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Propeller Open-Water Test Method for Hybrid Contra Rotating Propeller †

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Abstract: The Hybrid Contra Rotating Propeller is a developing propulsion system that combines a conventional single-shaft propeller with a POD propeller to achieve high energy-saving performance through a Contra Rotating Propeller. In this paper, a new towing tank test method for the Hybrid Contra Rotating Propeller was suggested. By conducting seven patterns of propeller open-water tests and measuring the individual propeller performance and the interaction between the propeller and the POD, the propeller's mutual interaction can be obtained. Towing tank tests for a study ship were conducted, and the analyzed results are shown. There exists the effect of the wake of the propeller open boat at an unusual (reversed) test layout, which simulates the Hybrid Contra Rotating Propeller, and this effect must be removed for the accurate estimation of the ship's performance. In conventional towing tank test methods, this effect on the front propeller was obtained and used to correct the performance of the total unit of the Hybrid Contra Rotating Propeller. The presented method allows for the correct removal of the open boat effect on the performance of each propeller and the propeller mutual interaction, resulting in more accurate power estimation. Furthermore, by using the individual performance of two propellers and interaction terms, the presented method enables us to conduct a power estimation at an arbitrary revolution rate of two propellers.

Keywords: hybrid contra rotating propeller; POD; contra rotating propeller; energy saving; towing tank; towing tank test method; propeller open-water test; power estimation

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1. Introduction

CRP (Contra Rotating Propeller) is an efficient propulsion system that recovers the rotational flow released by the propeller into the wake. Due to its high energy-saving performance, its installation on general merchant ships had long been anticipated, but the development of reliable bearings was a difficult obstacle. In 1989 [1] and 1990 [2], 150 years after the 1836 patent, its installation on two actual ships was finally realized by MHI and IHI, and its high energy-saving performance was demonstrated on actual ships. However, due to the high hurdles for installation, its adoption on actual ships was limited for a while. The number of CRP adoptions on actual ships began to increase significantly after 2005, when the Japanese government started supporting the construction of environmentally friendly diesel-electric propulsion vessels under the "Super Eco Ship Project" [3].

To design a ship with CRP, it is essential to accurately estimate the actual ship performance, and for that, appropriate towing tank tests and scale correction need to be conducted. The towing tank test method for CRP has a long history. Manen reported the high energy-saving performance of CRP through towing tank tests in 1968, and by this time, the towing tank test method was already an established technique [4]. The towing tank test method used by Manen was a simple method that treated the combined force of two propellers as if it were a single propeller, and by 1996, this method was used in almost all tanks conducting tests of CRP. On the other hand, research on towing tank test methods continues to improve the estimation accuracy of the actual ship performance equipped with CRP. Oh et al. presented a powering method using the individual performance of a single propeller that constitutes a CRP [5]. Inukai et al. conducted power estimation using various methods, demonstrating that performance differences arise depending on the estimation method, and validated them with speed trial results of actual ships [6]. The numerical approach is also a powerful tool for estimating propeller performance. Vlašić et al. studied the moderately loaded lifting line theory as an efficient tool for the preliminary design of a single propeller [7]. Paik investigated the characteristics of wake evolution for CRP using numerical simulations [8]. He studied the principles of reducing the rotating energy loss with CRP by observing the wake field obtained with CFD based on the RANS equation.

Another propulsion system expected for an environmentally friendly ship is the POD propeller. The advantages of the POD propeller were summarized by Mewis, including maneuverability, increased cargo weight due to the freedom of engine room layout, and low vibration [9]. The disadvantage is the low energy efficiency due to the use of a generator engine for driving a motor. Mewis also presented the towing tank test method for POD in the same paper, and he emphasized that for comparing the propulsion performance of POD systems and conventional propulsion systems, it is essential to compare the total performance of the propeller and rudder (or POD housing) units. The test method for POD is established as ITTC RP [10].

The Hybrid Contra Rotating Propeller (HCRP) is a developing propulsion system that combines a conventional single-shaft propeller with a POD propeller to achieve high energy-saving performance through CRP. MHI first adopted Hybrid CRP on a ROPAX ferry in 2004, reporting a 13% performance improvement [11]. This improvement was achieved through the high energy efficiency of CRP and resistance reduction by changing from a twin-screw ship. The EU's TRIPOD project investigated the experimental and computational estimation method of the performance of the HCRP, as well as the assessment of the economic cost–benefit analysis for the operation of a reference ship [12–14]. The benefits of introducing the HCRP include not only propulsion efficiency but also high maneuverability due to the use of POD, redundancy with the main engine and generator engine each contributing to propulsion, and low vibration due to the CRP [15]. Additionally, it does not require special bearings like coaxial CRP. With these numerous benefits, the number of applications on actual ships is gradually increasing.

Numerical and experimental studies have been conducted on the HCRP. Ying XIONG et al. investigated the effect of the distance between propellers on propeller performance and reported that increasing this distance results in a loss of unit thrust [16]. Zhan-Zhi Wang et al. studied the scaling effects of the propeller unit and proposed a scale correction method [17]. Yu-xin Zhang et al. conducted a detailed investigation into propeller interaction in open-water conditions and behind-hull conditions [18,19]. They emphasized the importance of appropriately setting the diameter ratio and distance between two propellers, as the aft propeller is subjected to a very complex flow accelerated by the fore propeller. A controllable pitch propeller can be adopted as the fore propeller of an HCRP. Yurtseven et al. investigated spindle torque for controllable pitch propellers during feathering maneuvers using a numerical approach [20].

Research on the towing tank test method for the HCRP faces complicated problems caused by the unusual equipment layout for the propeller's open-water test. A propeller open boat must be placed in front of the propeller, since the fore propeller needs to be driven from the front of the propeller. Therefore, the towing tank test simulating HCRP is conducted in a flow disturbed by the propeller open boat. The influence of the propeller open boat placed in front of the single propeller is reported by Omori et al. [21,22]. Sasaki et al. established a towing tank test method for a Hybrid CRP, treating the combined force of two propellers as if it were a single propeller [23]. Chang et al. studied the relationship between propeller revolution and power ratio with the towing tank test [24]. The towing tank test method suggested by their work is summarized as ITTC RP [25]. According to ITTC RP, the effect of the propeller open boat on the fore propeller is obtained and used as the representative value for correcting total unit performance. This paper presents a new method to accurately obtain the individual performance of the fore and aft propellers, the propeller mutual interaction, and the interaction between the propeller and the POD while carefully eliminating the influence of the wake of the propeller open boat. This considerate approach to eliminating harmful factors enhances the estimation accuracy. Querda et al. established the towing tank test method and the power estimation method for the fixed revolution rate of the HCRP in their work [14]. By using individual propeller performance and interaction factors with the presented method, it is possible to estimate the performance of the actual ship with high accuracy at any rotation ratio. The performance factors required to design the HCRP are introduced in Section 2. A detailed explanation of the towing tank test method and its analysis is described in Section 3. Towing tank test configurations and results for the study ship's propulsor are described in Section 4. This work is an extended version of paper published by authors, detailing the towing tank test method and its analysis [26].

2. Performance Factors Required to Design HCRP

As described in the Introduction, the HCRP is a propulsion system that combines a conventional single-shaft propeller with POD propellers. A photograph of the arrangement of the propulsion system for the study ship is shown in Figure 1.

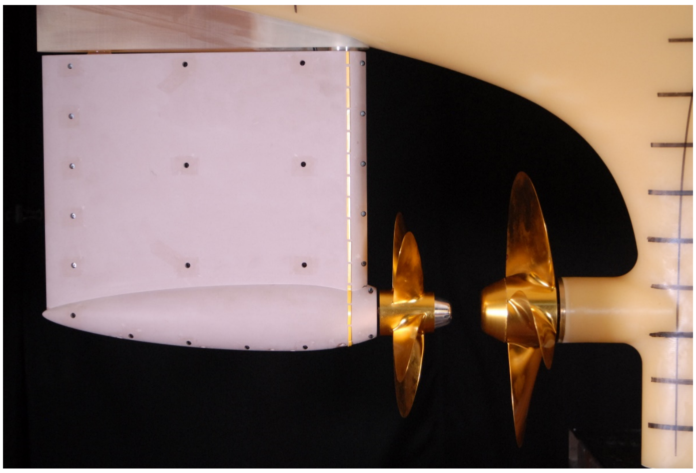


Figure 1. Photograph of arrangement of propulsion system.

For the appropriate propeller design and the accurate estimation of the ship's performance, the following performance factors must be obtained:

- Resistance of hull and POD
- Propeller open-water characteristics of fore propeller

- Propeller open-water characteristics of aft propeller
- Interaction between fore propeller and POD (POD–propeller interaction)
- Interaction between aft propeller and POD (POD–propeller interaction)
- Propeller's mutual interaction (CRP interaction)
- Thrust loss of propellers in behind-hull condition
- Interaction between fore propeller and hull
- Interaction between aft propeller and hull
- Scaling effect of each factor

Numerical computation is a powerful tool for estimating these factors. And experimental validation with the towing tank test and a speed trial at actual sea are essential for practical work. The underlined factors are unique to the HCRP and can be obtained with various patterns of propulsor tests, described in the following section.

3. Towing Tank Test Method

In this section, the towing tank test method and analysis method are described. The presented method can be applied to all types of ships equipped with HCRP and is suitable for ships that have various operations, like the low-speed operation of a survey vessel.

3.1. Propeller Open-Water Tests

Tests A to G, described below, are required to separate complex interaction factors. Test configurations are shown in Figure 2.

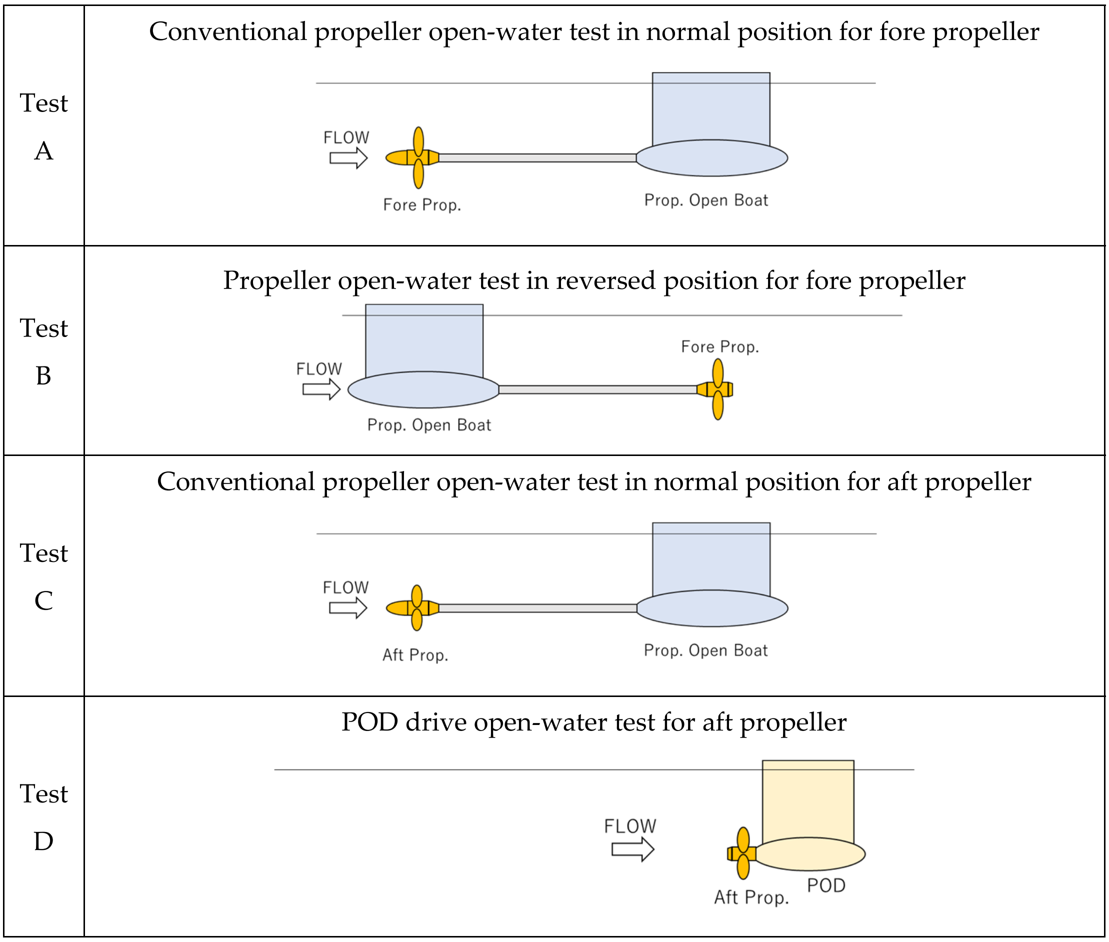


Figure 2. *Cont.*

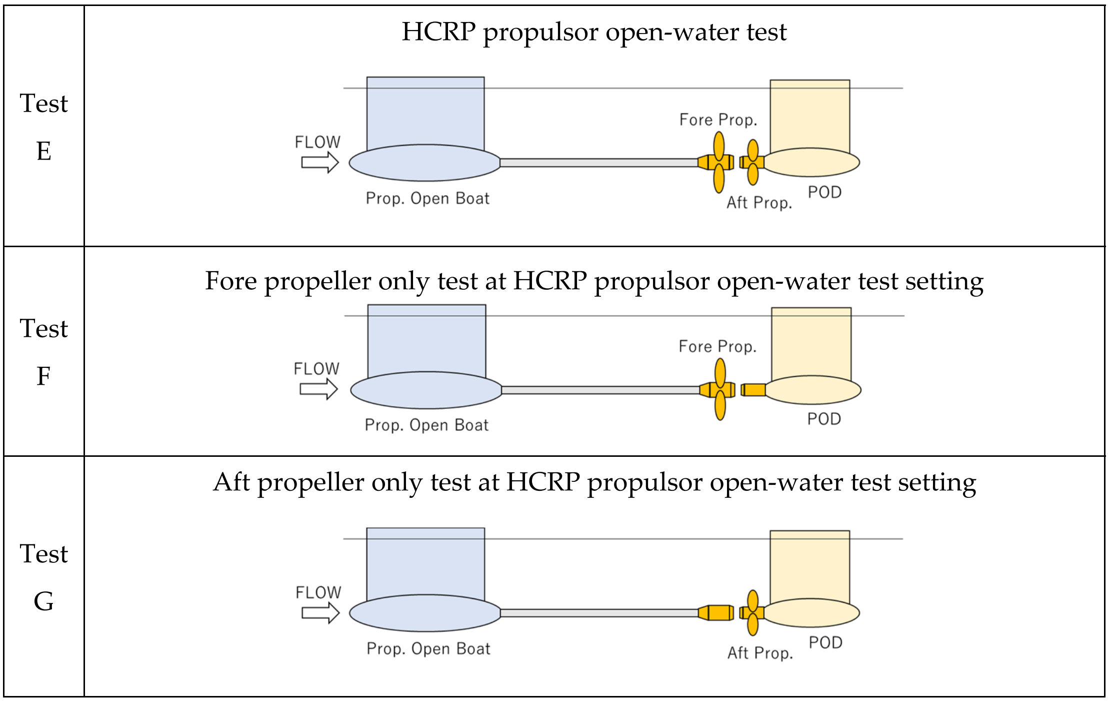


Figure 2. Open-water test configurations.

Test A is a conventional propeller open-water test in the normal position for the fore propeller. Test B is a propeller open-water test in the reversed position for the fore propeller. The difference between test A and test B is the position of the propeller open boat. Both test A and test B should be conducted to eliminate the effect of the wake of the propeller open boat for the fore propeller.

Test C is a conventional propeller open-water test in the normal position for the aft propeller. Test D is a POD drive open-water test. A small dynamometer set in the POD housing is used to measure propeller thrust and torque. By comparing the results of test C and test D, the POD–propeller interaction for the aft propeller can be obtained.

Test E is the HCRP propulsor open-water test, which is a combination of test B and test D. The rotational speed rate of two propellers is set to the designated value.

Tests A to E are recommended by ITTC R.P. [25]. Following tests F and G is a new proposal of this work.

Test F is a fore-propeller-only test at the HCRP propulsor open-water test setting. Test G is an aft-propeller-only test at the HCRP propulsor open-water test setting. POD–propeller interaction for the fore propeller can be obtained with test B and test F; also, CRP interaction can be obtained with test E, test F, and test G. It is important that test E, test F, and test G are conducted in the wake of the propeller open boat to eliminate the effect of it from the CRP interaction.

3.2. Propeller Open-Water Characteristics

The propeller open-water characteristics of each propeller can be obtained from the conventional propeller open-water tests A and C. Advance coefficients, thrust coefficients, and torque coefficients are obtained by the following equations. These are common expressions for a single propeller's performance defined in the ITTC RP for Open Water Test [27], and the suffixes F and A indicate the propeller's position.

$$J_F = \frac{V_{A\_F}}{n_F\, D_F} \tag{1}$$

$$K_{T\_F} = \frac{T_F}{\rho\, n_F{}^2\, D_F{}^4} \tag{2}$$

$$K_{Q\_F} = \frac{Q_F}{\rho\, n_F{}^2\, D_F{}^5} \tag{3}$$

$$J_A = \frac{V_{A\_A}}{n_A\, D_A} \tag{4}$$

$$K_{T\_A} = \frac{T_A}{\rho\, n_A{}^2\, D_A{}^4} \tag{5}$$

$$K_{Q\_A} = \frac{Q_A}{\rho\, n_A{}^2\, D_A{}^5} \tag{6}$$

3.3. POD–Propeller Interaction

The POD–propeller interaction of the fore propeller can be obtained from tests B and F, and that of the aft propeller can be obtained from tests C and D. The interaction factors are obtained by using the thrust identity method, which is commonly used for the analysis of self-propulsion test results and which is described in ITTC RP for the Propulsion/Bollard Pull Test [28]. In this work, the following equations are used to obtain the POD–propeller interaction. For calculating the POD–propeller interaction, only the propeller thrust is considered to determine the change in force on the propeller caused by the flow around the POD.

$$1 - w_{t\_POD\_F} = \frac{J_{F\ at\ testB}}{J_{F\ at\ testF}} \tag{7}$$

$$\eta_{R\_POD\_F} = \frac{K_{Q\_F\ at\ testB}}{K_{Q\_F\ at\ testF}} \tag{8}$$

$$1 - w_{t\_POD\_A} = \frac{J_{A\ at\ testC}}{J_{A\ at\ testD}} \tag{9}$$

$$\eta_{R\_POD\_A} = \frac{K_{Q\_A\ at\ testC}}{K_{Q\_A\ at\ testD}} \tag{10}$$

3.4. CRP Interaction

The CRP interaction can be obtained from tests E, F, and G. By the thrust identity method, the interaction factors are obtained by the following equations:

$$1 - w_{t\_CRP\_F} = \frac{J_{F\ at\ testF}}{J_{F\ at\ testE}} \tag{11}$$

$$\eta_{R\_CRP\_F} = \frac{K_{Q\_F\ at\ testF}}{K_{Q\_F\ at\ testE}} \tag{12}$$

$$1 - w_{t\_CRP\_A} = \frac{J_{A\ at\ testG}}{J_{A\ at\ testE}} \tag{13}$$

$$\eta_{R\_CRP\_A} = \frac{K_{Q\_A\ at\ testG}}{K_{Q\_A\ at\ testE}} \tag{14}$$

From the perspective of propeller momentum theory, the effect of the CRP interaction with one propeller is dominated by the propeller loading factor C_T of the other propeller.

$$C_{T\_F} = \frac{8\, K_{T\_F}}{\pi\, J_F{}^2} \tag{15}$$

$$C_{T\_A} = \frac{8\, K_{T\_A}}{\pi\, J_A{}^2} \tag{16}$$

3.5. Total Performance of HCRP

By using the propeller open-water characteristics of each propeller and CRP interaction factors, the total performance of two propellers acting as a CRP can be estimated. Because two propellers have mutual interaction, iterative calculations are needed to obtain the static condition. First, the initial state has to be set, where there is no induced velocity due to CRP interaction.

$$1 - w_{t\_CRP\_F} = 1 \tag{17}$$

Repeat Equations (18)–(21) until J_F and J_A converge. Here, the rate of revolution of each propeller n_F and n_A can be set as arbitrary values.

$$J_F = \frac{V_A\,(1 - w_{t\_CRP\_F})}{n_F\,D_F} \tag{18}$$

$$C_{T\_F} = \frac{8\,K_{T\_F}}{\pi\,{J_F}^2} \tag{19}$$

$$J_A = \frac{V_A\,(1 - w_{t\_CRP\_A})}{n_A\,D_A} \tag{20}$$

$$C_{T\_A} = \frac{8\,K_{T\_A}}{\pi\,{J_A}^2} \tag{21}$$

The first time it appears in Equation (18), the initial value of $1 - w_{t\_CRP\_F} = 1$ is used, as set in Equation (17), but the second time, $1 - w_{t\_CRP\_F}$ is determined by the relationship between $1 - w_{t\_CRP\_F}$ and C_{T_A}. K_{T_F} and K_{T_A} are determined with each propeller's open-water characteristics in isolated conditions and with updated J_F and J_A. And for each propeller's performance, a scale correction can be applied here. One example of a scale correction method is described in ITTC RP for the 1978 ITTC Performance Prediction Method [29]. Additionally, $1 - w_{t\_CRP\_A}$ is determined by the relationship between $1 - w_{t\_CRP\_A}$ and C_{T_F}.

After getting the static point of CRP interaction, total thrust and torque, as well as each coefficient, can be obtained from the following equations. In Equations (24) and (25), $\eta_{R\_CRP\_F}$ and $\eta_{R\_CRP\_A}$ are determined by the relationship between $\eta_{R\_CRP\_F}$ and C_{T_A}, and $\eta_{R\_CRP\_A}$ C_{T_F}.

$$T_F + T_A = \rho\,{n_F}^2\,{D_F}^4\,K_{T\_F} + \rho\,{n_A}^2\,{D_A}^4\,K_{T\_A} \tag{22}$$

$$K_{T\_F+A} = K_{T\_F} + \frac{{n_A}^2\,{D_A}^4\,K_{T\_A}}{{n_F}^2\,{D_F}^4} \tag{23}$$

$$n_F\,Q_F + n_A\,Q_A = \frac{\rho\,{n_F}^3\,{D_F}^5\,K_{Q\_F}}{\eta_{R\_CRP\_F}} + \frac{\rho\,{n_A}^3\,{D_A}^5\,K_{Q\_A}}{\eta_{R\_CRP\_A}} \tag{24}$$

$$K_{Q\_F+A} = \frac{K_{Q\_F}}{\eta_{R\_CRP\_F}} + \frac{{n_A}^3\,{D_A}^5\,K_{Q\_A}}{{n_F}^3\,{D_F}^5\,\eta_{R\_CRP\_A}} \tag{25}$$

$$\eta_{O\_F+A} = \frac{J_F\,K_{T\_F+A}}{2\,\pi\,K_{Q\_F+A}} \tag{26}$$

4. Towing Tank Test Configurations, Results, and Discussion

4.1. Towing Tank Test Configurations

4.1.1. Test Facility

Towing tank tests were carried out at the Tsu Ship Model Basin (TSMB) of the Japan Marine United Corporation, which has the largest sectional area of towing tank in the world [30]. The dimensions of the towing tank are shown in Table 1, and a photo of the tank is shown in Figure 3. Details of the towing tank are shown on the web page of ITTC [31].

Table 1. Dimensions of the towing tank.

Length	240 m
Width	18 m
Depth	8 m

Figure 3. Towing tank of TSMB.

4.1.2. Layout of Test Equipment

The layout of the test equipment in test E is shown in Figure 4. In order to avoid the influence of the wave generated by the propeller open boat, a wave restriction plate was set on the propeller open boat at the water level. A photograph of the test equipment and the wave restriction plate is shown in Figure 5. The effect of the wave restriction plate was reported by Ohmori et al. [21]. Propeller immersion was set at a consistent value at which the effect of the water surface can be ignored throughout all tests.

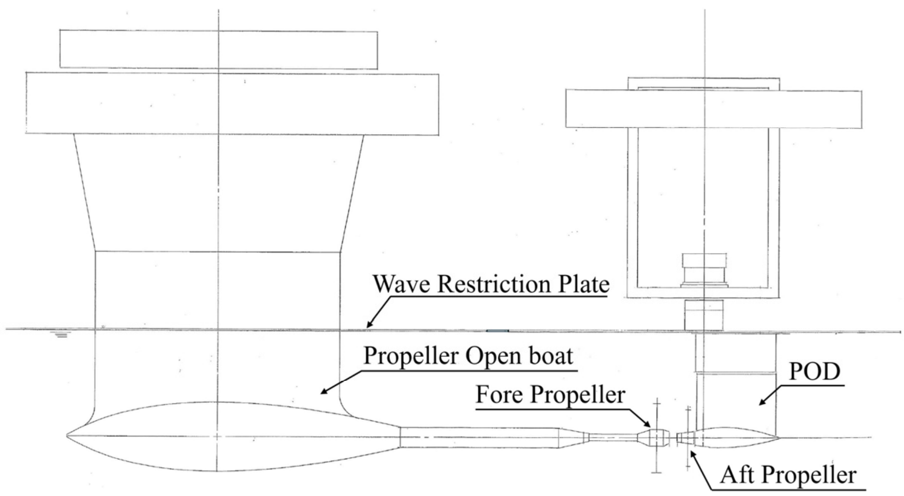


Figure 4. Layout of test equipment in test E.

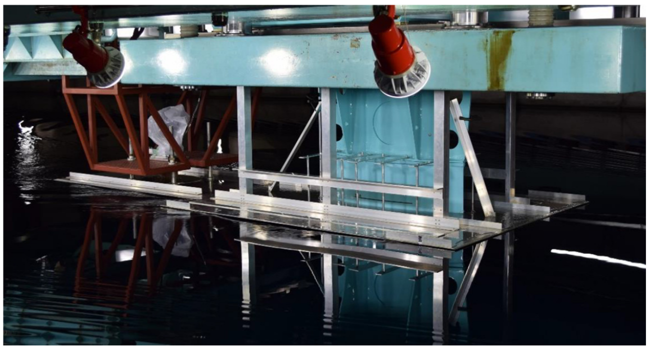


Figure 5. Photograph of test equipment.

4.1.3. POD Dynamometer

A small dynamometer was installed inside the POD, allowing for the measurement of the total resistance of the POD, as well as the thrust, torque, and rotational speed of the propeller. Figure 6 shows the 3D models of the POD model and the dynamometer.

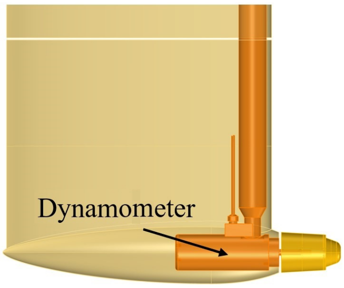


Figure 6. Small dynamometer settled in POD model.

4.1.4. Model Propellers

The dimensions of the model propellers are shown in Table 2, and photos of the model propellers are shown in Figure 7.

Table 2. Dimensions of the model propellers.

Position	Fore	Aft
Diameter	0.2800 m	0.2221 m
Pitch Ratio	0.7800	0.9600
Expand Area Ratio	0.5000	0.5000
Number of Blades	4	5
Rotation Direction	CW	CCW

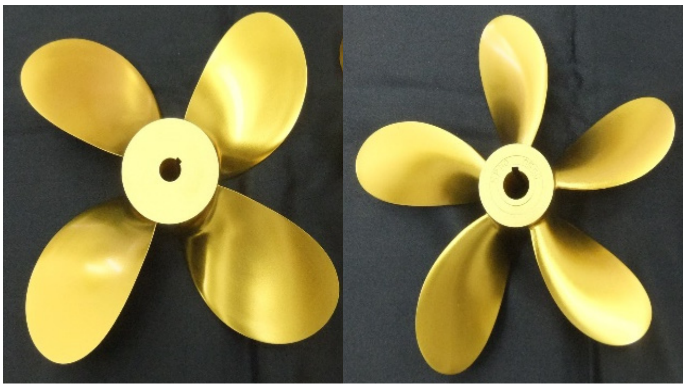


Figure 7. Photograph of model propeller. (**Left**: fore propeller; **right**: aft propeller).

4.2. Towing Tank Test Results

4.2.1. Propeller Open-Water Characteristics

The propeller open-water characteristics measured in tests A to G are shown in Figure 8. As reported by Chang et al., the effect of the aft propeller on the forward propeller is not significant [24]. On the other hand, the aft propeller's performance in the total unit diverges greatly from the propeller-only condition. The effect of the propeller open boat, the POD–propeller interaction, and the CRP interaction obtained with these performance curves are shown in the following section.

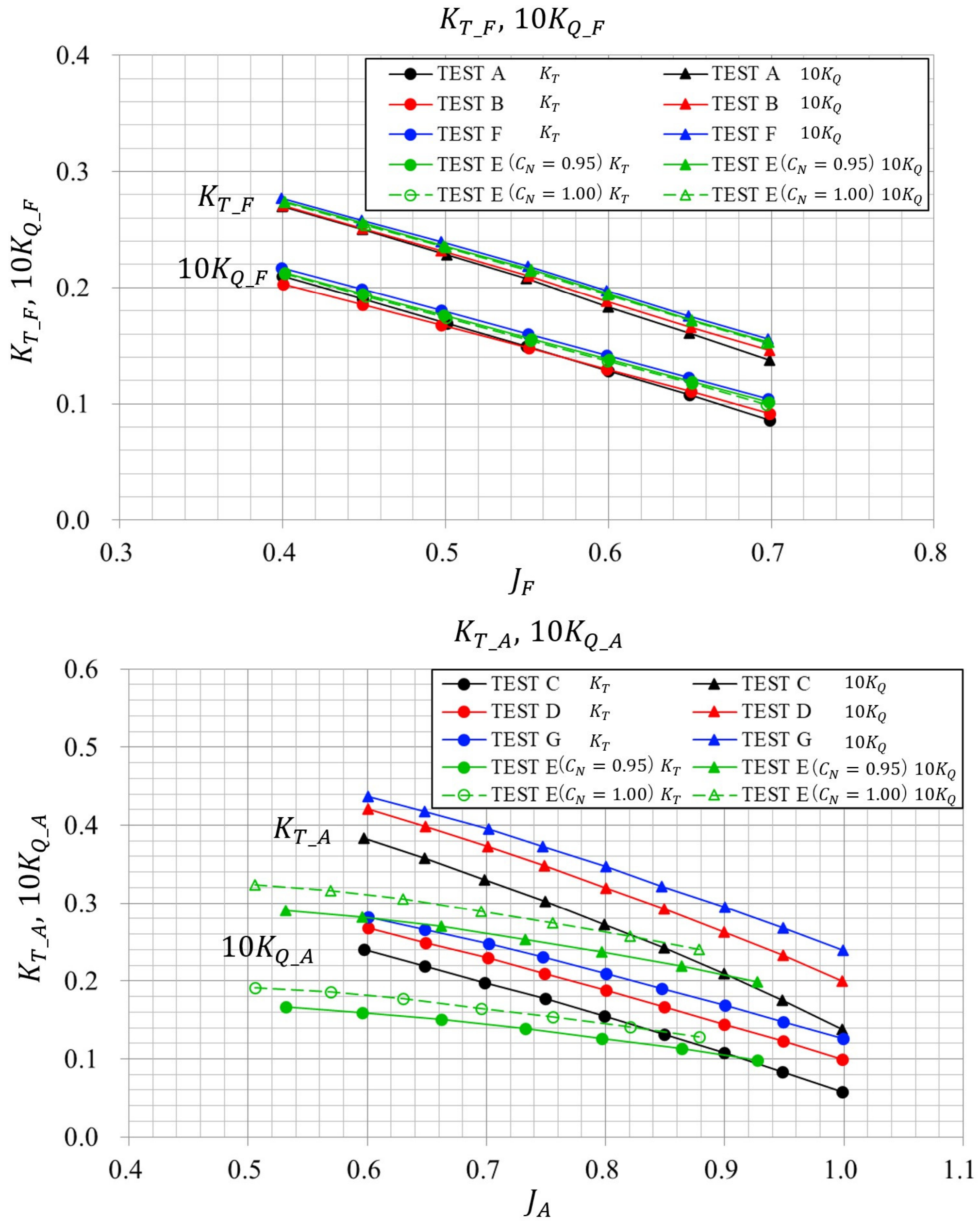


Figure 8. Propeller open-water characteristics.

4.2.2. Effect of the Wake of the Propeller Open Boat

With the present method, the POD–propeller interaction and the CRP interaction can be obtained without the effect of the wake of the propeller open boat. However, the effect of the wake of the propeller open boat was obtained according to the ITTC RP by comparing the results of tests A and B. Further, the effect of the wake of the open boat and the fore propeller's boss on the performance of the aft propeller was obtained by comparing the results of tests D and G. The following equations are used, and the results are shown in Figure 9:

$$1 - w_{t\_OB\_F} = \frac{J_{F\ at\ testA}}{J_{F\ at\ testB}} \quad (27)$$

$$1 - w_{t\_OB\_A} = \frac{J_{A\ at\ testD}}{J_{A\ at\ testG}} \quad (28)$$

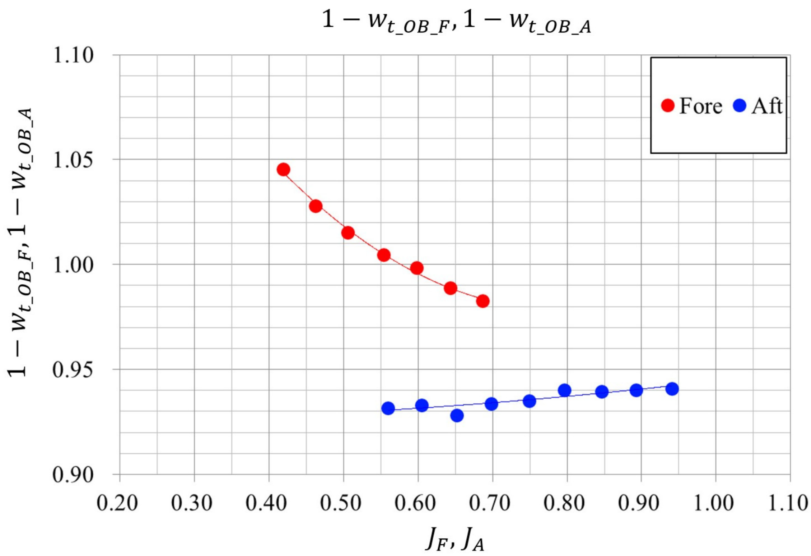


Figure 9. Influence of the wake of the propeller open boat.

The influence of the open boat on the fore propeller shows a dependency on J, and $1 - w_{t\_OB\_F} > 1$ when J is below 0.6. Normally, a propeller running in the wake generates greater thrust due to the wake effect, resulting in $1 - w_{t\_OB\_F} < 1$. As reported by Ohmori et al. [21], in the reverse propeller open-water test, the presence of the propeller boss cap and the increased resistance due to the hub vortex affect the propeller thrust. Since hub vortex resistance depends on the working propeller's load, it is natural to see a dependency of thrust loss on J. In the ITTC RP, another way, in which the dummy shaft (or dummy propeller open boat) is set behind the fore propeller to determine the effect of the wake of the propeller open boat without additional resistance from the hub vortex, was proposed.

The influence of the open boat on the aft propeller is greater than that on the fore propeller. No significant dependency on J is observed. The small diameter of the aft propeller and the presence of the fore propeller's boss cap in front of the aft propeller gives a small number to $1 - w_{t\_OB\_A}$.

Thus, comparing the normal and reverse POT or the presence or absence of the open boat does not allow for an evaluation of the pure open boat effect, and the influence on the fore and aft propellers is quite different. In the ITTC method, the effect of the wake of the propeller open boat on the fore propeller is used to correct the total performance in test E. However, a more detailed investigation of the open boat influence on the aft propeller and POD resistance is necessary. In this paper, the results of tests A and C, which are the usual POTs, are used to obtain the single-propeller performance. The POD–propeller interaction on the aft propeller is calculated with test results without the propeller open boat. The POD–propeller interaction with the fore propeller and the CRP interaction are calculated with the test results behind the open boat. These treatments allow the accurate elimination of the open boat influence on propeller open-water characteristics and interaction factors.

4.2.3. POD–Propeller Interaction

The performance changes of the propeller due to the POD are shown in Figure 10. The $1 - w_{t\_POD}$ varies with the propeller load, with a higher propeller load resulting in a smaller $1 - w_{t\_POD}$. This is a natural tendency because the effect of the wake of the POD appears against the accelerated flow by the propeller. The range of η_{R_POD} is from 1.02 to 1.03 for the fore propeller and from 0.99 to 1.00 for the aft propeller, with no significant slope observed due to the propeller load.

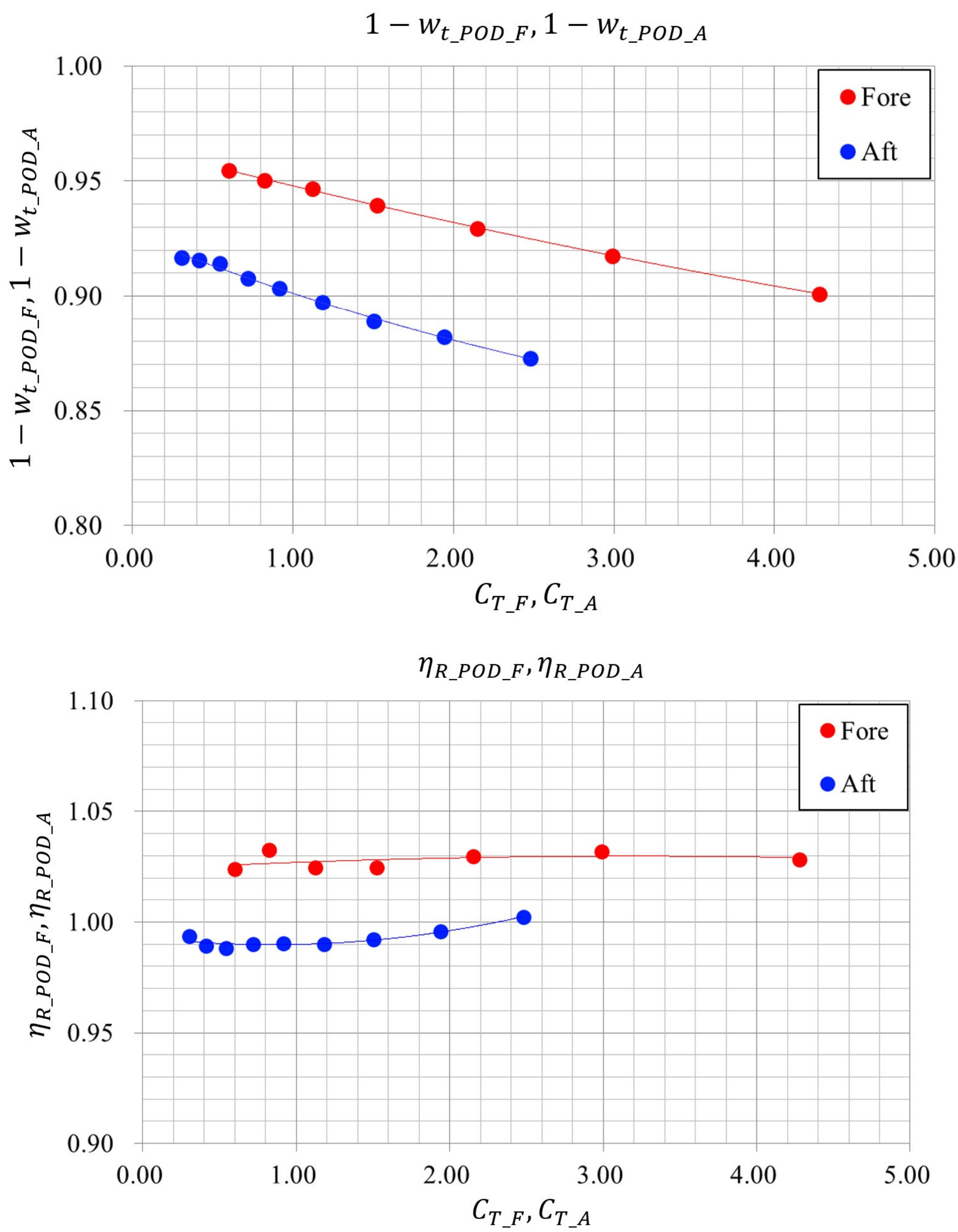
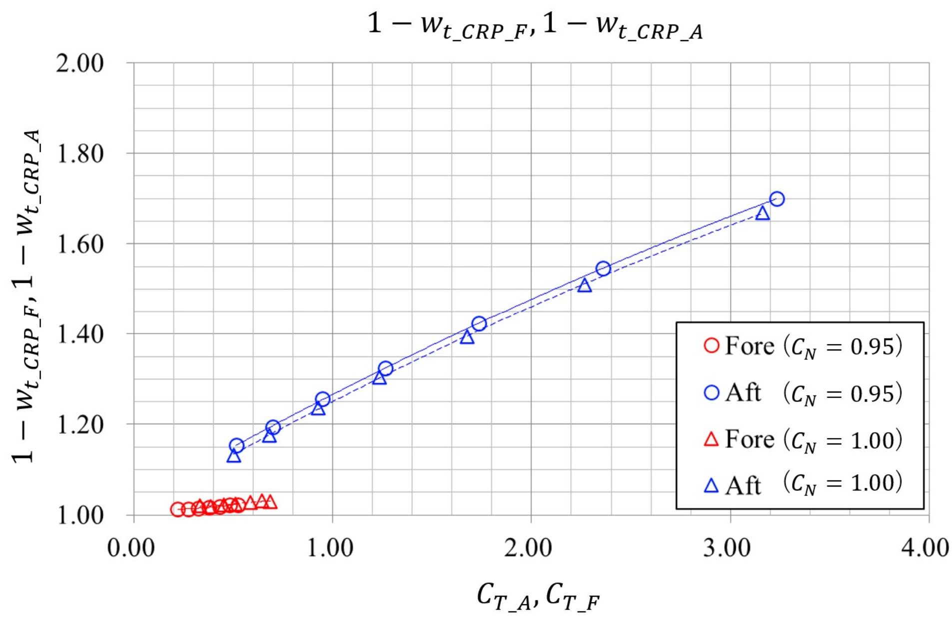


Figure 10. POD–propeller interaction.

4.2.4. CRP Interaction

The CRP interaction is shown in Figure 11. The $1 - w_{t\_CRP}$ and η_{R_CRP} of each propeller depend on the load of the other propeller. Therefore, it should be noted that the horizontal axis of the graph represents the load of the other propeller. Test E was examined for two cases at the propeller rotation ratio $C_N = N_A/N_F = 0.95$ and $C_N = 1.00$. It shows slight acceleration for the fore propeller and significant acceleration for the aft propeller.

These trends increase with propeller load, following the momentum theory. The range of η_{R_CRP} is from 0.98 to 1.00 for the fore propeller and from 1.00 to 1.01 for the aft propeller. No significant difference in the relationship between the interaction factors and the propeller loading factor is observed due to the rotation ratio. This suggests that the propeller operating conditions at any rotation ratio can be estimated using each propeller's open-water characteristics in isolation and the interaction factors obtained from the test results at the designated rotation ratio of propellers.



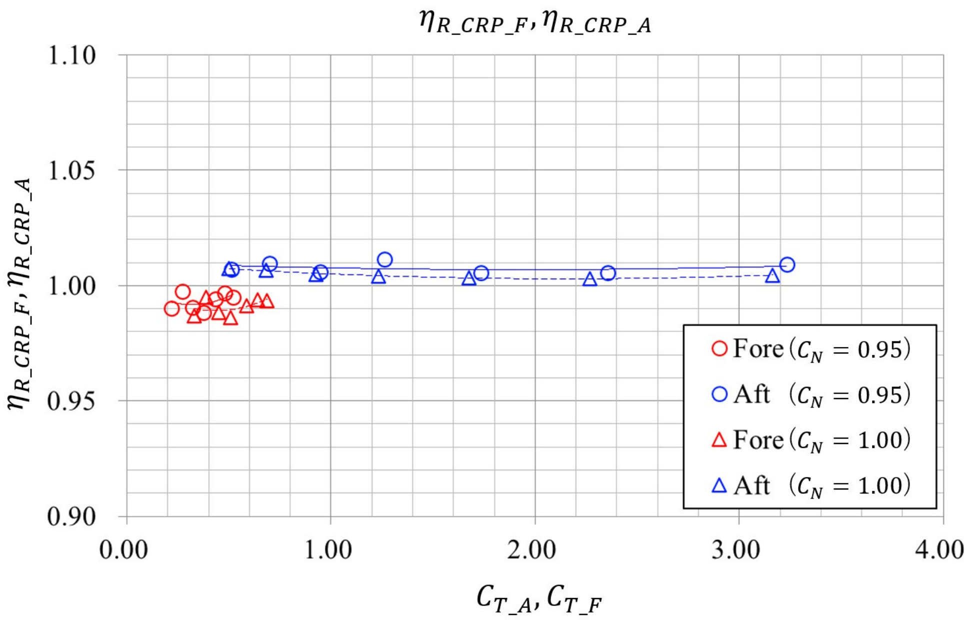


Figure 11. CRP interaction.

4.2.5. Total Performance of HCRP

The total performance of HCRP can be determined by performing the calculation process described in Section 3.5, with the individual performance of each propeller obtained with tests A and C, and the CRP interaction obtained in Section 4.2.4. The results are shown in Figure 12.

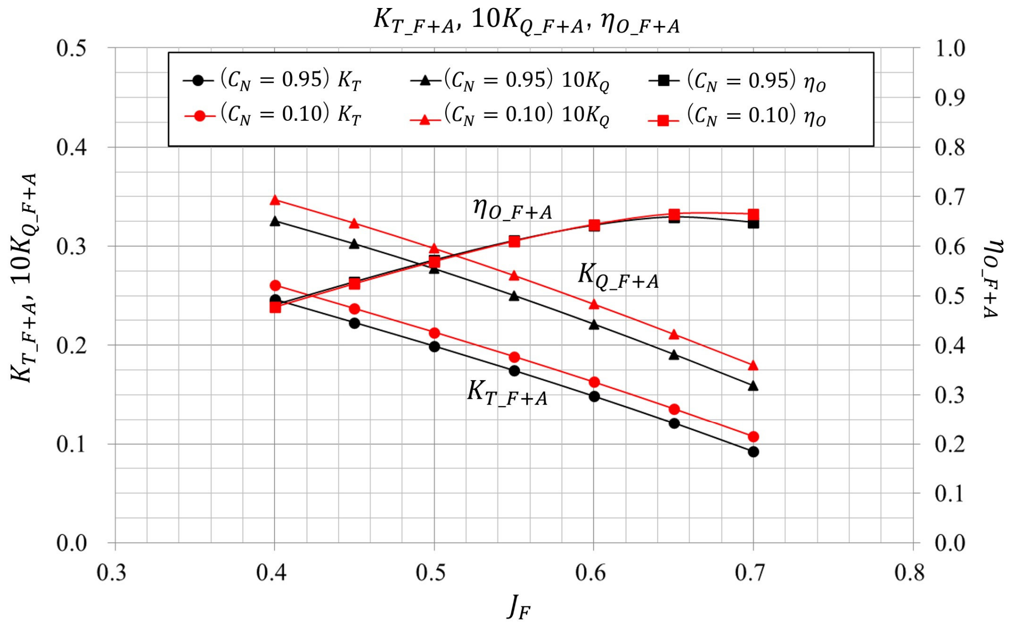


Figure 12. Total performance of HCRP.

5. Conclusions

A new towing tank test method to obtain propeller open-water characteristics and the interaction between the propeller and other devices of a complex HCRP propulsion system was presented. The towing tank test results of a study ship's propulsor were shown. The main points discussed in this paper are listed below:

- Seven POTs with different combinations of propellers and test devices were introduced to evaluate the detailed performance of HCRP.
- Each propeller's open-water characteristics and POD–propeller interaction and CRP interaction can be obtained with the presented method.
- The accurate elimination of the effect of the wake of the open boat on the fore and aft propellers, as well as the POD, can be conducted with the presented method.
- The total performance of two propellers that are acting as CRP can be obtained with an arbitrary propeller revolution ratio with the presented method
- The influence of the rotation ratio of the fore and aft propellers on the relationship between the CRP interaction and the propeller loading factor is not significant within the tested range of propeller rotation ratios. CRP interaction follows the momentum theory, affected by the load of the other propeller.

An estimation of the wake gain is crucial to design the actual propeller to avoid torque-rich and over-rotation conditions, and the influence of the open boat on the propeller must be carefully removed to accurately estimate the wake gain. Thus, the prescribed advantage of the present method is essential for designing the HCRP.

Furthermore, the present method greatly expands the freedom of power estimation of the actual ship by separating the individual propeller performance and interaction factors. In practical ship design, the propeller design may be revised due to progress in the ship's design after towing tank tests. Ideally, to estimate the performance of the revised ship, the towing tank tests should be redone. However, by using the present method as a convenient approach, it is possible to estimate the difference in propulsion performance by reflecting the individual open-water performance of the revised propeller.

In this work, a new towing tank test method and analysis method were presented. Validation through comparison between the estimated performance based on towing tank test results and the actual ship's performance remains as future work.

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Abbreviations

The following abbreviations are used in this manuscript:

Variable	Definition
D	Propeller diameter
n	Rate of revolution
V_A	Advance speed
J	Advance coefficient of the propeller
ρ	Mass density of water
T	Propeller thrust
Q	Propeller torque
K_T	Thrust coefficient
K_Q	Torque coefficient
η_O	Propeller efficiency in open water
C_T	Propeller loading factor
w_t	Wake fraction factor
η_R	Relative rotative efficiency
C_N	Propeller rotational speed ratio
Subscript	Definition
F	The association with the fore propeller
A	The association with the aft propeller
$F + A$	The association with a combination of two propellers
POD	The effect due to POD–propeller interaction
CRP	The effect due to CRP interaction
OB	The effect due to the propeller open boat

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