defined as

$$J = \frac{V_A}{n_1 D_1}, K_T = \frac{T_1 + T_2}{\rho {n_1}^2 {D_1}^4}, K_Q = \frac{n_1 Q_1 + n_2 Q_2}{\rho {n_1}^3 {D_1}^5} \quad (1)$$

for CRP as a single propulsion unit (CRP unit method),

$$J_{ci} = \frac{V_A}{n_i D_i}, K_{TCi} = \frac{T_i}{\rho {n_i}^2 {D_i}^4}, K_{QCi} = \frac{Q_i}{\rho {n_i}^2 {D_i}^5} \quad (2)$$

for CRP as a combination of two single propellers with CRP setup (SP with CRP setup method) and

$$J_i = \frac{V_A}{n_i D_i}, K_{Ti} = \frac{T_i}{\rho {n_i}^2 {D_i}^4}, K_{Qi} = \frac{Q_i}{\rho {n_i}^2 {D_i}^5} \quad (3)$$

for CRP as a combination of two single propellers (SP method).

Where V_A = advance speed, T = thrust, Q = Torque, D = Diameter and n = rotation speed. Subscript i = *1* for forward propeller and *2* for aft propeller. It should be noted that the SP with CRP setup method uses the thrust and torque of each propeller working with CRP setup and SP method uses those of propellers working individually. The self-propulsion factors are analyzed by thrust identity method for all methods according to the ITTC procedure (ITTC 1978). Thrust deduction fraction t, w and η_R are defined as follows:

$$t = \frac{T_1 + T_2 + F_D - R_M}{T_1 + T_2} \quad (4)$$

$$w_i = 1 - \frac{n_i D_i J_i}{V} \; or \; w_i = 1 - \frac{n_i D_i J_{ci}}{V} \quad (5)$$

$$\eta_{Ri} = \frac{\rho {n_i}^2 {D_i}^5 K_{Qi}}{Q_i} \; or \; \eta_{Ri} = \frac{\rho {n_i}^2 {D_i}^5 K_{Qci}}{Q_i} \quad (6)$$

Where F_D = skin friction correction force, R_M = resistance of the hull and V= ship speed. Subscript i = *1* for forward propeller, *2* for aft propeller and no subscript for CRP unit.

Sasaki et al and Ishida et al considered an influence on w due to the interference between two propellers as described below.

2.2.1 Sasaki's method

In w analyzed using the SP with CRP setup method, the influence of the interference is removed to some extent because POC used in the analysis originally includes the interference. However, the power balance between two propellers in behind condition changes from that in open water due to an existence of a rudder and a hull. The induced velocity from the other propeller also changes as a result.

Sasaki et al focused on the influence on w due to the rudder. He calculated the interference component w_I in the w by using dw_R, which represents the difference of the wake fraction due to a rudder to aft and forward propellers. The w_{Ii} is calculated as,

$$w_{I1} = -0.25 dw_R, w_{I2} = 0.60 dw_R \quad (7)$$

$$dw_R = w_{R2} - w_{R1}$$

The w_{Ri}, which represents wake fraction due to the rudder, can be calculated by a simplified formula as a function of the rudder thickness, the distance between propellers and the rudder and inflow velocity to the rudder. The detail is described in the publication (Sasaki et al 1996).

The substantive wake fraction due to the rudder and hull w_{ex} (i.e. w excluding the interference component between two propellers) is derived by subtracting the w_{Ii} from the w_i.

$$w_{exi} = w_i - w_{Ii} \qquad (i=1, 2) \quad (8)$$

2.2.2 Ishida's method

In w analyzed using the SP method, an induced velocity from the other propeller is completely included in the value of the w. Ishida et al separated the interference component w_I in the w by using relationship between an induced velocity and a propeller loading factor of the other propeller.

As shown in Figure 2 as an example, J-K_T curves of two propellers working with CRP setup differ from those when working individually. They regarded this difference of J at the same K_T as a mean interference wake fraction w_O and calculated it by the following equation.

$$w_{Oi} = 1 - \frac{J_{oi}}{J_{ci}}, C_{Ti} = \frac{8 K_{TCi}}{\pi {J_{Ci}}^2} \quad (9)$$

Each of subscript C and O represents the value of CRP setup and single setup respectively. The w_O is defined as a function of a propeller loading factor C_T of the other propeller. Figure 3 shows an example of the relationship between w_{Oi} and C_{Ti}. By using the relationship, the interference component w_{Ii} in the w_i is calculated as

$$w_{Ii} = (1 - w)w_{Oi} \tag{10}$$

With C_{Ti} of the propellers in self-propulsion test, the w_{Oi} are obtained from the relationships derived in open water test. The w in the equation is obtained by the CRP method. The substantive wake fraction w_{ex} due to the rudder and hull is derived from Equation (8) as well as Sasaki's method.

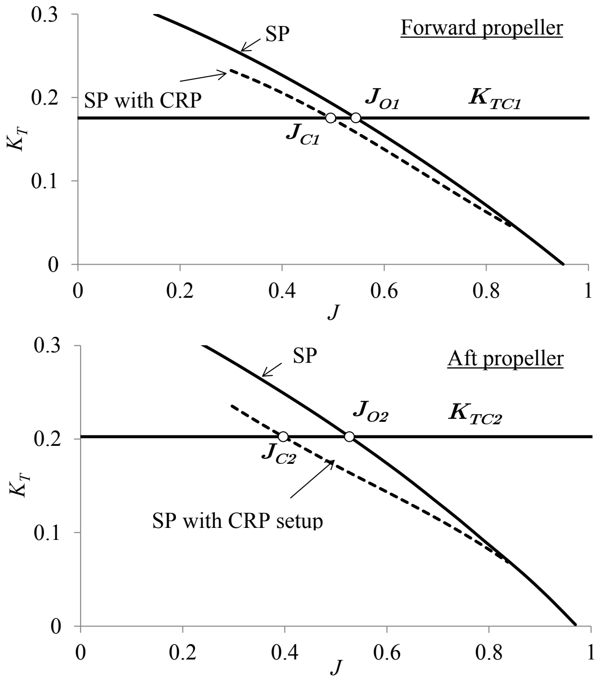


Figure 2: Example of J-K_T curves of propellers working with CRP setup and working individually

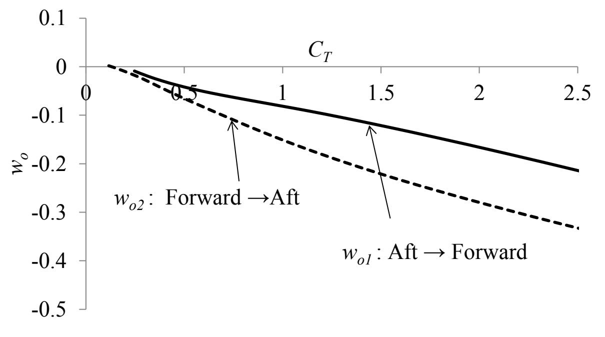


Figure 3: Example of relationships between propeller loading factor C_{Ti} and mean interference induced velocity fraction w_{oi}

2.3 Present Method

A new method presented in this paper is based on the Ishida's method with modification on the way of obtaining w_I. In addition, we applied an interference coefficient not only for w but also for η_R.

2.3.1 Equivalent rotation speed of aft propeller n_{2E}

Ishida et al did not separate an induced velocity from a forward propeller to an aft propeller into an axial and a tangential component although it actually includes both two components (u_{2IT} and u_{2IA}) as shown in Figure 4.

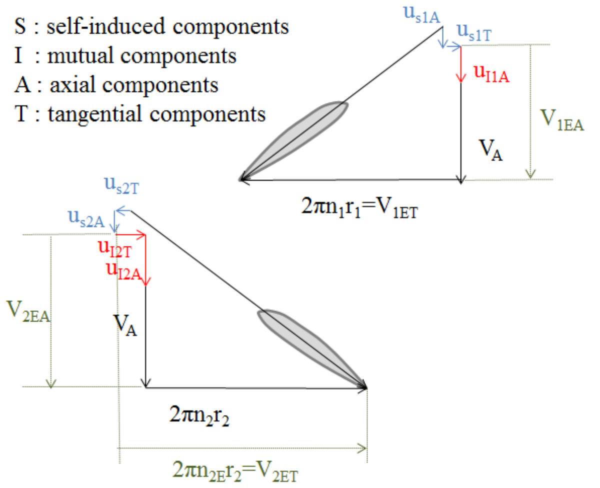


Figure 4: Velocity diagram of CRP

Since it is obviously more reasonable to consider both components separately, we used a simplified propeller theory (Moriyama 1979) to separate them. The tangential component $u_{I2T}(r)$ of the induced velocity by a circulation $\Gamma(r)$ of the forward propeller at a radial position r_2 of the aft propeller is calculated by the following equation with forward propeller geometries (number of blade N_1, chord length c_1, radius r_{O1} and pitch a_1) and working condition (angular rate Ω_1, and inflow velocity V_{1EA}).

$$u_{I2T} = -\frac{V_{1EA}\Gamma_1(r)}{r_2} \tag{11}$$

$$\Gamma_1(r) = \frac{\Omega_1 a_1(r) - V_{1EA}}{\dfrac{2\sqrt{r^2 + a_1(r)^2}}{k_1 r N_1 c_1(r)} + \dfrac{r^2 + {h_1}^2}{2h_1 r^2 \kappa(r, h_1)}}$$

$$h_1 = \frac{1}{2}(a_1(r_e) + \frac{V_{1EA}}{\Omega_1}), r_e = 0.7r_{O1}$$

$$k_1 = 1.07 - 1.05\frac{c_1(r_e)}{r_{O1}} + 0.375\left(\frac{c_1(r_e)}{r_{O1}}\right)^2$$

$$\kappa(r, h_1)$$

$$= \frac{2}{\pi}cos^{-1}exp\left\{-N_1\left(1 - \frac{r}{r_{O1}}\right)\frac{\sqrt{{r_{O1}}^2 + {h_1}^2}}{2h_1}\right\}$$

The increase of the velocity with u_{I2T} is regarded as that of the substantial rotation speed of the aft propeller. Taking the induced velocity at the 0.7R of the aft propeller as the representative value, we defined an equivalent rotation speed n_{2E} of the aft propeller as,

$$n_{2E} = n_2 + n_{I2},\ n_{I2} = \frac{u_{I2T}}{0.7\pi D_2} \tag{12}$$

In the present method, open water characteristics for the aft propeller are normalized not by n_2 but by n_{2E}.

Therefore, POC of the aft propeller with CRP setup are redefined as,

$$J_{C2E} = \frac{V_A}{n_{2E} D_2} \tag{13}$$

$$K_{TC2E} = \frac{T_2}{\rho {n_{2E}}^2 {D_2}^4}, K_{QC2E} = \frac{Q_2}{\rho {n_{2E}}^2 {D_2}^5}$$

2.3.2 Interference coefficient

Using the n_{2E}, a mean interference wake fraction w_{Oi} is calculated as,

$$w_{O1} = \frac{{w_1}'}{(1 - {w_2}')}, w_{O2} = \frac{{w_2}'}{(1 - {w_1}')} \tag{14}$$

$${w_1}' = 1 - \frac{J_{O1}}{J_{C1}}, {w_2}' = 1 - \frac{J_{O2}}{J_{C2E}}$$

Compared with Equation (9), it should be noted that the w_{Oi} in Equation (14) is normalized by the wake ratio of the other propeller unlike Ishida's method, because the induced velocity is evidently a function of not the mean inflow velocity of the two propellers but the inflow velocity of the other propeller. The w_{Oi} derived with the present method is different from that of Ishida's method. Especially the absolute value of w_{O2} is larger than Ishida's method due to separating the axial and tangential component of the induced velocity as shown in Figure 5.

The interference component w_I in the w_i is calculated as,

$$w_{Ii} = (1 - w_i) w_{Oi} \tag{15}$$

Where w_i is the value analyzed with the SP method.

The substantive wake fraction w_{ex} due to the rudder and hull is derived from the Equation (8) as well as Sasaki's or Ishida's method.

Furthermore an interference coefficient of relative rotative efficiency η_{ROi} is defined as function of the C_{Ti} of the other propeller. The η_{ROi} is calculated as,

$$\eta_{RO1} = \frac{K_{QC1}}{K_{QO1}}, \eta_{RO2} = \frac{K_{QC2E}}{K_{QO2}} \tag{16}$$

Where, each value of K_Q is derived by thrust identity method. Figure 6 shows an example of the η_{ROi}.

The η_{ROi} absorb the following errors in the analysis.

・Analytical error due to using POC of each propeller which works individually in complete homogeneous flow, while actually working in the flow including the interference between two propellers.

・Analytical error due to deviation of Reynolds number of each propeller in CRP arrangement from that of each propeller used in analysis.

・Estimation error of the equivalent rotation speed n_{2E}.

The substantive relative rotative efficiency, η_{Rexi} due to the rudder and hull is calculated as,

$$\eta_{Rexi} = \eta_{Ri} \eta_{ROi} \tag{17}$$

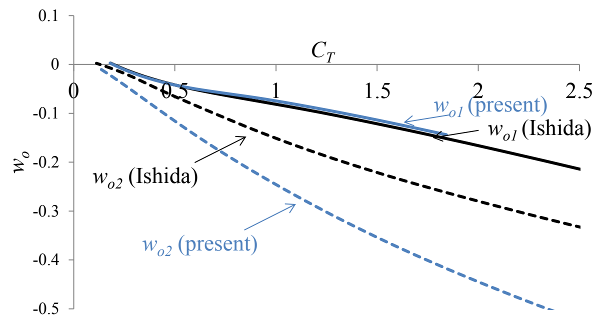


Figure 5: Comparison of relationship on C_{Ti} - w_{oi} between Ishida's method and present method

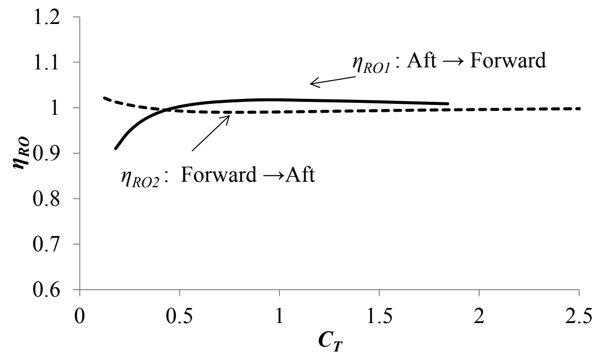


Figure 6: Example of relationships on C_{Ti} - w_{oi}

2.3.3 Analysis flow

Figure 7 shows the flow chart of the present self-propulsion analysis method.

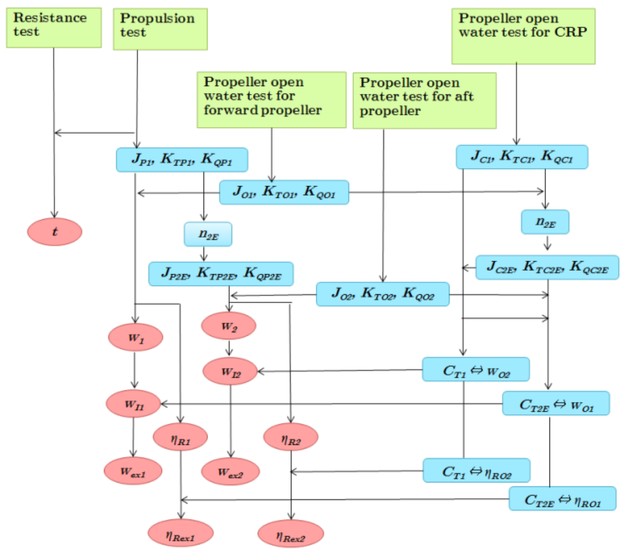


Figure 7: Flow chart of the present self-propulsion analysis method

2.4 Analysis for CRP Working in a Simplified Flow

2.4.1 Virtual simplified flow

Since it is difficult to say which method is appropriate by comparing analysis results of actual self-propulsion tests, self-propulsion factors in a simplified flow was investigated instead. We assumed an inflow of which velocity to an aft propeller is 90% of that to a forward propeller. The POC in the assumed flow was calculated with the potential method developed by the authors (Inukai et al 2015). In the calculation, the undisturbed inflow velocities V_i used for satisfying the boundary condition in the calculation were set to $V_1=V_A$ for the forward propeller and $V_2=0.9V_A$ for the aft propeller. The deformation of wake vortex sheet was not considered in the calculation because the assumed flow was virtual one.

We analyzed the effective wake ratio $1\text{-}w$ and η_R for CRP working in the assumed flow with same procedure as the aforementioned self-propulsion analysis method. The method with which expected values ($1\text{-}w_1$=1.0, $1\text{-}w_2$=0.9 and η_{R1}=η_{R2}=1.0) are obtained can be considered appropriate one. The values of $1\text{-}w_i$ for Sasaki's, Ishida's and present method mean $1\text{-}w_{exi}$ and the values of η_{Ri} for the present method mean η_{Rexi} in this subsection.

Table 1 shows particulars of CRP in the calculation.

Table 1: Principal particulars of CRP

	MP5001	
	Forward	Aft
Diameter (m)	0.21	0.18
Pitch Ratio	0.8	0.86
Number of Blades	4	4
n_1/n_2	1.0	

2.4.2 Results

Figure 8 shows analyzed $1\text{-}w$ and η_R with each method. The features of each method are shown below.

<u>Present method</u>

・All values of $1\text{-}w_i$ and η_{Ri} are analyzed correctly as expected.

<u>CRP unit method</u>

・$1\text{-}w$ and η_R of two propellers are not obtained separately. However, mean values of the expected value are obtained.

<u>SP with CRP method</u>

・In case without consideration of the interference effect, $1\text{-}w_1$ gets larger and $1\text{-}w_2$ gets smaller. The reason on the $1\text{-}w_1$ is that the induced velocity from the forward propeller to the aft propeller increases as the C_{T2} increases due to the decrease of the inflow velocity. The reason on the $1\text{-}w_2$ is vice versa. When considering the interference like Sasaki's method, the $1\text{-}w_1$ becomes close to the expected, but the $1\text{-}w_2$ gets 2% excessive. It shows that Equation (7) on the relationship of w_{Ii} and dw_R is not enough when the difference of the inflow velocity between the two propellers, (i.e. dw_R in the equation) deviates from the assumed range.

・The η_R of each propeller gets larger. The reason is assumed because the interference effect on the η_R is not considered.

<u>SP method (other than the present method)</u>

・In case without consideration of the interference effect, $1\text{-}w_1$ and $1\text{-}w_2$ are over predicted because the induced velocity from the other propeller is included in them. When considering the interference like Ishida, $1\text{-}w$ is analyzed as expected.

・The η_R of each propeller gets smaller. Especially η_{R2} is under predicted. The aft propeller works in complicated flow in the slipstream of the forward propeller. The reason for the under prediction is considered to be due to the treatment without separation of the induced velocity into the axial and tangential component.

The key on a performance prediction of CRP is to comprehend the working condition of each propeller correctly. In this sense, the present self-propulsion analysis method can be said to be the most reliable method with treating the interference between the two propellers adequately.

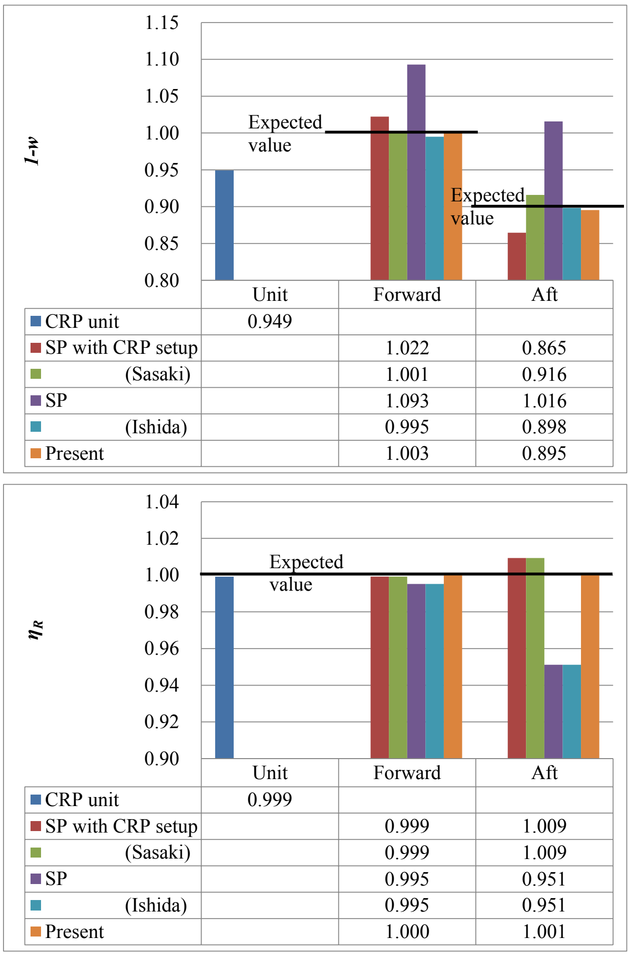


Figure 8: Comparison of $1\text{-}w_i$ (above) and η_{Ri} (below) among each method

3 FULL SCALE POWER PREDICTION

3.1 The Procedure of Present Method

It is necessary to consider the scale effect on frictional hull resistance and w in full scale power prediction. The same manner with the ITTC procedure (ITTC 1978) is applied to the scale effect on the frictional resistance in the present method. For the w, we use the framework of the ITTC procedure but separate it into each component as,

$$w_{si} = Cw_{vmi} + w_{Hi} + w_{Ri} + w_{Ii} \tag{18}$$

Where, the subscript s and m represent the value in full scale and model scale respectively, and v, H, R and I represent the viscous component, potential component due to the hull, due to the rudder and due to the interference between the two propellers respectively. C represents a correlation factor on the viscous component from model scale to ship scale. As same as the ITTC procedure, it is assumed that w_H is equal to t and the mean value of the w_R of the two propellers is set to 0.04, while the w_R of each propeller is calculated with the same method as Sasaki's. The interference coefficient w_I is obtained in accordance with the procedure described in the section 2.2 using the C_T in full scale. Since thrust balance of aft and forward propeller is unknown, we defined the ratio of the forward propeller to the total is defined as α. Calculation of α is performed until the ratio of the forward propeller rotation speed to the aft propeller n_1/n_2 gets the design value. Figure 9 shows a flow chart of the present method.

The other methods also follow the ITTC procedure. In case of Sasaki's and Ishida's method, the w_I are used as in the present method. In Sasaki's method, the mean value of w_R is also adjusted to 0.04 and w_{Ri} in other methods are set to 0.04.

3.2 Full Scale Power Prediction for a VLCC

As an example, we estimated P_D with each method for the same ship as that used by Ishida et al (1998). The particulars of the ship and CRPs are shown in Table 2 and Table 3. More detailed information on the ship and propellers are described in the publication (Ishida et al, 1998). The self-propulsion tests were performed with a combination of MS1136 for the ship and MP5014 for the CRP at JMU (former IHI) Yokohama towing tank.

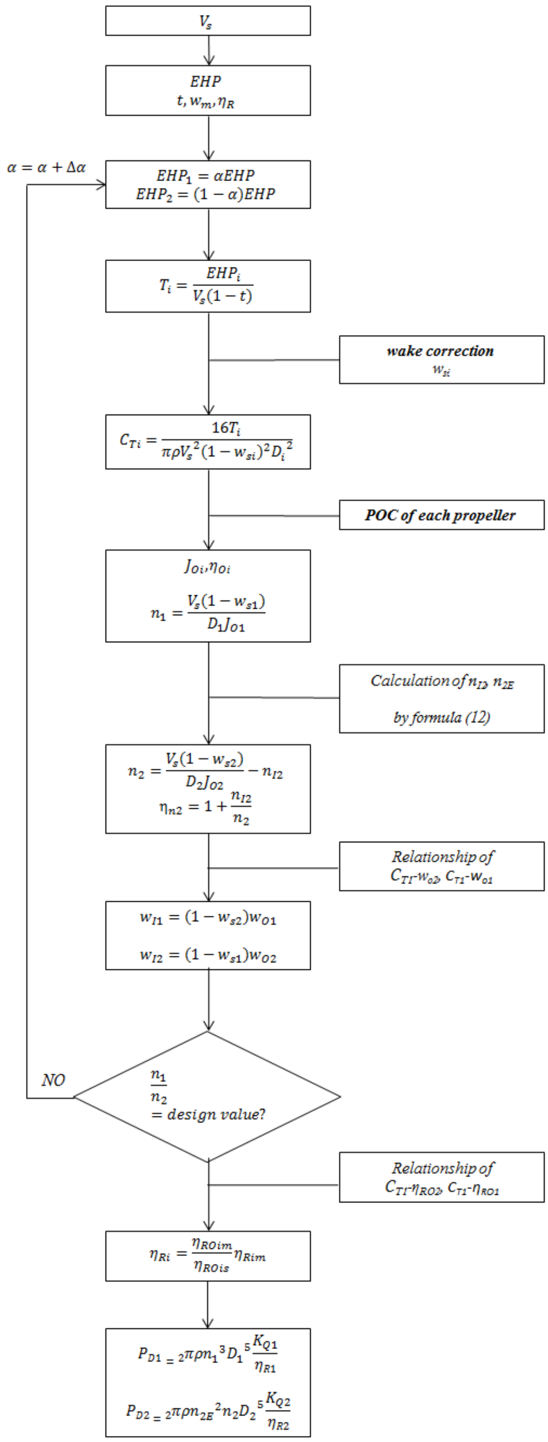


Figure 9: Flow chart of the present powering method

Table 2: Principal particulars of ship and CRPs

	MS1136
L_{model} (m)	7.0
L_{ship} (m)	314.0
L/B	5.414
B/d	2.974

Table 3: Principal particulars of CRP

	MP5014		MP5007	
	Fore	Aft	Fore	Aft
Diameter (m)	0.210	0.193	0.210	0.200
Pitch Ratio	0.800	0.860	0.800	0.860
Number of Blades	4	4	4	5
n_1/n_2	1.1		1.1	

3.2.1 Case that POC is identical in model and full scale

Table 4 shows propulsive coefficients ($1\text{-}w$ or $1\text{-}w_{ex}$, η_R or η_{Rex} and propeller efficiency η_O) and P_D normalized by that of the present method in case that POC of CRP in full scale is identical to that used in the self-propulsion test. As shown in the table, although propulsion coefficient is various for each method, sum of P_D of the two propellers is estimated almost same by the all methods other than the SP method without consideration of the mutual interference. As for the SP method without consideration of the mutual interference, w includes completely the interference as aforementioned. As a result, $1\text{-}w_s$ is estimated largely, which leads to the underestimation of P_D. It shows an importance to consider the interference between two propellers in powering prediction for a ship with CRP.

3.2.2 Case that POC is different in model and full scale

In actual design, a full scale ship often equips a propeller with different geometries from that used in the self-propulsion test for the following reasons,

- Some geometries (ex. Pitch) are revised based on the model test
- A stock propeller is used in the model test

In order to investigate the influence that POC is different in model and ship scale, we estimated P_D using POC of MP5007, which also was used by Ishida et al (1998), instead of MP5014. The particulars are shown in Table 5. The forward propeller of MP5007 is same as MP5014, while the aft propeller is different. The power balance of forward propeller to the total is smaller compared with that of MP5014. The η_O and P_D are showed in Table 4. Figure 10 shows total P_D normalized by the present method in both cases using identical POC and different one. From the figure, it is found that the difference of P_D between each method gets larger compared with in the case that POC is identical. If the interference between the aft and forward propeller in full scale doesn't change from that in model scale, the influence on the estimation on P_D is limited. However, if it changes much, it influences much on the estimation result. It implies that the propulsive coefficients for a ship with CRP include more or less the influence of the mutual interaction between the two propellers. Therefore, we can say that it is very important to separate their influence from the self-propulsion factors adequately like the present method.

3.3 Comparison with Trial Results

3.3.1 Particulars of ships

Finally, we compared the predicted P_D with those of trial results against two ships whose particulars are shown in Table 5. Ship A is a VLCC and Ship B is a domestic cement carrier. Both ships equip different propellers from those used in model tests. The propellers for Ship A are revised on the pitch based on the model test results and the model tests for Ship B were performed with stock propellers. The P_D of Ship A was measured as the sum of two propellers because she was driven by one diesel engine, while that of Ship B driven by two diesel electric engines was measured individually against two propellers.

Table 4: Full scale powering results for MS1136

		CRP unit	SP with CRP setup	(Sasaki)	SP	(Ishida)	Present
$1\text{-}w_s$ or $1\text{-}w_{exs}$	fore	0.646	0.668	0.671	0.693	0.657	0.667
	aft		0.619	0.620	0.686	0.635	0.627
η_R or η_{Rs}	fore	1.009	1.032	1.032	1.015	1.015	1.029
	aft		1.000	1.000	0.966	0.966	0.990
with MP5014							
η_O	fore	0.589	0.615	0.619	0.664	0.666	0.670
	aft		0.553	0.544	0.648	0.661	0.673
PD /PD(Present)	fore	-	1.009	0.994	0.972	1.010	1.000
	aft		0.988	1.004	0.983	0.997	1.000
	total	1.001	0.998	0.999	0.978	1.003	1.000
with MP5007							
η_O	fore	0.617	0.641	0.646	0.675	0.680	0.684
	aft		0.587	0.577	0.649	0.644	0.656
PD /PD(Present)	fore	-	1.005	0.985	1.061	1.043	1.000
	aft		0.987	1.000	0.988	1.014	1.000
	total	0.997	0.994	0.994	1.017	1.025	1.000

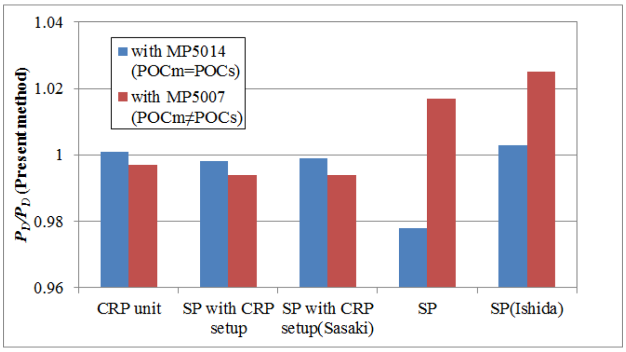


Figure 10: Comparison of estimated total P_D

Table 5: Principal particulars of ships

	Ship A		Ship B
Kind	VLCC		Bulk Carrier
Conditioin	Laden	Ballast	Ballast
Length (m)	324.0		109.0
Breadth (m)	60.0		18.2
Sea Condition	Moderate	Moderate	Calm

3.3.2 Trial results

Figure 11 and Figure 12 show speed-power curves for Ship A and B respectively. Solid lines represent the prediction by the present method and marks represent trial results. It can be seen that the predictions agree very well with the trial results regardless of the conditions, laden or ballast condition, for Ship A. As for Ship B, both power absorbed by the aft and forward propeller can be also predicted well. Table 6 shows predicted values of P_D by the other methods against the present method. Discrepancies in the total power are about 2%, while the discrepancies enlarge for the individual power of each propeller to the maximum 7.2%. The power balances of the two propellers predicted by the SP methods are obviously apart from the actual. Since various possible errors (ex. influence due to wind, wave and tide or measurement error) are included in the obtained data during sea trials, it is not easy to say which method is the best by comparing absolute values of P_D. However, even a few percent differences in P_D make large impact on total fuel consumption through the whole life of ships. Thus, the estimation on P_D should be done with a reliable method. From this view point, we say that the present method is most desirable because it is based on the rational treatment of the interaction between aft and forward propellers.

4 CONCLUSION

We presented a new power prediction method for a ship with CRP in which CRP is regarded as a combination of two single propellers. The main feature is to consider an interaction between the aft and forward propeller adequately. The present method to treat the interaction is based on the preceded works by Ishida et al (1998), however more rigorously by separating the induced velocity from the forward propeller to the aft propeller into an axial and tangential component. Furthermore, the interference effect on the relative rotative efficiency, which is not included in Ishida's work, is considered as well as the effective wake fraction. Through the study, the followings are found.

- In the analysis for CRP working in virtual simplified flow, the present method can more correctly analyze the expected effective wake fraction and relative rotative efficiency compared with other methods.
- If the propeller open water characteristics used in full scale power prediction is different from that in the self-propulsion test, a deviation on the estimated power among various methods gets large.
- Speed-power curves were compared with those obtained by sea trial results against two ships and we confirmed the present method estimates them accurately.

Table 6: Comparison of deviation of P_D from the present method

Ship (Condition)		CRP unit	SP with CRP setup		SP		Present
				(Sasaki)		(Ishida)	
Ship A (Laden)	Total	1.0%	0.4%	0.8%	-1.9%	1.8%	base
Ship A (Ballast)	Total	0.8%	0.1%	1.1%	-1.6%	1.8%	base
Ship B (Ballast)	Total	0.2%	-1.2%	-0.7%	-0.6%	-1.2%	base
	Forward	-	-0.8%	-2.3%	5.5%	5.2%	base
	Aft	-	-1.6%	0.9%	-6.4%	-7.2%	base

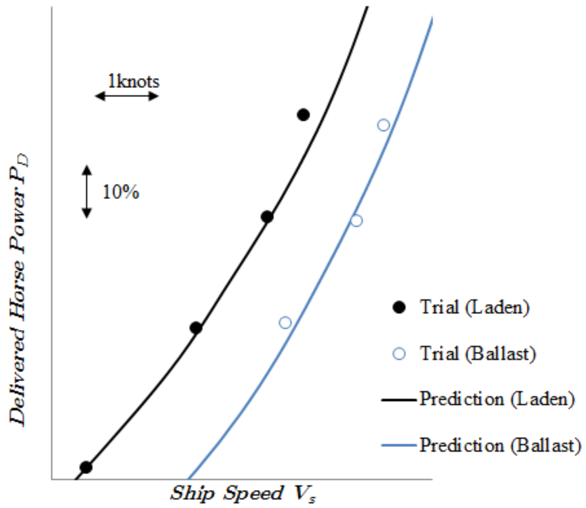


Figure 11: Speed-power Curves for Ship A

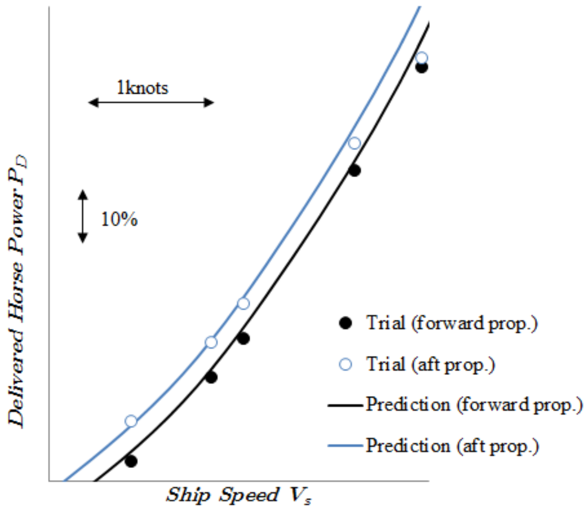


Figure 12: Speed-power Curves for Ship B

REFERENCES

Ishida, S.et al. (1998). 'A Performance Prediction Method for Contrarotating Propeller Ships' Journal of the Society of Naval Arcitects of Japan, **183**.

ITTC. (1978).'Performance Prediction Method for Single Screw Ships, Computer Program, Proceedings of 15th ITTC.

Moriyama, F. (1979). 'On an Approximate Numerical Method for Estimating the Performance of Marine Propellers'. Annual Report of Ship Research Institute, **16(5)**.

Oh, S. et al. (2014). 'Study on Hydrodynamic Characteristics of Contra-Rotating Propeller System'. Proceedings of the 24th International Ocean and Polar Engineering Conference.

Sasaki, N. et al. (1996). 'Design System for Optimum Contra-Rotating Propellers'. Transaction of the West Japan Society of Naval Architects, **62**.