

# A study on the characteristics of self-propulsion factors for a ship equipped with Contra-Rotating Propeller

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## ABSTRACT

Contra-rotating propeller (CRP) is well known as an efficient energy saving device recovering the loss of rotational energy of forward propeller by aft propeller and its performance is said to be improved around 10% compared with conventional propeller (CP).

It is also known that not only the open water efficiency but also the self propulsion factors are changed from a ship with CP. Especially effective wake factor indicates the drastic change from CP which sometimes reaches to the gain of 10% order power reduction.

Although effective wake factor is one of the major parameter to constitute vessel's performance with CRP, detailed investigation on the characteristics of this factor is not yet appeared. Accordingly in this paper, both experimental and theoretical investigations were carried out to clarify the physical characteristics of this factor. Furthermore, we conducted sea trial for two actual ships and a large benefit in effective wake factor by the amount of 10% was verified which was almost equivalent value derived from model test.

## Keywords

Contra-rotating propeller, energy saving device, effective wake factor, thrust load factor, sea trial

## 1 INTRODUCTION

To meet the recent requirement for energy saving according to the rise in oil price and demand for GHG reduction, application of contra-rotating propeller (CRP) will be one of the solutions. CRP is well known as an efficient energy saving device recovering the loss of rotational energy of forward propeller by aft propeller and its performance is said to be improved around 10% compared with conventional propeller (CP).

Several vessels are equipped with CRP, such as bulk carriers and very large crude carriers, have already been in service successfully and a high energy-saving effect was respectively reported (Nakamura et al 1989, Fujino et al 1990 and Sakamoto et al 1994). Recently, IHI Marine United Inc. has completed several diesel electric driven vessels equipped with CRP in succession and numbers of vessels applying CRP is increasing (Furuta et al 2006).

Many researchers have made great efforts to clarify the hydrodynamic performance of CRP and revealed that the open water efficiency was remarkably improved from CP by experimental and theoretical approach (eg. Morgan 1960 and Ishida 1988). Their efforts contributed greatly to the reduction of fuel consumption for a ship with CRP. On the other hand, some papers reported that not only open water efficiency but also interaction between propeller, hull and rudder, which is so called self-propulsion factors, was changed. For example, Sasaki (1990), Ukon et al (1988) and Fujino et al (1990) carried out self-propulsion tests and found that thrust reduction factor of CRP got worse compared with CP. Sasaki (1990) studied the principle of the deterioration of thrust reduction factor by experiment and calculation and concluded that the increase of drag of rudder made thrust reduction factor worse in case of CRP. Meanwhile, it was reported that an effective wake fraction of CRP got often better than CP. Fujino et al (1990) conducted model tests for bulk carriers and obtained the results of higher effective wake fraction beyond 10% compared with CP. Sasaki (1990) collected the model test results which were provided in several papers and summarized the

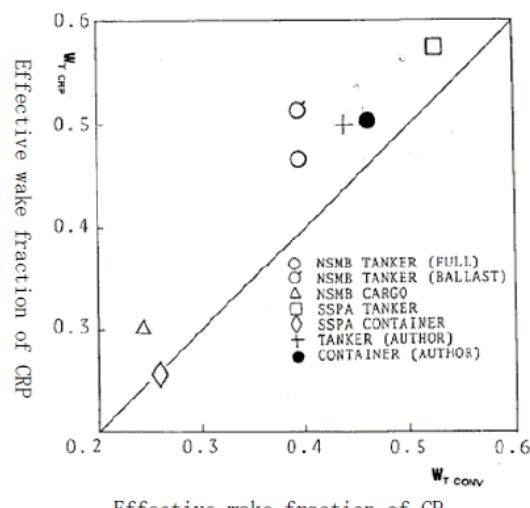


Figure 1 Comparison of effective wake fraction between CP and CRP (Sasaki 1990)

relationship of effective wake fraction between CRP and CP as shown in Figure 1. From this figure, it is found that effective wake fraction of CRP was improved regardless of type of vessels. Sasaki (1990) implied this advantage to be the influence of rudder, however further investigation was not continued more.

Although effective wake factor is one of the major parameter to govern vessel's performance with CRP, detailed investigation on the characteristics of this factor is not yet appeared. Accordingly in this paper, both experimental and theoretical investigations were carried to clarify the physical characteristics of this factor.

At first, influence of rudder on effective wake factor ( $1-w_e$ ) of CRP and CP was confirmed by model test. Secondly, flow field in front of propellers were measured and compared with calculation. Thirdly, relationship between propeller loads,  $1-w_e$  and flows in front of propeller were correlated through flow tube concept based on the momentum theory utilizing number of tank test data. Finally,  $w_e$  conducted sea trial for two actual ships equipped with CRP. As results, a remarkable wake gain by the amount of 10% was verified for actual ship, which is almost equivalent value derived from model test.

This paper presents the results of the above research works and introduces the advantage in wake gain when CRP is equipped to a vessel.

## 2. INFLUENCE OF RUDDER ON EFFECTIVE WAKE FACTOR

In order to investigate the influence of rudder on effective wake factor ( $1-w_e$ ) of CRP and CP, self-propulsion tests were carried out for a model ship with and without rudder respectively.

### 2.1 Model ship and propeller

The model tests were carried out at the IHI towing tank (Length 200m\*Breadth 10m \* Depth 5m). The principal dimensions of model ship and propellers (CP, CRP1) are shown in Table 1 and 2. As shown in Table 2, the diameter of fore propeller of CRP is same as CP. The propeller revolution ratio between fore and aft propeller was 1:1.3. The longitudinal location of CP was set at the middle of fore and aft propeller of CRP.

### 2.2 Tank test results

The test results are shown in Figure 2. It was found that  $1-w_e$  of CRP was smaller than that of CP for all range of Froude number regardless of the presence of rudder. Although the values of  $1-w_e$  change by rudder, the effect of the rudder on  $1-w_e$  seems to be the same level for CRP and CP. This shows that rudder doesn't much influence on the difference of  $1-w_e$  between CRP and CP.

### 3. FLOW FIELD IN FRONT OF PROPELLER

Since tank test data suggested that rudder would not be a cause of difference of  $1-w_e$  between CRP and CP, it was assumed that flow field itself in front of propeller would be changed among them. To clarify this point, induced velocity in front of propellers were investigated by both experiment and calculation.

Table 1 Particulars of model ship

Type	Tanker
Length b p (m)	7.00
Breadth (m)	1.30
draft (m)	0.41
Design Fn	0.146

Table 2 Particulars of model propeller

	CP	CRP1	CRP2		
Model	MP42 3	MP71 4 (fore)	MP71 5 (aft)	MP71 2 (fore)	MP71 3 (aft)
Diameter (m)	0.21	0.21	0.18	0.21	0.18
Pitch ratio	0.70	0.88	0.92	0.974	0.893
Boss ratio	0.18	0.215	0.251	0.215	0.251
Number of blades	5	5	4	5	4
Direction of turning	Right handed	Right handed	Left handed	Right handed	Left handed

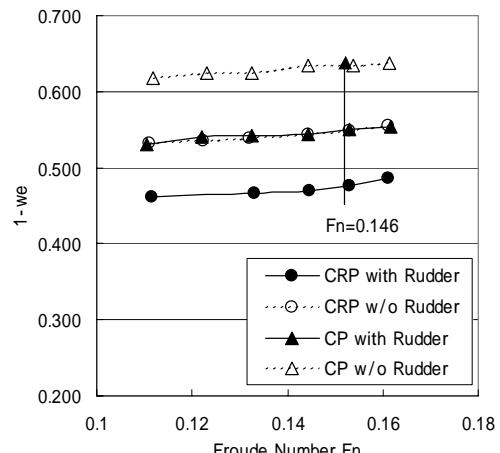


Figure 2 Experimental results of ( $1-w_e$ ) for CRP and CP (with/without rudder)

### 3.1 Condition of measurement and calculation

Flow field in front of propeller working in open water condition was measured. The principal dimensions of model propellers (CP, CRP2) are shown in Table 2. Propeller revolution was adjusted for CRP and CP to generate the same thrust under the same advance speed. The flow velocity at 25%Dp, 50%Dp, 100%Dp forward from CP and fore propeller of CRP was measured with 5 hole Pitot tube at the IHI towing tank (Dp indicates diameter of CP and the fore propeller of CRP). In parallel, induced velocity was calculated by applying the

infinite blade theory (Sasaki 1990) for comparison purpose.

### 3.2 Results of flow measurements

Figure 3 shows the axial velocity distribution of CRP and CP by measurement and calculation. Transverse axis represents the axial velocity unified by the advance speed of propeller. Vertical axis shows distance from propeller shaft unified by the radius of propeller. From both experiment and calculation, it was found that the flow velocity in front of CRP was lower than CP. Figure 4 shows the estimated streamline through the tip of CP and fore propeller of CRP by calculation. This figure shows the induced velocity field of CRP is smaller than that of CP.

From the above, it was found that the flow field in front of CP and CRP were different even if they generate the same thrust.

## 4. INFLUENCE OF PROPELLER LOAD ON EFFECTIVE WAKE FACTOR

### 4.1 Concept of flow tube diameter

Many studies on an effective wake for a ship with CP have been carried out and revealed that induced velocity in front of propeller has strong effect on the effective wake due to a deformation of boundary layer of hull (e.g. Toda et al 1984 and Nagamatsu et al 1978). Therefore the difference of induced velocity between CRP and CP might possibly cause the difference of  $1-w_e$ .

Since induced velocity varies with thrust loading factor ( $C_T$ ), Nagamatsu et al (1975) and Adachi (1983) expressed the  $1-w_e$  as a function of  $C_T$  from the viewpoint of flow contraction effect of propeller. Especially Nagamatsu (1975) introduced a concept of flow tube diameter ( $D_p'$ ) by formula (1) derived from momentum theory as illustrated in Figure 5. And it was found that  $1-w_e$  have a clear correlation with nominal wake factor ( $1-w_n$ ) which is an integrated value within a disk area of  $D_p'$ .

$$D_p' = \sqrt{\frac{1}{2} \left( 1 + \sqrt{1 + C_T} \right)} D_p \quad (1)$$

$$C_T = \frac{T}{\rho A V^2} \quad (2)$$

$$w_n(D_p') = \int_{r_b}^{D_p'^{1/2}} dr \int_0^{2\pi} w_n(r, \theta) r d\theta \quad (3)$$

Where  $D_p'$  = flow tube diameter;  $D_p$  = propeller diameter;  $C_T$  = thrust loading factor;  $T$  = thrust;  $\rho$  = water density;  $A$  = propeller disk area;  $V$  = propeller advance speed;  $w_n$  = nominal wake fraction.

Based on the forerunner's work, we also estimated  $D_p'$  of CRP by applying formula (1).  $C_T$  and  $D_p'$  of propellers already presented in chapter 3 are tabulated in Table 3. Also,  $D_p'$  derived by infinite blade theory shown in Fig.4 is described in the same table.  $C_T$  of fore and aft propellers for CRP are smaller than CP because two propellers divide propeller thrust of CRP. Furthermore  $C_T$  of the aft propeller is rather smaller than that of fore

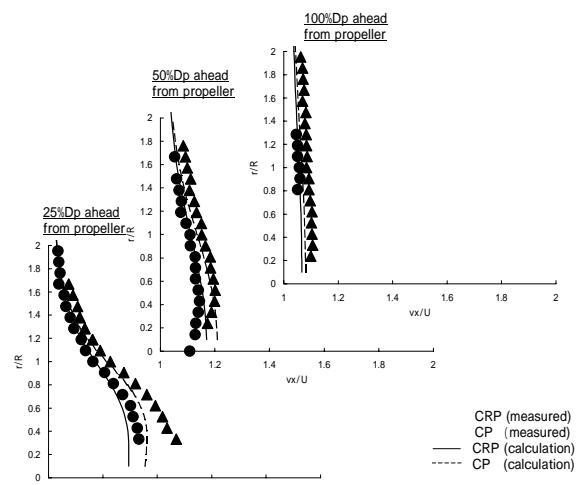


Figure 3 Axial velocity distributions of CRP and CP by measurement and calculation

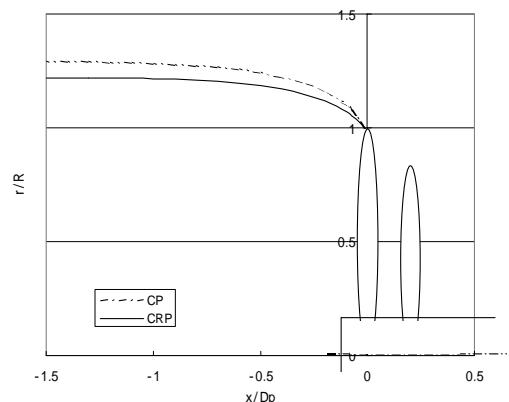


Figure 4 Estimated streamlines of CRP and CP

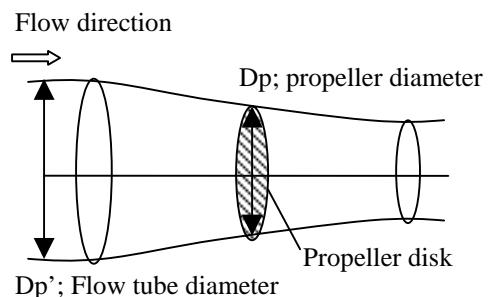


Fig.5 Illustration of flow tube diameter

Table 3  $C_T$  and  $D_p'$  of CP and CRP

	CP	CRP	
		Fore	Aft
$C_T$	4.52	2.44	1.08
$D_p / D_p$ from formula (1)	1.29	1.19	0.95
$D_p / D_p$ from Fig.4	1.29	1.22	

propeller because it works in an accelerated flow behind fore propeller. Therefore, corresponding  $D_p'$  are smaller in order of CP > fore propeller (CRP) > aft propeller (CRP) consequently.

#### 4.2 Comparison between $1-w_e$ and $1-w_n$ integrated within disk area of flow tube diameter

In this chapter, comparison are made between  $1-w_e$  and  $1-w_n$  which was an integrated value within disk area of  $D_p'$  for fore propeller of CRP. Assumption was made for this comparison that  $D_p'$  of CRP system mainly depends on  $C_T$  of fore propeller because  $D_p'$  of aft propeller is relatively small and less dominant.

Number of tank test data derived at IHI towing tank in the past are utilized and the relationship between  $1-w_e$  and  $1-w_n$  are shown in Figure 6. In this figure, both  $1-w_n$  integrated by use of  $D_p'$  and  $D_p$  of fore propeller are plotted. It was found that  $1-w_n$  integrated within disk area of  $D_p'$  shows clear relationship with  $1-w_e$  compared with that integrated by  $D_p$ .

From the above, it can be concluded that the difference of flow tube diameter should be focused as a cause of inherent characteristics of effective wake for CRP although further investigation is necessary for the deformation of boundary layer of hull and so on.

#### 4.3 Model tests with varying $C_T$ of fore propeller

Since fore propeller load has close relationship with  $D_p'$  of CRP, it can be assumed that  $1-w_e$  of CRP would be also strongly affected by fore propeller load. In order to confirm the above, self-propulsion tests with varying  $C_T$  of fore propeller was carried out at the IHI towing tank using the same model ship and propeller shown in chapter 2.

In order to change  $C_T$  of fore propeller, propeller revolution ratio between fore and aft propeller ( $N_a/N_f$ ) was set for 1.0, 1.1 and 1.3. Each  $N_a/N_f$  ratio corresponds to the horsepower ratio of fore propeller to the total power ( $P_f/P$ ) of 0.77, 0.65, and 0.45. CP loading condition can be defined by this ratio as  $P_f/P = 1.0$ . In addition, rudder was not equipped during all tests in order to focus on an clarification of interaction between hull and propeller only.

Figure 7 shows the relationship between  $P_f/P$ ,  $1-w_e$  and  $1-w_n$  integrated within each disk area of  $D_p'$ .  $1-w_e$  of CRP reached to that of CP as  $P_f/P$  increased up to 1.0 and same tendency was observed in case of  $1-w_n(D_p')$ . From this figure, it was confirmed that  $1-w_e$  and  $1-w_n(D_p')$  of CRP were strongly influenced by  $C_T$  of fore propeller.

#### 4.4 Sea trial tests

Sea trial tests were conducted for two different ships equipped with CRP. These ships were driven by diesel electric system and propeller revolution of fore and aft propeller can be controlled independently. By using this system, we carried out speed tests with varying horsepower ratio between fore and aft propeller like the aforementioned model tests.

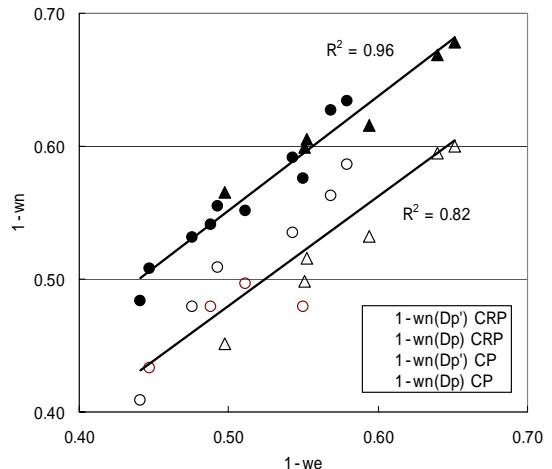


Figure 6 Relation between  $(1-w_e)$  and  $(1-w_n)$

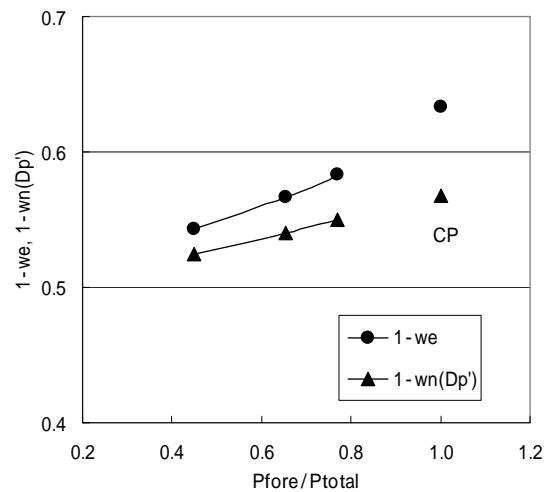


Figure 7  $(P_f/P) - (1-w_e), (1-w_n)$

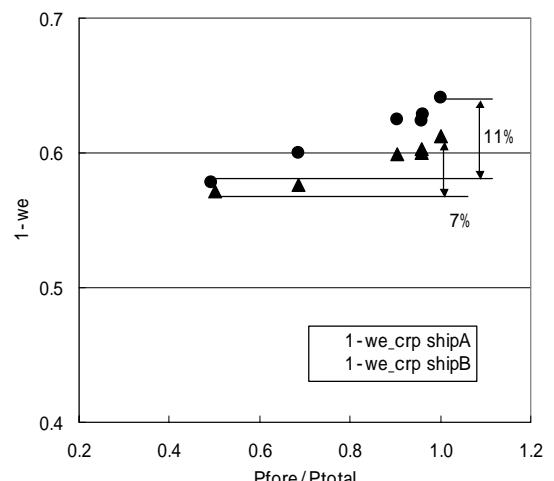


Figure 8  $(P_{fore} / P_{total}) - (1-w_e)$  relation obtained from sea trial results

The principal dimension of the ships is shown in table 4. Propeller revolution of fore and aft propeller were varied to achieve  $P_f/P=0.5, 0.7, 0.9, 0.95$  by keeping the same total horsepower. In addition, we also carried out a test of aft propeller free to be rotated. Figure 8 shows the relationship between  $P_f/P$  and  $1-w_e$  derived from sea trial analysis results. Similar to the model test result, it was found that  $1-w_e$  is increased as  $P_f/P$  increased and reached to the value in case of only fore propeller working condition (aft propeller free to rotate). Compared with the normal operating condition at around  $P_f/P=50\%$ , effective wake was strongly changed by the amount of 7-11%.

Table 4 Particulars of ship

	Ship A	Ship B
Length b p (m)	61.8	69.95
Breadth (m)	10.0	11.5
Draft at mid. (m)	4.18	4.76

## 5. Conclusion

In this paper, research on the characteristics of effective wake for a vessel equipped with contra-rotating propeller was carried out by experimental and theoretical approach. Concluding remarks are summarized as follows.

- 1) According to self-propulsion test, the rudder doesn't much influence on the difference of  $1-w_e$  between CRP and CP.
- 2) Flow velocity in front of CRP is lower and the induced velocity field is smaller than those of CP even if they generate the same thrust.
- 3) Flow tube concept was applied to the investigation of CRP' effective wake. Nominal wake integrated within a disk area of flow tube ( $1-w_n(D_p')$ ) shows clear relationship with effective wake. This implies the flow field in front of propeller would cause the difference of effective wake between CRP and Cp.
- 4) CRP's effective wake and  $1-w_n(D_p')$  are strongly influenced by fore propeller load:  $C_T$ .
- 5) Sea trial results indicated a large benefit in effective wake by the amount of about 10%, which was almost equivalent value derived from model test.

In this paper, investigations on the physical characteristics of effective wake for a ship is equipped with CRP are carried out by experimental and theoretical approach. Since wake gain of CRP is comparable to that of open water efficiency, it is important to improve the interaction effect between hull and propeller at design stage. In order to maximize energy saving effect, more detailed investigation about interaction phenomena, such as deformation of hull boundary layer by propeller, should be continued in the future.

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