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A Study on the Propulsion Performance in the Actual Sea by means of Full-scale Experiments

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ABSTRACT: The IMO has adopted Energy Efficiency Design Index (EEDI), Ship Energy Efficiency Management Plan (SEEMP) and Energy Efficiency Operational Indicator (EEOI) in order to reduce GHG emissions from international shipping. And, the shipping industry is required to develop and improve the energy saving ship operation technologies to meet the above IMO guideline. The weather routing is one of the energy saving navigation technologies and widely adopted by oceangoing merchant ships. The effectiveness of the weather routing mainly depends on the accuracy of weather forecast data and the ship's propulsion performance prediction. The propulsion performance in the actual sea is usually predicted using the Self Propulsion Factors obtained by model tests. It is necessary to understand the propulsion performance characteristics in the actual sea conditions for the improvement of propulsion performance prediction. From the above points of view, the authors performed full-scale experiments using a training ship in order to investigate the propulsion performance characteristics in the actual sea. This paper describes the analysis results on the characteristics of Power Curves and Self Propulsion Factors under various weather and sea conditions.

1 INTRODUCTION

From the view point of earth environment protection, the shipping industry is required to develop and improve energy saving ship operation technologies. For example, the weather routing is one of the above technologies and it is often used for the navigation planning of oceangoing merchant ships in order to minimize the distance traveled and fuel consumption. The effectiveness of the weather routing on the energy saving mainly depends on the accuracy of the weather forecast data and that of the propulsion performance prediction in the actual sea where the effect of wind and wave on ship's motion exists. The weather forecast technology has been improved year by year and an easier method to obtain the worldwide accurate weather forecast data has been proposed (Yokoi 2010). On the other hand, the propulsion performance in the actual sea is usually predicted using the Self Propulsion Factors obtained by model tests due to the small amount of full-scale experiment data in the actual sea (Sasaki 2009, Tsujimoto 2000).

In general, ship's speed in the actual sea is low compared to the speed measured at the speed trial in the still water. In order to improve the accuracy of a propulsion performance prediction, it is necessary to understand the effect of external disturbances such as wind and wave on the propulsion performance qualitatively.

It is said that the effect of the wave on the Self Propulsion Factors are small and the propulsion performance under the wave is often predicted taking into account both an increase of resistance by the wave and the propulsive efficiency reduction by a propeller loading increase. Recently, some scholars have tried to measure the Self Propulsion Factors under the wave conditions by means of self propulsion tests, and the examination of the scale effect is considered to be necessary in the above model tests. A full-scale experiment that includes a thrust measurement seems to be necessary in order to investigate the characteristics of the Self Propulsion Factors in the actual sea.

From the above points of view, the authors conducted an experimental study using a training ship in order to investigate the characteristics of propulsion performance under various weather and sea conditions. In the study, the effects of winds and waves on the propulsion performance are analyzed separately according to the wind direction and wind force. The characteristics of Self Propulsion Factors in the actual sea are also examined. This paper describes the characteristics of a Power Curve (speed–BHP curve) and wake coefficient ($1-w_t$) in the actual sea compared with those obtained by model tests.

2 EXPERIMENTS AND DATA ANALYSIS

2.1 *Full-scale Experiment*

The test ship was a 6,720 G.T. training ship Ginga Maru and her principal particulars are shown in Table 1. A precise shaft horsepower meter with a shaft thrust load meter produced by the Shoyo Engineering Co.,Ltd has been installed in the test ship. The shaft thrust load meter uses a high sensitivity sensor to detect minute compression strains on the shaft (SEC power ship performance monitor).

Table 1. Principal particulars of the test ship

Hull	
Length: Loa (m)	105.00
Breadth: B (MLD, m)	17.90
Depth: D (MLD, m)	10.80
Cb	0.5186
Draft: d (m)	5.96
Main Engine	
Diesel	1 set
MCR	6,620 kW x 167 rpm
Propeller (CPP)	
Prop. Brade. No.	4
Prop. Dia.: Dp (m)	4.30
P.R. (Brade Angle)	0.9965 (24.4°)

The experiments were performed during her 2-month annual training cruises (from the middle of July to the middle of September) between Japan and Hawaiian Islands conducted years 2008, 2010 and 2011. The tracks of her 3 training cruises are shown in Figure 1. In the experiments, the propulsion performance data, engine operation data and navigation data were recorded automatically every 10 seconds using the Local Area Network System.

And, the following data were used for the analysis; main engine handle notch, propeller revolution, BHP (brake horse power), torque, thrust, ship's position, heading, speed, wind direction and wind velocity.

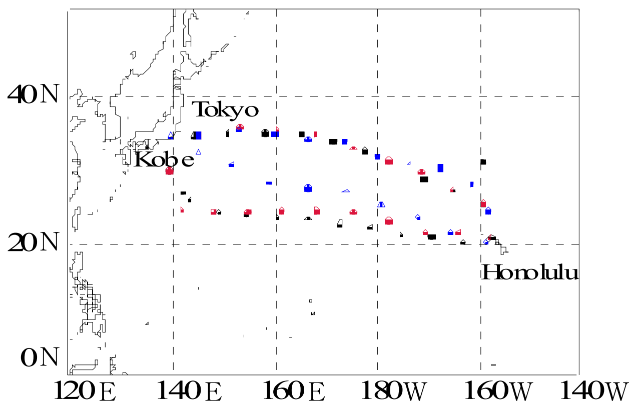

Figure 1. Track chart

2.2 *Data Processing*

In the propulsion performance analysis, the above raw data are processed according to the following procedure.

1 Identified first were steady parts of the raw data where the test ship proceeded at the steady condition continuously for two hours. The steady condition is judged by the main engine handle notch, propeller revolution, ship's heading, speed, wind direction and velocity.
2 The basic data are made by calculating average values of the steady parts mentioned above and these average values were divided into 5 wind directions relative to the ship's head and stern centerline as shown in Figure 2. In the figure, the word "Oblique Head Wind" indicates the port or starboard bow wind.
3 For each of the wind directions, the mean values of basic data were calculated separately according to the Beaufort scale and were used for the analysis.

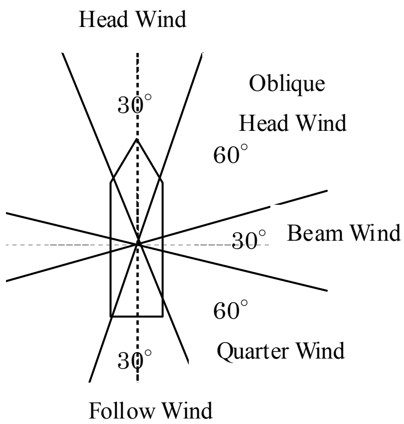

Figure 2. Definition of wind direction

2.3 *Prediction Method of Self Propulsion Factors*

When the actual value of thrust (T) and torque (Q) are measured at a ship, the propulsive efficiency (η_D) can be calculated using equation (1). Self Propulsion Factors such as wake coefficient ($1-w$) and relative rotating efficiency (η_R) can be also calculated using the propeller characteristic curve obtained by the propeller open test.

$$\eta_D = (T \cdot V_s)/DHP$$
$$DHP = BHP \cdot \eta_T \tag{1}$$

where V_s =speed; DHP =delivered horse power; BHP =brake horse power; and η_T =transmission efficiency.

The equations to obtain Self Propulsion Factors using the propeller open test results, speed, propeller revolution, BHP, thrust and torque are shown from (2) to (7). The above procedure is shown in Figure 3. When predicting the Self Propulsion Factors, it is necessary to measure the data accurately in an appropriate time interval and to know the effect of ship's condition such as displacement and trim on propulsion performance.

$$N_D = \frac{T \cdot V_S}{2\pi(N/60)Q} \tag{2}$$

$$K_T = \frac{T}{\rho(N/60)^2 D^4} \tag{3}$$

$$K_Q = \frac{Q}{\rho(N/60)^2 D^5} \tag{4}$$

$$1 - w_T = \frac{(N/60) \cdot D \cdot J_T}{V_S \times 0.5144} \tag{5}$$

$$1 - w_Q = \frac{(N/60) \cdot D \cdot J_Q}{V_S \times 0.5144} \tag{6}$$

$$\eta_R = \frac{K_{Q0}}{K_Q} \tag{7}$$

where N = propeller revolution.

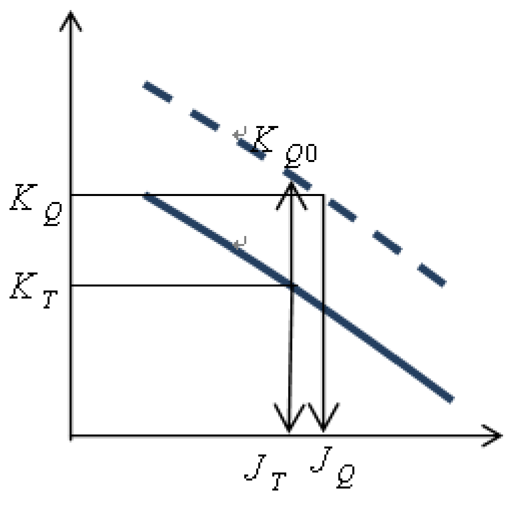

Figure 3. Calculation procedure to obtain Self Propulsion Fators

3 CHARACTERISTICS OF THE PROPULSION PERFORMANCE

3.1 *Power Curve*

In order to investigate the propulsive characteristics of the test ship, the obtained data are compared with the Power Curve obtained by the power prediction using the model ship and the one obtained by the speed trial of the test ship as shown in Figure 4. The Power Curve obtained by the speed trial agrees well with that by the power prediction. The measured BHP values were transformed so that they were comparable with those obtained in the model test condition (displacement; 5,763 tons) using the 2/3 power rule based on the idea of the Admiralty Coefficient. The plotted data indicate mean values calculated according to the procedure described in the previous section. The relationship between measured BHP and her speed was found to be in good order with that of trial result qualitatively.

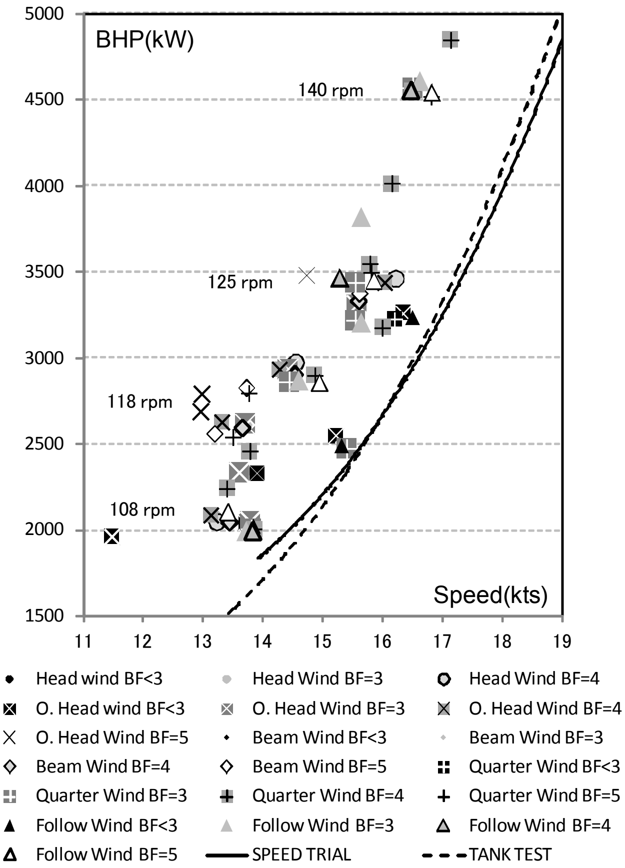

Figure 4. Comparison of measured data and Power Curves

Next, the authors examined the effect of wind on the propulsive characteristics for each of the wind directions shown in Figure 2. The comparison results of the Power Curves are shown in Figure 5 to 9. In the figures, Power Curves are shown for each of the Beaufort scale. On each of the wind directions, the Power Curves generally agree with those of speed trial and power prediction qualitatively.

When the test ship proceeds at steady BHP, her speed decreases as the wind force increases, and the degree of speed reduction decreases as the wind direction changes to afterward. The degree of speed reduction in the higher BHP region is greater than that in the lower BHP region. When the test ship proceeds under gentle sea condition (the range of the Beaufort scale less than 3), her speed is slow compared with that of speed trial and the two Power Curves are not in agreement. The same characteristics of the Power Curves as the above were observed in the follow wind, and the effect of wave is considered to be one of the causes.

As the above propulsive characteristics are observed in the actual sea, it is important to predict a Power Curve taking into account the effect of wind direction, wind force and wave.

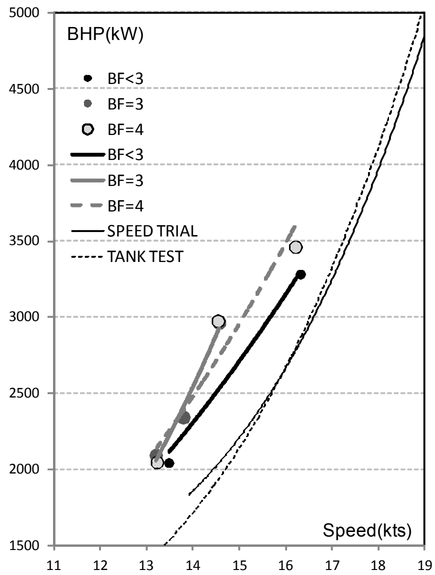

Figure 5. Comparison of Power Curves (Head Wind)

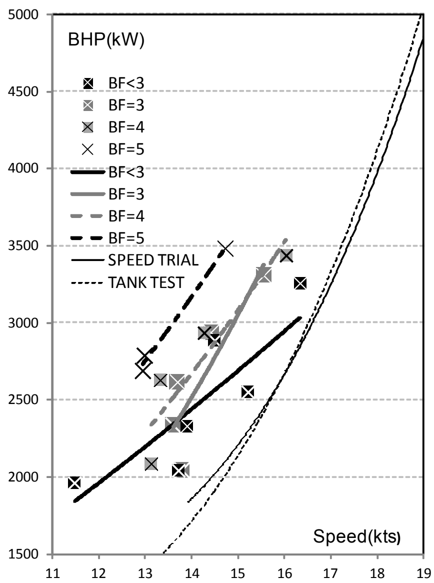

Figure 6. Comparison of Power Curves (Oblique Head Wind)

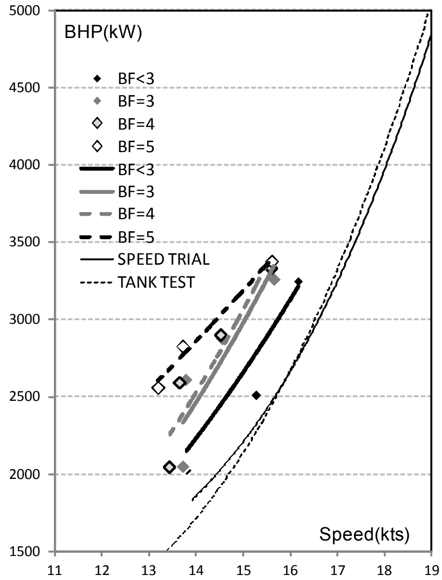

Figure 7. Comparison of Power Curves (Beam Wind)

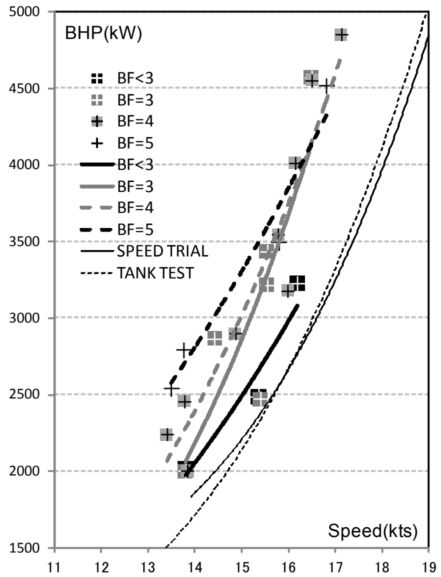

Figure 8. Comparison of Power Curves (Quarter Wind)

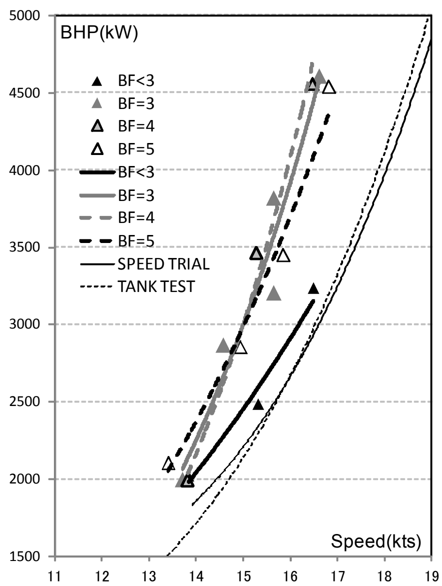

Figure 9. Comparison of Power Curves (Follow Wind)

3.2 *Self Propulsion Factors*

Although the effect of wind and wave is included in the propulsion performance data shown in the previous section, obtained Power Curves agree well with that obtained by the speed trial qualitatively. The authors examined the characteristics of Self Propulsion Factors using the data in the region of 16 knots where enough data were obtained.

When discussing the effect of displacement on the propulsion performance, it is necessary to examine the effect of both mean draft and trim. The authors performed the analysis considering the effect of displacement alone due to scarce model test data on the trim.

The Power Curves of the test ship at full load (6,308 tons) and 75 % load (5,763 tons) obtained by the model tests are shown in Figure 10. Also shown in the figure are the Power Curves predicted under the same conditions using the propulsion performance prediction program "HOPE Light," which was developed by the National Maritime Research Institute Japan (Sasaki 2009). As the predicted values agree well with the observed values in the region of 16 knots, the HOPE Light can be used as a tool to discuss the characteristics of Power Curve in the waves under the above conditions.

From the Power Curves shown in Figure 10, the authors considered that the measured horse power value can be transformed into the horse power at the displacement in the model test using the equation (8).

$$BHP' = BHP \cdot \left(\frac{16}{V_s}\right) \cdot \left(\frac{5763}{Displacement}\right)^{0.9} \qquad (8)$$

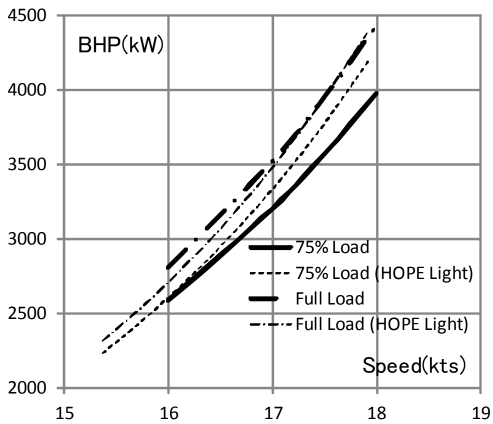

Figure 10. Power Curves obtained by model test and HOPE Light

3.2.1 *Effect of wind and wave*

The authors estimated the DHP under wind and wave disturbances using HOPE Light and the results are shown as the dotted line in Figure 11 together with measured DHP. Measured DHP are transformed into the value at the standard condition (displacement; 5,763 tons, speed; 16 knots) using the equation (8).

As shown in the figure, measured DHP data tend to increase in proportion to the increase of wind velocity and wave height, and this is mainly due to the increase of resistance by wind and wave. However, on the distribution of measured data in the region of stronger wind and higher wave, regularity is difficult to be observed. Figure 12 shows the comparison results of DHP between measured and estimated. It seems that estimated DHP is lower than measured DHP in the region mentioned above.

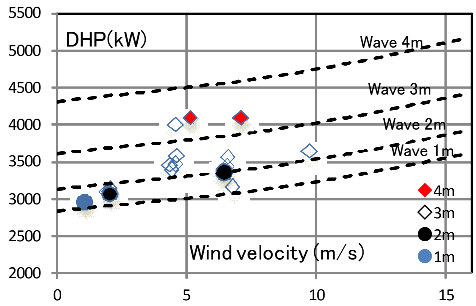

Figure 11. Comparison of measured DHP and estimated DHP for wind velocity

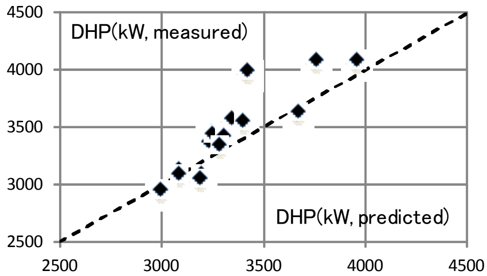

Figure 12. Comparison of measured DHP and estimated DHP by HOPE Light

In order to investigate the cause of the above results, the authors calculated propulsive efficiency (η_D) using measured BHP, thrust and speed according to the equation (1), and the obtained results are plotted against the propeller loading ($C_T = T / 0.5\rho \cdot V_a^2 (\pi D^2/4)$) as shown in Figure 13. The propulsive efficiency (η_D) decreases in proportion to the propeller loading. In the figure, estimated propulsive efficiency (η_{D0}) using the following simple equation that takes into account only the change of propeller efficiency (η_0) is also shown in dotted line.

$$\eta_{D0} = \eta_H(const) \cdot \eta_R(const) \cdot \eta_0(C_T) \qquad (9)$$

where η_H =Hull efficiency; and η_R = Relative rotating efficiency.

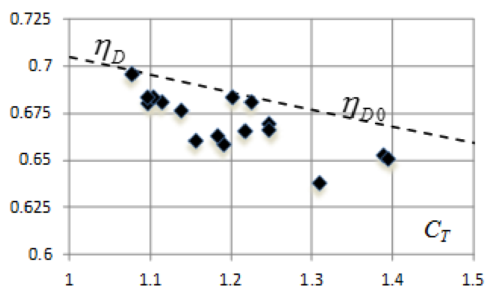

Figure 13. Comparison of measured propulsive efficiency and estimated propulsive efficiency

As is obvious from the figure, measured propulsive efficiency values (η_D) are generally lower than estimated values (η_{D0}). The difference between measured values and estimated values is about 5 % on average and this value is difficult to be disregarded. The reduction of the propulsive efficiency under wind and wave disturbance seems not to be only due to the increase of propeller loading.

3.2.2 *Wake coefficient in the actual sea*

The authors examined the relationship between wake coefficient $(1-w_t)$ and propeller loading (C_T) in order to analyze the cause of propulsive efficiency reduction shown in Figure 14.

Figure 14 shows the relationship between propeller loading and wake coefficient in the region of 16 knots. Although some dispersion is observed in the data, it seems that wake coefficient increases in proportion to the propeller loading. As the propeller loading will be changed by wind, wave and displacement, the difference of the displacement is considered to be one of the causes of wake coefficient increasing.

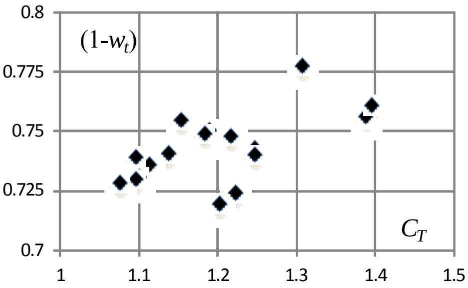

Figure 14. $(1-w_t)$ and propeller loading (C_T)

The authors investigated the relationship between displacement and wake coefficient as shown in Figure 15. In the figure, the wake coefficients obtained by the model test are also displayed as the dotted line. The wake coefficients obtained by the full-scale experiments increase in proportion to the displacement. On the other hand, the wake coefficients obtained by the model tests in this region remain almost constant.

Therefore, there is a possibility to explain the cause of difference between measured (η_D) and estimated (η_{D0}) shown in Figure 13 by the effect of displacement on the wake coefficient. Further model tests seem to be necessary in order to clarify the effect of displacement on the wake coefficients.

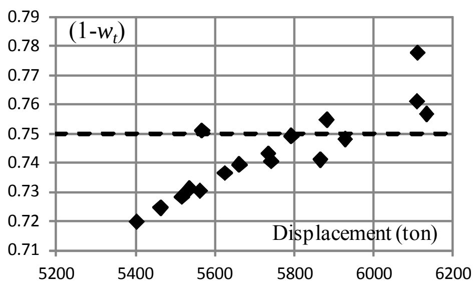

Figure 15. $(1-w_t)$ and displacement

4 CONCLUSION

The authors performed an experimental study in order to clarify the characteristics of propulsion performance in the actual sea. Results obtained in this study are summarized as follows.

1 The power curve of a ship in the actual sea with wind and wave disturbances decreases compared with the power curves obtained by power prediction and a speed trial. The degree of propulsive power reduction depends on the wind direction, wind force and wave height.
2 As the propulsion performance decreases compared with the speed trial results even if a ship proceeds under the follow wind, the effect of wave is considered to be greater than that of wind.
3 Causes of BHP increasing in the wave conditions can be divided into the resistance increasing and the change of propulsive efficiency.
4 Causes of propulsive efficiency reduction in the actual sea can be divided into the unavoidable reduction of propeller efficiency due to the resistance increase by wind and wave and others.
5 In order to determine the characteristics of Self Propulsion Factors in the actual sea, it is important to measure the thrust and calculate the propulsive efficiency directly.
6 The wake coefficient $(1-w_t)$ in the actual sea can be estimated directly by measuring her thrust. However, as the accuracy of thrust measurement is generally inferior to that of the torque measurement, it is necessary to examine their mutual relation beforehand.
7 The effect of propeller loading on the wake coefficient in the actual sea is small and the ship's condition such as displacement and trim seems to have a larger impact on the wake coefficient. The authors consider that the above results are necessary to be examined by model tests.
8 In order to improve energy saving ship operation technologies, it is important to predict the Power Curve more precisely taking into account the characteristics of the effect of wind and wave obtained in the present study.

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