On the Full-Scale Powering Extrapolation of Ships with Gate Rudder System (GRS)

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Abstract: A novel energy-saving device known as the Gate Rudder system (GRS) has proved its effectiveness to improve the propulsive efficiency, hence reduce the fuel consumption of ships on full-scale sea trials. However, the power-saving measured on the sea trials has been more than the predictions, based on the CFD analyses and model tests. This study experimentally investigates the propulsive efficiency of the Gate Rudder system by introducing the four different extrapolation methods to estimate the required power, based on model test results. In view of this the comparative tests of the two sisterships of 2400 GT Containership model, SAKURA appended with the conventional rudder system (CRS) and SHIGENOBU appended with the Gate Rudder System (GRS) are carried out at the Ata Nutku Ship Model Testing Laboratory's towing tank of Istanbul Technical University (ITU). The results of extrapolations compared with the sea trial data to properly show the differences between the methods. Gate Rudder system assumed as an appendage shows better agreement with the sea trials. The powering predictions show that the GRS configuration is able to reduce the powering requirement by 2 % at the design speed as compared to that of the CRS configuration in full loaded condition.

Keywords: Energy saving devices, towing tank experiment, propulsion, Gate Rudder system.

1 INTRODUCTION

International Maritime Organization (IMO) will implement new restrictive regulations to decrease the carbon emissions by ships. Ship owners must provide the Energy Efficiency Design Index (EEDI) and Energy Efficiency Existing Ship Index (EEXI) values of the ships below a certain level. An energy-saving device which may reduce the required power by ships, resulting in less carbon emissions. Gate Rudder system is one of the energy-saving devices that can be integrated into existing ships or installed on newly design ships.

Gate Rudder system has several advantages in terms of propulsive efficiency, seakeeping, and maneuverability (Sasaki et al., 2016). The GRS works as a ducted propeller and accelerates the flow around the propeller to improve the propulsive efficiency. Gate Rudders are twin rudders that can be operated individually during sailing, which enhances the manoeuvring performance of ships. Comparative full-scale measurements of the two sisterships of 2400 GT Containership model, SAKURA (Fukazawa et al., 2018) appended with the conventional rudder system and SHIGENOBU (Sasaki et al., 2018) appended with the Gate Rudder System have been also performed, showing a 14% energy saving. Model scale investigations were carried out both experimentally and numerically on a large bulk carrier (Sasaki et al., 2016). GRS reduced the fuel consumption up to 7-8% in powering analysis. It is well known that conventional ducted propellers may have disadvantages in terms of cavitation and vibration. There are also available studies that focus on cavitation and vibration problems comparing the CRS and GRS. Numerical (Yilmaz et al., 2018) and experimental (Turkmen et al., 2018) studies reported that sheet and tip vortex cavitation volumes have been reduced with the GRS. One further full-scale experience from the SHIGENOBU's captain is that GRS resulted in less vibration and quieter aft (Sasaki et al., 2019).

This study presents the analysis and the results of resistance and propulsion tests of two sisterships, SAKURA and SHIGENOBU of 2400 GT Containership were performed by aiming to investigate the differences, due to use of Conventional Rudder (CRS) and Gate Rudder (GRS) systems. The towing tank tests were performed in accordance with the EU Project entitled with acronym GATERS and hull form and other technical design details were supplied by the coordinator of the project.

Besides, four different full-scale extrapolations regarding the effect of GRS on total resistance and thrust deduction have been performed in powering analysis for the GRS. Details of the methods are presented in Section 3. Results are discussed in Section 4, which also shows the comparison of extrapolation methods with CRS.

2 EXPERIMENTAL SETUP

A wooden model with a scale of 1/21.75 coded as M445 was built in the workshop of ITU Ata Nutku Ship Model Testing Laboratory and tested in the towing tank of the laboratory. The tests were carried out for two loading conditions, namely full loaded (T_{mid}=5.208 m) and ballast (T_{mid}=4.175 m) conditions. The geometry and hydrostatic details are given in **Error! Reference source not found.** and Table 1.

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2.1 Properties of Ship and Propeller

The model and hydrostatic details are given in **Error! Reference source not found.** and Table 1 respectively.

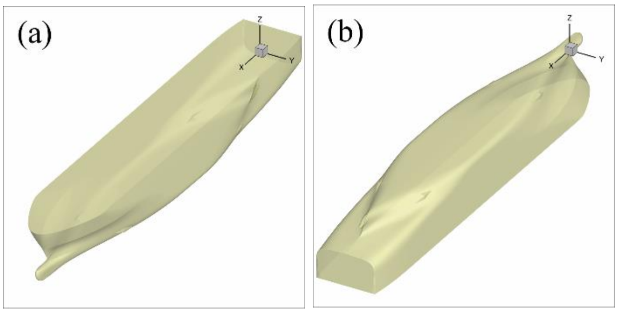

Figure 1. Perspective view of the hull.

Table 1. Model and ship characteristics.

M445	Loading Condition			
Scale	Full Load		Ballast Load	
21.75	Model	Ship	Model	Ship
L_{OA} (m)	5.127	111.51	5.127	111.51
L_{PP} (m)	4.685	101.90	4.685	101.90
L_{WL} (m)	4.860	105.71	4.808	104.57
B_{WL} (m)	0.818	17.80	0.818	17.80
T (m)	0.239	5.208	0.192	4.175
∇ (m^3)	0.614	6318.4	0.470	4835
Δ (ton)	0.614	6476.4	0.470	4955.9
S (m^2)	4.859	2298.8	4.167	1971.1
C_B	0.613	0.613	0.582	0.582

The ships have two different four-bladed controllable pitch propellers with different characteristics. In model tests, a scaled model propeller of the ship with the GRS (λ=21.75) with fixed-pitch blades was used. This model propeller was used in all propulsion tests (w/GRS & w/CRS). Details of the model propeller are presented in Table 2.

Table 2. Properties of the model propeller.

Diameter (D)	0.152 m
P/D	0.835
BAR	0.512
Z	4
Direction of rotation	Right-handed

2.2 Test Procedure and Physical Configuration of Experiment System

All resistance and propulsion tests were performed in Ata Nutku Ship Model Testing Laboratory. The tank is 160 m long, 6 m wide, and 3.4 m deep and equipped with a manned carriage which is able to run at a speed of up to 6 m/s. Turbulence stimulation was obtained by the application of studs behind the stem (bow) as well as on the rudder. Resistance characteristics of the hull model were measured by using a single component electronic resistance dynamometer, OPN500.

The propulsion tests were carried out in order to determine the required power of the ship with CRS (Figure 2) and GRS (Figure 3Figure 6) configurations at the full loading draught and ballast loading draught.

In GRS design, the propeller is slightly shifted towards the stern due to the Gate Rudders' position and the stern tube geometrical design changed accordingly.

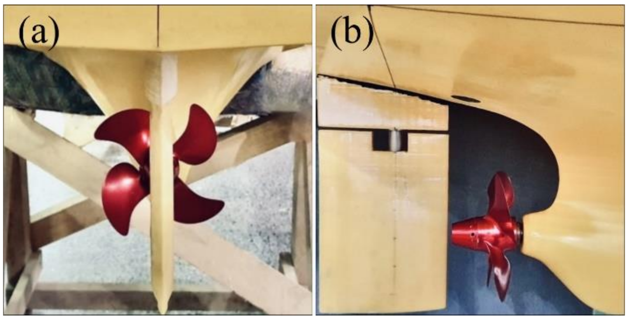

Figure 2. CRS configuration for propulsion test cases.

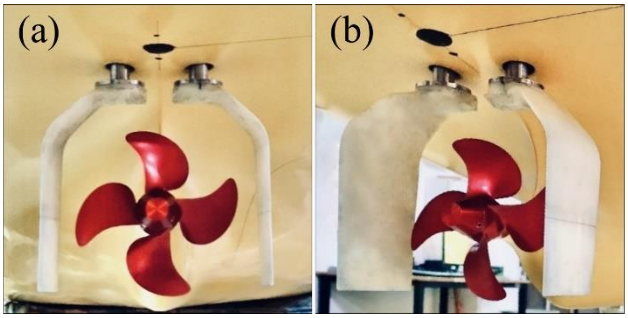

Figure 3. GRS configuration for propulsion test cases.

In the self-propulsion tests, an electric motor, one Cussons Technology R25 propeller dynamometer and a single component OPN500 electronic resistance dynamometer, bearings, etc. were installed in the 1/21.75 scaled M445 hull model. A right-handed model propeller whose open water characteristics have already been measured in Japan, was used for both configurations (CRS&GRS) during the tests.

During the self-propulsion tests an additional towing force should be applied or taken into account to obtain the full-scale ship propulsion point. This external force F_D also called as the Skin Friction Correction (SFC) takes into account the differences between Reynolds numbers of the model and the ship. The F_D can be calculated as in the following equation (1) according to ITTC Propulsion/Bollard Pull Test Procedure (7.5-02-03-01.1) as:

$$F_D = \frac{1}{2}\rho S V^2[(1+k)(C_{FS} - C_{FM}) - \Delta C_F] \quad (1)$$

The characteristics of the full-scale propeller were calculated from the model propeller characteristics in open water, which were corrected for the scale effect according to 1978 ITTC Performance Prediction Method Procedure (7.5-02-03-01.4). The model wake fraction was converted to the full-scale wake fraction for CRS regarding the same procedure.

The load of the full-scale propeller is obtained from:

$$\frac{K_{TS}}{J_S^2} = \frac{1}{N_P}\frac{S_S}{2D_S^2}\frac{C_T}{(1-t)(1-w_{TS})^2} \quad (2)$$

With this K_T/J^2 as input value the full-scale advance coefficient J_{TS} and the torque coefficient K_{QTS} are read off

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from the full-scale propeller characteristics and the following quantities are calculated.

- propeller rate of revolutions

$$n_S = \frac{(1-w_{TS})V_S}{J_{TS}D_S} \tag{3}$$

- thrust of each propeller

$$T_S = \frac{K_T}{J^2} J_{TS}^2 \rho_S {D_S}^4 {n_S}^2 \tag{4}$$

- torque of each propeller

$$Q_S = \frac{K_{QTS}}{\eta_R} \rho_S {D_S}^5 {n_S}^2 \tag{5}$$

- delivered power

$$P_D = 2\pi Q_S n_S \tag{6}$$

3 DIFFERENT EXTRAPOLATION APROACHES

Resistance tests were, initially, carried out for the bare hull and then repeated with the different rudder configurations. The effect of air drag was included in the analysis. The model was tested free to trim and sink in calm water, however, the model was fixed to roll, sway, and yaw. Form factor analysis was carried out by Prohaska's method.

Four different performance prediction methods have been compared for the GRS installed case. Details of the methods are explained in following subsections considering the effect of GRS on the total resistance and thrust deduction.

3.1 ITTC 1978 Performance Prediction- Original Method

In this approach extrapolation to the full scale was carried out by the original ITTC 1978 method. The conventional rudder and gate rudder systems were considered as appendages and extrapolated to the full scale by means of the beta factor, which is $\beta = 0.70$. The effect of air drag was included in the analysis.

In the powering calculations, the total resistance (R_{TM}) includes bare hull (R_{TBH}) and the conventional rudder (R_δ) or the gate rudder (R_{GR}) appendage resistances respectively as;

$$R_{TM} = R_{TBH} + R_\delta \; or \; R_{GR} \tag{7}$$

The thrust deduction (t) is calculated as;

$$t = \frac{T_M + F_D - R_{TM}}{T_M} \tag{8}$$

Here, T_M is the propeller thrust at the self-propulsion point.

The open water characteristics of the model propeller is directly utilized to determine the propulsion characteristics without considering the GRS effect on the propeller.

3.2 Gate Rudder Assumed as a Propulsor - I

In this extrapolation approach, the propeller with GRS is considered as a propulsor unit. Evaluation of total resistance and thrust deduction is given in equations (9) and (10), respectively.

In powering calculations of GRS case, the R_{TM} is taken as a bare hull resistance.

$$R_{TM} = R_{TBH} \tag{9}$$

t is calculated as;

$$t = \frac{T_M + T_{GRM} + F_D - R_{TM}}{T_M + T_{GRM}} \tag{10}$$

where, T_{GRM} is the thrust force generated by the GRS.

For this approach, open water characteristics with the GRS, which were calculated by Tacar et al., (2020) using CFD computations, were used for the propulsion analysis. A comparison of the open water curves with the gate rudder and without gate rudder cases in model-scale is shown in Figure 4.

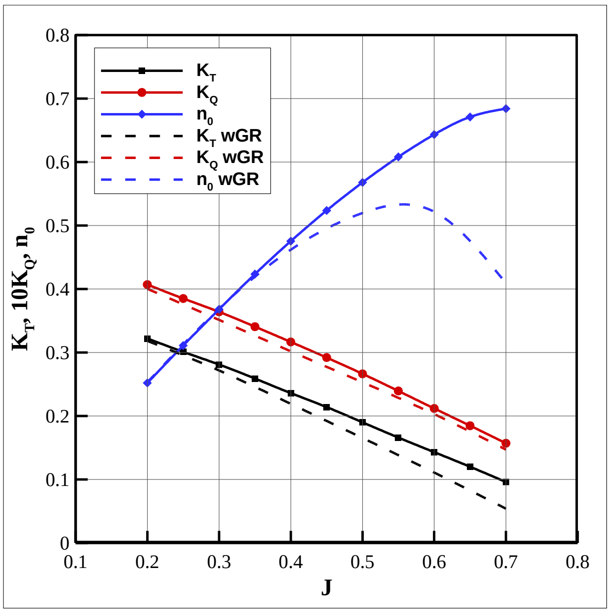

Figure 4. A comparison of the open water curves with the gate rudder and without gate rudder cases in model-scale.

3.3 Modified ITTC1978, Gate Rudder Assumed as an Appendage – - II

This approach, in general, uses ITTC1978 method, but does not convert the model wake fraction to full-scale, instead uses the below approach:

$$\frac{(1-w_S)}{(1-w_M)} = 1 \tag{11}$$

Based on the previous sea trial results of ships with GRS.

3.4 Modified ITTC1978, Gate Rudder Assumed as an Appendage – - III

This approach, in general, uses ITTC1978 method, but does not convert the model wake fraction to full-scale, instead uses the below approach:

$$\frac{(1-w_S)}{(1-w_M)} = 0.96 \tag{12}$$

4 RESULTS AND DISCUSSIONS

Depending on the low-speed model test data form factors as determined from the Prohaska's analysis are given in . The model scale resistance coefficients for the bare model is presented on both full loaded and ballast loaded conditions in Figure 5 and Figure 6, respectively.

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Table 3. Form factors

Loading Condition (Bare hull)	Form Factor (1+k)
Ballast Load	1.187
Full Load	1.185

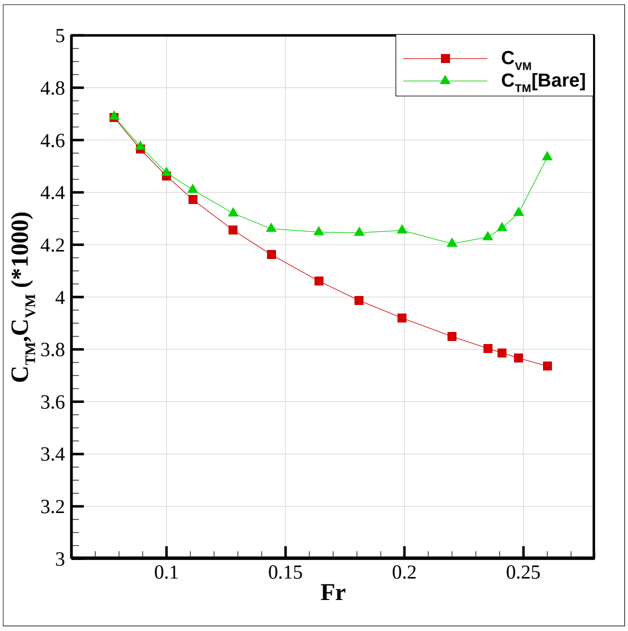

Figure 5. Model scale resistance coefficients for the ballast load.

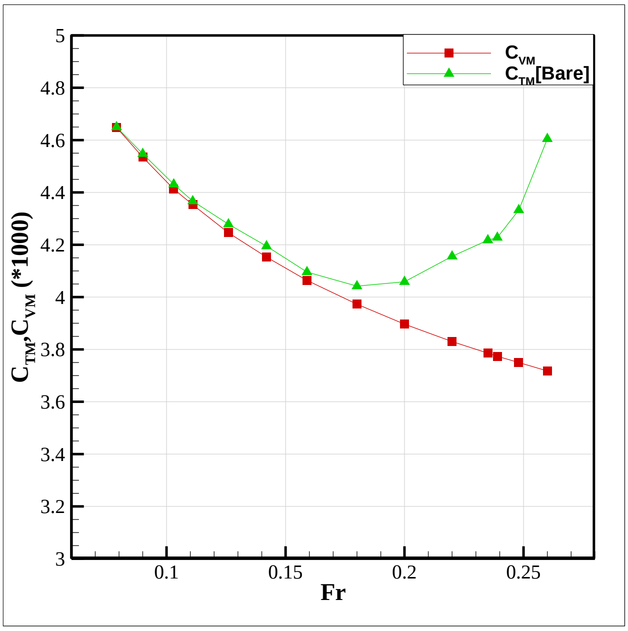

Figure 6. Model scale resistance coefficients for the full load.

The CRS powering calculations are carried out with respect to the 1978 ITTC Performance Prediction Method. Effective power and minimum break power were depicted in Figure 7 for the ballast loaded condition.

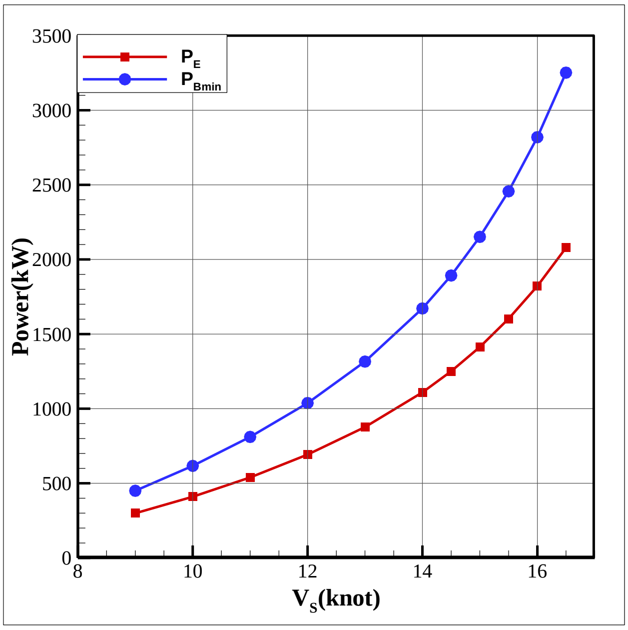

Figure 7. Power requirement plots of the ship with CRS for the ballast load draught.

The effective and break power results of GRS assumed as an appendage wth different wake corrections are shown with the sea trails in Figure 8 and Figure 9 for the ballast loaded condition.

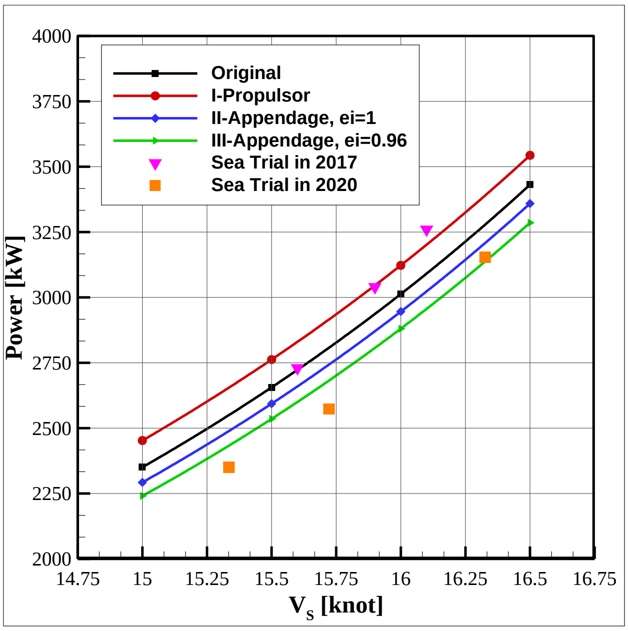

Figure 8. Comparison of the extrapolation methods with sea trial results at the ballast loading condition.

Break power predictions of GRS for the ballast loading have been analyzed regarding the corresponding extrapolation methods described in Section 3. Figure 8 shows comparisons of the prediction results and sea trial results. If the Gate Rudder assumed as a propulsor, the results show that this method overpredicted the sea trial results in 2020, but similar to the results in 2017. Once the original ITTC 1978 Method was applied, the results

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underpredicted the sea trails obtained in 2017 but overpredicted those of 2020. In the case of modified ITTC 1978-II and III cases, the predictions are in good agreement with the sea trial results in 2020. Based on this information all the comparisons of the GRS are based on the modified ITTC 1978-II.

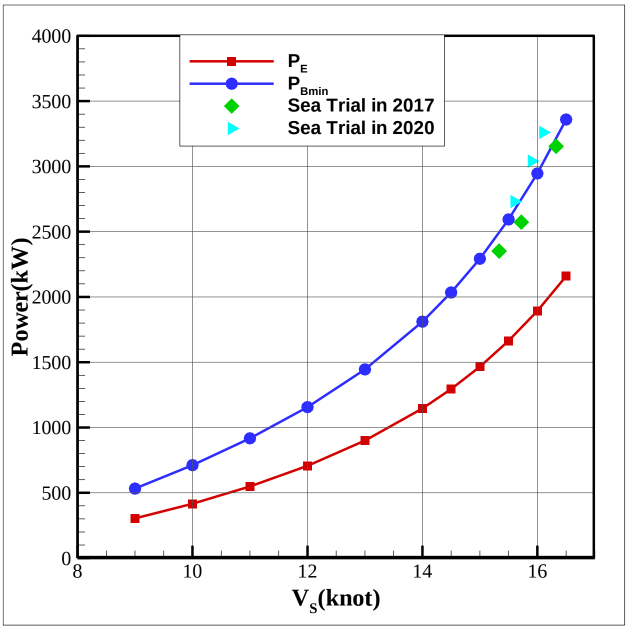

Figure 9. Power requirement plots of the ship with GRS and comparison of sea trial results for the ballast load draught.

Figure 10 and Figure 11 show the comparison between the CRS and GRS with for the full and ballast loading conditions.

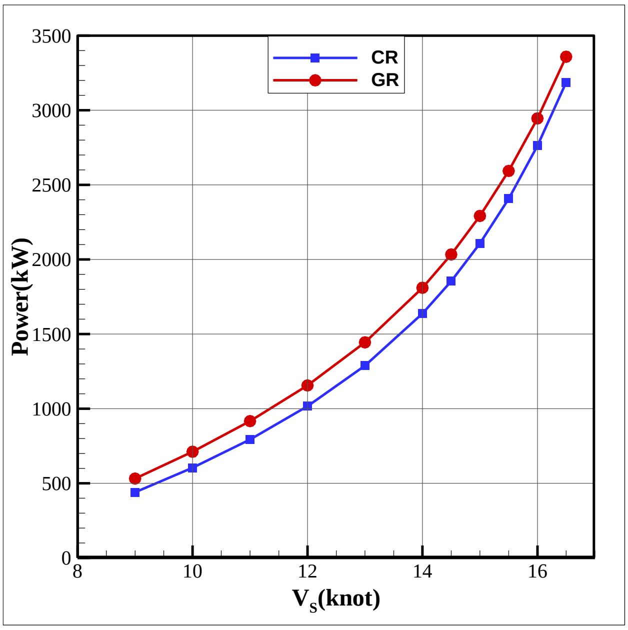

Figure 10. Comparisons of power requirements of the ship for the ballast load draught.

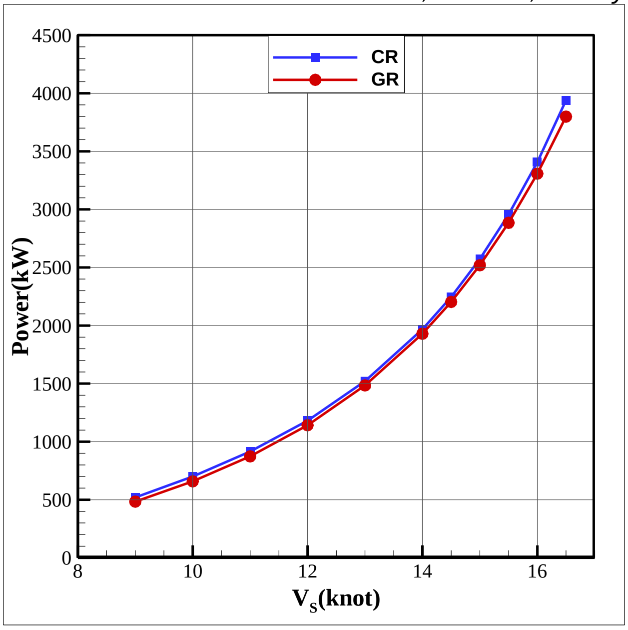

Figure 11. Comparisons of power requirements of the ship for the full load draught.

Results of the powering predictions show that GRS configuration is able to reduce the powering requirement by 2 % at the design speed as compared to CRS configuration in full loaded condition, but the powering requirement of GRS configuration appears to be increased by 6.5% as compared to CRS configuration in ballast condition.

5 CONCLUSIONS

Resistance and propulsion tests of two sisterships, SAKURA and SHIGENOBU of 2400 GT Containership were performed by aiming to investigate the differences, due to use of Conventional Rudder (CRS) and Gate Rudder (GRS) systems. The tests were carried out for two loading conditions, namely full loaded (T_{mid}=5.208 m) and ballast (T_{mid}=4.175 m) conditions. x- and y-component forces and turning moment on the CRS and GR are measured for full and ballast conditions in resistance tests as well. Extrapolations to full scale from model scale resistance data indicate that, although the resistances of the CRS and GRS cases are almost the same in full loaded condition, there is more than 2 % increase in the GRS resistance as compared to CRS resistance in ballast condition. Self-propulsion tests and powering predictions show that GRS configuration is able to reduce the powering requirement by 2 % at the design speed as compared to CRS configuration in full loaded condition, but the powering requirement of GRS configuration appears to be increased by 6.5% as compared to CRS configuration in ballast condition.

As a further study, the extrapolation methods will be evaluated considering the sea trials of the GATERS target ship, M/V ERGE.

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