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Research paper

Powering extrapolation approaches of ship model tests with the gate rudder system

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ABSTRACT

This study evaluates several approaches to extrapolate the model test-based powering results to the full-scale for two coastal ships with the Gate Rudder System (GRS) using their model test results and sea trials data. Ship model resistance and self-propulsion tests were conducted in the Ata Nutku Ship Model Testing Laboratory of Istanbul Technical University (ITU) for a 450 TEU and 2400 GT container ship (SHIGENOBU) and a 7241 DWT multi-purpose dry-cargo ship (M/V ERGE) both fitted with the GRS. The model test-based powering results were extrapolated by implementing three approaches, including the standard ITTC 1978 performance prediction method and its two variations. In the first variation (Method I), the GRS blades with the propeller were treated as a single propulsor unit, similar to the treatment of the ducted propulsors, due to the inherent similarities between the GRS blades and a typical accelerating duct. In contrast, the second variation (Method II) treated the GRS blades as the appendage, like a conventional rudder, but with a pragmatic approach for the full-scale wake correction based on the limited experience of ships with the GRS. The effectiveness of the three methods was evaluated based on the validations of the sea trials data for the two ships. While the evaluations clearly supported the appendage treatment of the GRS blades, Method II was the most favourable approach in spite of some overestimations of the sea trials data for both ships, hence requiring further investigations and full-scale data for ships with the GRS.

Nomenclature

A_E/A_0	Blade area ratio	P_D	Delivered power
B	Beta factor	P_E	Effective power
C_A	Correlation allowance	Q	Propeller torque
C_{AA}	Air resistance coefficient	R_e	Reynolds number
C_B	Block coefficient	S	Wetted surface area
C_F	Frictional resistance coefficient	T	Propeller thrust
C_R	Residual resistance coefficient	T_M	Draught at midship
C_T	Total resistance coefficient	t	Thrust deduction factor
D	Propeller diameter	V	Ship speed
F_D	Skin friction correction	β	Appendage scale effect factor
J	Propeller advance coefficient	w or w_T	Taylor wake fraction
K_Q	Propeller torque coefficient	ΔC_F	Roughness allowance
k_s	Roughness of hull surface	η_D	Propulsive efficiency
K_T	Propeller thrust coefficient	η_H	Hull efficiency
n	Propeller rate of revolution	η_O	Propeller open water efficiency
N_P	Number of propellers	η_R	Relative rotative efficiency
P/D	Pitch ratio	η_S	Shaft efficiency

1. Introduction

In recent years, both experimental and numerical studies have been conducted to investigate the effects of the Gate Rudder System (GRS) on various aspects of ship performances, including ship powering, sea-keeping, manoeuvrability, cavitation, and underwater radiated noise (URN). Many of these studies have focused explicitly on enhancing powering performance and achieving energy savings in ships. Turkmen et al. (2015) carried out a series of tests in the Emerson Cavitation

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Tunnel (ECT) and measured the forces on the GRS and the Conventional Rudder System (CRS) behind the ship. All of these measurements were conducted at the model scale, and the open water data for the propeller with the GRS were obtained from these tests. The measurements show that the GRS provides additional thrust with the increased rotational rate of the propeller, while the CRS causes additional resistance. Turkmen et al. (2015) found 4–8% higher thrust deduction in propulsion tests with the GRS compared to the CRS. Additionally, in a comparative analysis of open water data for a propeller with the GRS and a propeller with the CRS, a 15–25% higher wake fraction was obtained with the GRS. Turkmen et al. (2015) also investigated the effect of full-scale GRS on the aft flow field by CFD analysis and observed that when the GRS was placed closer to the propeller plane (at 1.25r/R compared to 1.5r/R), there was a 10% increase in thrust. Sasaki et al. (2016) conducted experimental and computational studies on the application of the GRS for a large bulk carrier. The forces on the GRS were measured, and it was shown that the GRS decreased the hull resistance. The study indicated that the GRS provides an energy saving of 7–8% and would refund the investment cost within 0.37–0.9 years. Köksal et al. (2022), Köksal et al. (2024a) examined the results of resistance, propulsion, and seakeeping experiments conducted for the H2020 GATERS project's target ship model, M/V ERGE, at the Kelvin Hydrodynamics Laboratory (KHL) of the University of Strathclyde. In the calm water resistance test results, the ship with the GRS reduced the hull resistance by 4% compared to the ship with the CRS. In the propulsion experiment, the GRS improved the performance by over 10%. Seakeeping tests were conducted in regular waves to simulate oblique wave conditions. A comparison of the powering performance of the vessel with the CRS and GRS in the oblique conditions revealed that torque was 20% less for the GRS than that in the model with the CRS configuration.

In addition to computational and numerical studies, full-scale sea trials have made a significant contribution to the investigations of the GRS. Sasaki et al. (2019) shared the sea trials data of two 2400 GT sister container ships, one equipped with the GRS for the first time (SHIGENOBU) and the other with the CRS (SAKURA), and examined the powering method from model scale to full-scale. These two vessels are true sisters in every aspect, including the engine sizes; the only differences are the rudder systems and the propellers. When the sea trials data were examined, the GRS presented a 14% reduction in fuel consumption compared to the CRS. Furthermore, it was seen that the utilisation of the GRS can lead to a performance improvement of up to 30% in rough seas. It was also stated that using the standard approach in the powering procedure would not give accurate results, specifically in the prediction of the effective wake fraction. Sasaki and Atlar (2018) conducted a comparative analysis of the propulsion characteristics (thrust deduction, wake fraction) of a ship with the GRS in comparison with a ship with the CRS by model tests, CFD studies, and sea trials of those sister ships. As a result of these investigations, it was demonstrated that the thrust deduction of the GRS was expected to be lower compared to the CRS, while the wake fraction was expected to be larger. Tacar et al. (2020) conducted experimental and numerical studies to investigate the effect on ship performance of a container ship with the GRS for trial and full load conditions. The experimental and numerical studies were carried out for models of two different scales, 2 m and 5 m, and the scale effect was examined. Tacar et al. (2020) demonstrated that as the speed of the vessel increased, the advantages of the GRS became more pronounced compared to the CRS at the trial conditions. Furthermore, they highlighted that at a service speed of 15 knots, the ship with the GRS consumes approximately 17% less brake power than one with the CRS. Concerning the scale effects, the authors found that the smaller model tends to overpredict the power requirement, whereas the larger model tends to underpredict when compared to the sea trials. Within the framework of the H2020 project GATERS, Çelik et al. (2023), Köksal et al. (2024b) analysed the results of three different sea trial data for the M/V ERGE to examine the accuracy of extrapolating model test results to full-scale, including the frictional resistance due to ageing and fouling for full-scale extrapolation and compared with the sea trials.

Optimisation studies for improving the powering performance of the GRS were presented in Gürkan et al. (2023a), Gürkan et al. (2023b), and Gürkan et al. (2023c). In addition to studies on performance and energy efficiency, there has also been a focus on investigating the effects of the GRS on manoeuvrability. Sasaki et al. (2017) developed a practical design tool that analyses the manoeuvring performance of a ship with the GRS considering the interaction between the rudder blades and the propeller. In the study, five different numerical prediction methods were applied to three ships with the model test results in hand. As a result, combining simple propeller theory with linearised vortex lattice theory was seen as the most effective method. Fukazawa et al. (2018) identified reduced sea margin requirements and improved speed-drop during manoeuvring in ports as two significant performance advantages of a ship equipped with GRS. They investigated the reasons for these advantages based on data collected not only from model tests but also from the operational data of the ship over seven months. When the data from the two ships were examined, it was observed that the ship equipped with GRS improved power performance by 15% compared to the ship with the CRS. Carchen et al. (2021) conducted the first known investigation to develop a practical numerical tool for predicting the manoeuvrability performance of a ship with the GRS. Within the scope of the study, a modified MMG (the Manoeuvring Modelling Group) was developed, and the validity of this model was demonstrated through detailed computational fluid dynamics (CFD) analyses, towing tank tests, and sea trials. Gürkan et al. (2023d) investigated the manoeuvring performance of a ship with the GRS using CFD, MMG, model tests, and full-scale sea trials data. According to their findings, GRS reduced the overshoot angles in zig-zag tests and improved the turning ability in terms of increased speed, response time, and lateral force generation while increasing the tactical and circle diameters.

Turkmen et al. (2018), Özsayan et al. (2023, 2024), Santic et al. (2023), Köksal et al. (2023a, 2023b), Köksal et al. (2023c) and Köksal et al. (2024c) conducted investigations into the effects of the GRS on cavitation and URN. New extrapolation methods were studied to extrapolate the investigations carried out for ships with the GRS at model scale to the full scale. Sasaki et al. (2020) investigated the impact of scale effect on the powering performance of the GRS, utilising data obtained from towing tank tests and full-scale sea trials. At the model scale, the flow around the GRS tends to be laminar due to low Reynolds numbers, resulting in a significant influence of scale effect on the drag and lift coefficients of the GRS blades. Çelik et al. (2022) extrapolated the model scale results for a container ship obtained from the towing tank tests to the full-scale, implementing different approaches. Comparing these extrapolated results with the sea trials, the method where the GRS was considered as an appendage showed better agreement with the sea trials in 2017. The powering predictions indicated that the GRS configuration could reduce the power requirement by 2% at the design speed compared to the CRS configuration under the full-load condition.

The extrapolation of ship model test results with energy-saving devices, such as a pre-swirl stator, ducted stator, wake equalising duct, and hull vane, introduces challenges beyond those addressed by the standard ITTC (2017b) procedure. These challenges arise due to the flow regimes in which the devices operate at model and full-scale. An adjustment to the extrapolation procedure can be applied while still adhering to ITTC guidelines to improve the accuracy. Chen et al. (2018) designed a pre-swirl stator as a retrofit for a bulk carrier and evaluated its effect using experimental and numerical methods. Unlike the standard ITTC wake correction formula, the effective wake at full scale was assumed to be the same as at model scale. Nicorelli et al. (2023) conducted a comprehensive study on the scale effect of a pre-swirl duct, pre-swirl fin, and wake equalising duct. In this study, three approaches were applied to correlate the effective wake between model and full-scale. The first approach utilised the ITTC 1978 (ITTC, 2017b) formula, while the second accounted for differences in the model scale effective wake with and without the energy-saving device. The third approach incorporated both tangential and axial components of the velocity field, as proposed by Kim et al. (2017). Çelik and Danışman (2023) analysed the powering performance of a semi-displacement ship retrofitted with a Hull Vane. Two methods were applied; one treated the Hull Vane as an integral part of the hull, while the other considered it an appendage.

The GRS is a novel propulsion and manoeuvring system that was relatively recently introduced to the maritime industry. As with any emerging technology, comprehensive research and full-scale data are essential to thoroughly understand its working principles as well as the extrapolation procedure for power predictions. As highlighted in the aforementioned critical review analysis, while the effect of the GRS has been investigated from the perspectives of the ship resistance, propulsion, manoeuvring, cavitation and URN, it is essential to establish a proper and reliable procedure for the full-scale powering extrapolation of ships with the GRS, supported by the full-scale data.

In order to address the gap regarding the powering extrapolation procedures and the lack of full-scale data of ships with the GRS, this paper investigated the two different extrapolation methods for the trial case powering prediction alongside the ITTC 1978 performance prediction method. For this investigation, two coastal commercial ships were used, including their full-scale trial data. Firstly, the model-scale propulsion tests were conducted for the newly built 450 TEU (2400 GT) container ship with the GRS (SHIGENOBU) at the Ata Nutku Ship Model Testing Laboratory. Then, the full-scale powering results were predicted by the proposed three extrapolation methods, which were compared with the sea trials data conducted in 2017 by Sasaki et al. (2018). Based on the favourable comparison of the three prediction methods with the sea trials, further evaluations of the two selected methods were performed for the second coastal ship, the 7241 DWT (90m) general cargo vessel (M/V ERGE). She was the target vessel of the H2020 GATERS project, GATERS (2021) and was retrofitted with the GRS in the project through comprehensive model tests and sea trials conducted in 2023. It is believed that the experimental investigation presented in this paper contributes to the state-of-the-art process of improving the earlier-mentioned gap regarding the power extrapolation of ships with the GRS and their validation with the full-scale data.

Therefore, following this introductory part, Section 2 of the paper describes the details of the towing tank tests, providing information on the two coastal ships and propeller properties, as well as the propulsion test procedures. The details of the three extrapolation methods are presented in Section 3. The powering extrapolation results of SHIGENOBU and their validations with the full-scale trial data are given in Section 4, which also includes the further evaluation and discussion of the most favourable extrapolation method in predicting the full-scale trial power of the target ship, M/V ERGE. Finally, further discussions and concluding remarks are given in Sections 5and 6, respectively.

2. Towing tank tests

2.1. Ship and propeller properties

The two ship models representing SHIGENOBU and M/V ERGE vessels (Fig. 1), made to scales (λ) of 1/21.75 and 1/23.7, respectively, were manufactured at the Ata Nutku Ship Model Testing Laboratory of Istanbul Technical University (GATERS, 2023). The main particulars of these vessels for the model and full scales are provided in Table 1. The GRS configurations for propulsion tests are shown in Fig. 2, illustrating the experimental setup (Fig. 2 b, d) for propulsion tests in the towing tank, including the rudder force measurement system (Fig. 2 a, c) details.

The face view and technical details of the right-handed stock propeller used for propulsion tests are shown in (Fig. 3) and Table 2, respectively.

2.2. Test procedure

The ship model tests were conducted in the Ata Nutku Ship Model Testing Laboratory towing tank at Istanbul Technical University. The towing tank has dimensions of 160 m in length, 6 m in width, and 3.4 m in depth, with a towing carriage capable of achieving speeds of up to 6 m/s. Resistance tests were initially performed using the bare hull and were subsequently repeated with the GRS-fitted hull without the propeller. Air resistance was accounted for in the extrapolation procedure. Propulsion tests were conducted in calm water, free to trim and sink but constrained in roll, sway, and yaw motions. Form factor analysis was carried out using Prohaska's method as part of the ITTC 1978-based extrapolation procedure. The load-varying method was applied to determine the propulsion point. In this method, multiple tests were conducted at the same ship model speed but with varying propeller loads. The measured variables for the hull included speed, resistance,

Table 1
Main particulars of ships.

Ship Name (Scale)		SHIGENOBU (1/21.75)		M/V ERGE (1/23.7)	
Characteristics	Symbol	Model	Ship	Model	Ship
Length overall	L_{OA} (m)	5.127	111.51	3.795	89.950
Length between perp.	L_{PP} (m)	4.685	101.90	3.584	84.950
Waterline length	L_{WL} (m)	4.808	104.57	3.578	84.790
Breadth	B_{WL} (m)	0.818	17.800	0.650	15.400
Draught (midship)	T_M (m)	0.192	4.1800	0.139	3.3000
Displacement volume	∇ (m^3)	0.470	4835.0	0.263	3497.6
Displacement	Δ (ton)	0.470	4955.9	0.263	3585.0
Wetted surface area	S (m^2)	4.167	1971.1	2.882	1618.9
Block coefficient	C_B	0.582	0.5820	0.806	0.8060

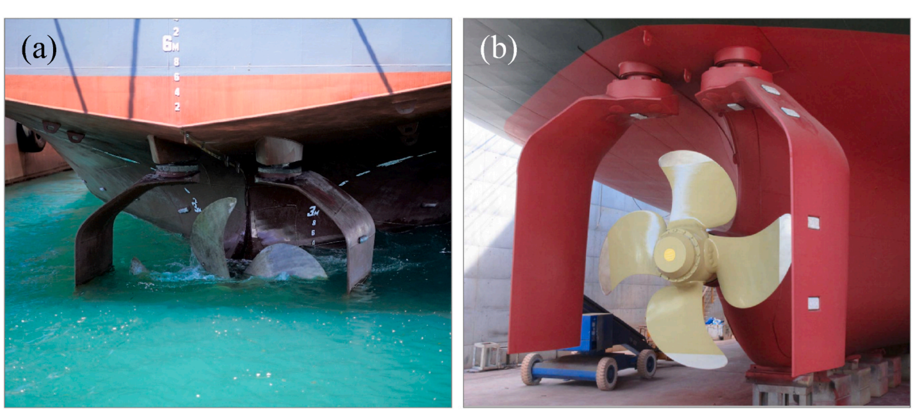

Fig. 1. (a) M/V ERGE (retrofitted) and (b) JCV, SHIGENOBU (newly built) with the GRS.

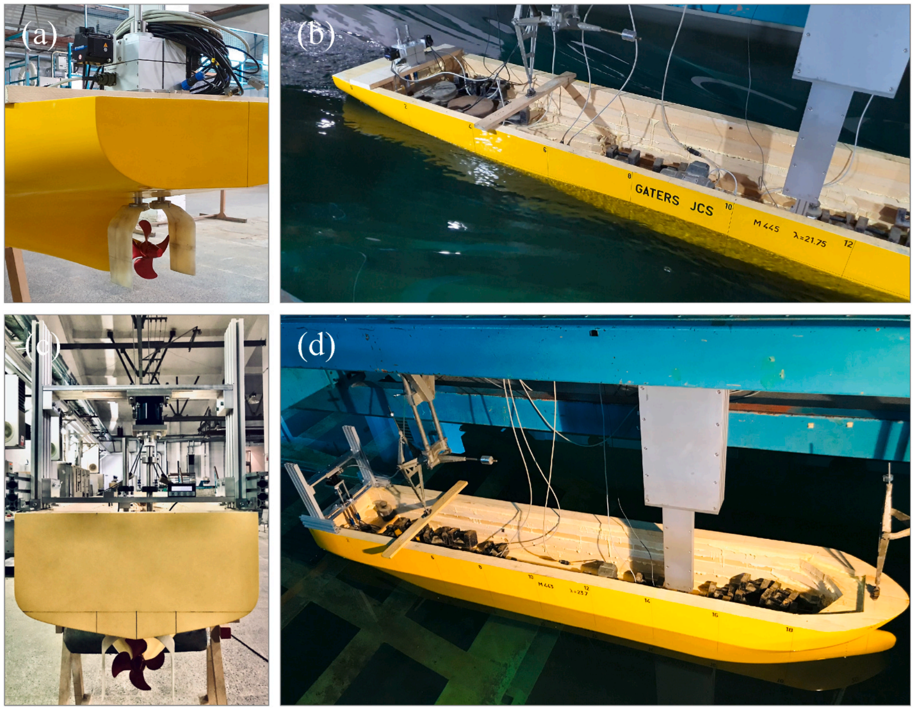

Fig. 2. Rudder force and torque measurement and self-propulsion test setup with GRS. (a) and (b) for SHIGENOBU; (c) and (d) for M/V ERGE.

Fig. 3. Model propeller used for propulsion tests.

Table 2
Stock propeller main particulars.

Parameters	Symbol	Value
Diameter	D	0.152 m
Chord length	$c_{0.7}$	0.050 m
Pitch ratio	$P_{0.7}/D$	0.835
Blade area ratio	A_E/A_0	0.512
Hub ratio	d_h/D	0.250
Number of blades	Z	4

trim, and sinkage, while those for the propeller included thrust, torque, and the propeller's rate of revolution.

In self-propulsion tests, it is imperative to introduce an additional towing force to ascertain the propulsion characteristics of the full-scale vessel precisely. This additional force, denoted as F_D and commonly referred to as the Skin Friction Correction (SFC), is implemented to compensate for the order difference in Reynolds numbers between the model and the full-scale ship for the correct self-propulsion point determination of the full-scale ship. The calculation for F_D is given in Eq. (1) by the procedure proposed by the ITTC Propulsion/Bollard Pull Test Committee (ITTC, 2017a).

$$F_D = \frac{1}{2}\rho_M S_M V_M{}^2[(1+k)(C_{FS} - C_{FM}) - \Delta C_F] \tag{1}$$

In the subsequent sections of the paper, subscripts *M* and *S* denote the model scale and full-scale ship, respectively. While C_F is the frictional resistance coefficient, ΔC_F denotes the roughness allowance. The terms ρ, S, and V are the density of the water, wetted surface area, and speed, respectively. The full-scale propeller's characteristics were obtained by analysing the model propeller's characteristics in open water, corrected for scale effect using the 1978 ITTC Performance Prediction Method Procedure (ITTC, 2017b). The load on the full-scale propeller is then derived from Eq. (2).

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

Using the K_T/J_S^2 as the input parameter, the full-scale advance coefficient J_{TS} and torque coefficient K_{QTS} are extracted from the full-scale propeller characteristics. The thrust deduction (t) and wake fraction (w_T) factors are defined in Section 3 in the context of the extrapolation procedure. Subsequently, additional performance metrics were calculated as described below.

Propeller rate of revolutions (n_S),

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

the thrust of the propeller (T_S),

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

torque of the propeller (Q_S),

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

delivered power (P_D),

$$P_D = 2\pi Q_S n_S \quad (6)$$

effective power (P_E),

$$P_E = C_{TS} \frac{1}{2} \rho_S V_S{}^3 S_S \quad (7)$$

propulsive efficiency (η_D),

$$\eta_D = \frac{P_E}{P_D} \quad (8)$$

minimum brake power (P_{Bmin}),

$$P_{Bmin} = \frac{P_D}{\eta_S} \quad (9)$$

Here, the shaft efficiency (η_S) was taken as 0.98 in all calculations.

3. Extrapolation approaches

The extrapolation analyses were carried out to include the proper effect of the GRS, adhering to the outlined standard ITTC 1978 procedure and its two variants. The analyses were designed to represent a methodologically sound approach to understanding the extrapolation process of the GRS, ensuring the reliability and validity of the results obtained. In the case of the extrapolation of the trial power based on the model tests with the GRS, in addition to the ITTC 1978 method, as stated earlier, two further performance prediction methods (Methods I and II), as the variants of the ITTC 1978, have been introduced. Method I treats the GRS as a propulsor, i.e., the propeller and the twin gate rudder blades are treated as a single propulsor unit (GRS), while Method II treats the twin gate rudder blades as an appendage. Fig. 4 illustrates these methods in a flow chart by highlighting the associated differences for each variant. The specific details of each method are explained in the following subsections.

3.1. ITTC 1978 Performance prediction method

Initially, the established standard ITTC 1978 procedure was described and applied using the model test data with the GRS. In this standard method, the GRS blades are treated as appendages, the same as the CRS configuration, to predict the full-scale performance of the ship with the GRS. The scale effect factor (1-β) accounts for the differences in

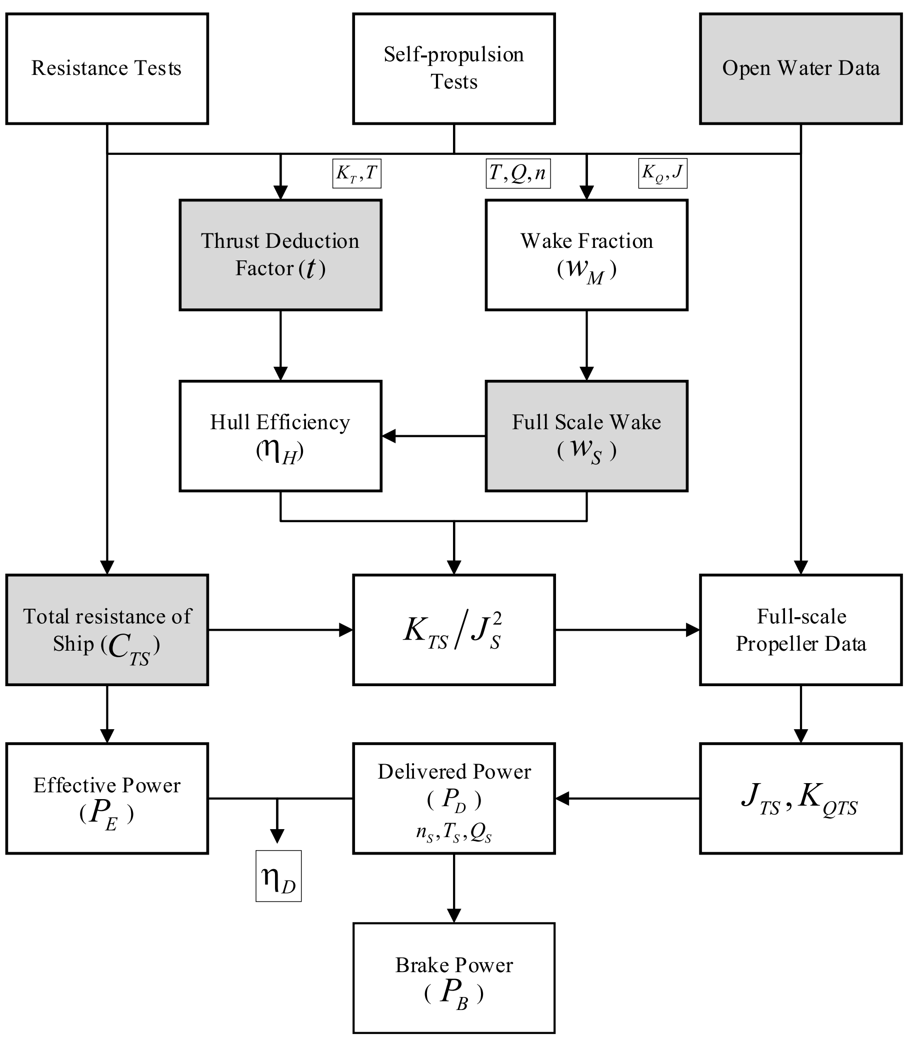

Fig. 4. The framework of powering extrapolations (grey boxes represent method-based variants).

the flow field between the model and the full-scale associated with the appendage resistance. This factor adjusts the resistance measured in model tests to more accurately represent the results on a full-scale by compensating for scale-related effects, such as Reynolds number variations, with the appendages. The factor is empirically derived and typically ranges between 0.6 and 1.0, with 0.70 being the value adopted in the Ata Nutku Ship Model Testing Laboratory. In the calculation of C_{TS}, the full-scale appendage resistance coefficient (C_{APPS}) is determined as $C_{APPS}=(1\text{-}\beta)C_{APPM}$.

In the powering calculations, the total resistance (R_{TM}) includes bare hull (R_{TBH}) and the GRS (R_{GR}) appendage resistances, respectively.

$$R_{TM} = R_{TBH} + R_{GR} \tag{10}$$

The thrust deduction is calculated as;

$$t = \frac{T_M + F_D - R_{TM}}{T_M} \tag{11}$$

where, T_M is the propeller's thrust at the self-propulsion loading.

The full-scale wake (w_{TS}) is calculated using the ITTC 1978 formula, following the acquisition of the thrust deduction and model wake fraction (w_{TM}) from the self-propulsion tests.

$$w_{TS} = (t + w_R) + (w_{TM} - t - w_R)\frac{(1+k)C_{FS} + \Delta C_F}{(1+k)C_{FM}} \tag{12}$$

As proposed in the ITTC 1978 (ITTC, 2017b) procedure, the effect of the rudder (w_R) on the wake fraction was taken as the standard value of 0.04 since no estimated value was available for w_R. The open water characteristics of the model propeller are directly utilised to determine the propulsion characteristics without accounting for the gate rudder blades' effects on the propeller thrust.

3.2. GRS treated as a propulsor - method I

Some similarities of the GRS with the ducted propellers, thrusters or azimuthing podded propulsors raises the question of whether the GRS (i.e., propeller and the GRS blades) can be treated as a single propulsor unit, as in the above mentioned three propulsor cases. Therefore, the earlier described ITTC 1978 is modified as in the following and named Method I:

In Eq. (10), R_{TM} is modified as the bare hull resistance only, i.e.:

$$R_{TM} = R_{TBH} \tag{13}$$

The axial forces on the GRS blades are included in the GRS as the propulsor unit. Therefore, the thrust deduction is calculated, including the GRS axial forces (T_{GRM}) by modifying Eq. (11) as in Eq. (14).

$$t = \frac{T_M + T_{GRM} + F_D - R_{TM}}{T_M + T_{GRM}} \tag{14}$$

The full-scale wake is calculated following the original ITTC 1978 formula in Eq. (12). Now, the open water data of the propeller cannot be directly applied in calculations, as the propeller with the GRS blades is assumed to operate as an integrated single propulsor unit. Consequently, Tacar et al. (2020) conducted CFD simulations to generate the open water data for the GRS of SHIGENOBU. This dataset was employed to define the self-propulsion characteristics in our study. Fig. 5 illustrates the comparison of the open water curves of the propeller in isolation (i.e., without the GRS blades) and as the GRS (i.e., including the twin gate rudder blades).

3.3. GRS treated as an appendage - method II

In Method II, the total resistance and thrust deduction factor were calculated using the ITTC 1978 formulations, as shown in Eq. (10) and Eq. (11), respectively, described in Section 3.1. There is no doubt that the twin rudders and their spatial distribution around the propeller of the GRS make the propeller-rudder-hull interaction phenomena more

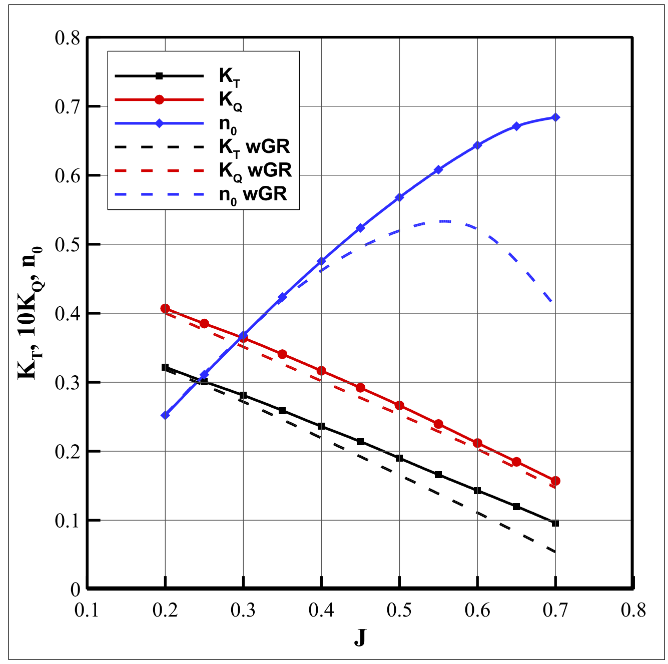

Fig. 5. Open water curves of the model propeller of SHIGENOBU with the gate rudder blades (e.g. K_T wGR) and without (e.g. K_T) (Tacar et al., 2020).

complex and challenging. Especially in the presence of a limited number of full-scale data available for ships with the GRS, as the scale effect may play an important role in the extrapolation procedures. Therefore, the full-scale wake formulation requires modification to account for the distinct nature of the propeller-twin rudders-hull interaction and the lack of related data due to the short service history of ships with the GRS. The leading computational and experimental investigations in the GATERS project (GATERS, 2024) and close collaborations with one of the GRS inventors, based on their experiences with limited full-scale sea trials in Japan, implied the following pragmatic approximation, which is the model and full-scale wake flow are the same.

$$w_{TM} \approx w_{TS} \tag{15}$$

In this method, the open water data of the model propeller without the GRS blades (i.e., the propeller in isolation) is used in the powering calculations.

3.4. Comparison of the methods

The effective power prediction was conducted using Eq. (7) as defined in Section 2. In the calculation of the total ship resistance coefficient C_{TS}, both the ITTC 1978 method and Method II treat the GRS blades as appendages. Therefore, in addition to considering the bare hull resistance, the calculation of C_{TS} incorporates forces acting on the GRS blades, which were extrapolated using the beta factor specified in Section 3.1. In contrast, Method I only considers the bare hull resistance in powering calculations by lumping the GRS' axial blade forces onto the propeller's thrust due to the unit propulsor assumption. These methods were compared with each other alongside full-scale sea trials in Section 4. Table 3 summarises the details of the three methods in a comparative manner.

4. Results and discussions

The effective power prediction of SHIGENOBU, using Eq. (7), illustrated in Fig. 6, shows that the P_E curve predicted by Method I is lower than that predicted by Method II.

The propulsive power calculations have been conducted following

Table 3
Comparison of the proposed extrapolation characteristics.

Methods	Effective Power Prediction	Delivered Power Prediction		
	Total Resistance	Thrust Deduction	Wake Fraction	Open Water
ITTC 1978	$R_{TM} = R_{TBH} + R_{GR}$	$t = \frac{T_M + F_D - R_{TM}}{T_M}$	ITTC Original	Propeller only
Method I - Propulsor	$R_{TM} = R_{TBH}$	$t = \frac{T_M + T_{GRM} + F_D - R_{TM}}{T_M + T_{GRM}}$	ITTC Original	Propeller with the GRS
Method II - Appendage	$R_{TM} = R_{TBH} + R_{GR}$	$t = \frac{T_M + F_D - R_{TM}}{T_M}$	$w_{TS} \approx w_{TM}$	Propeller only

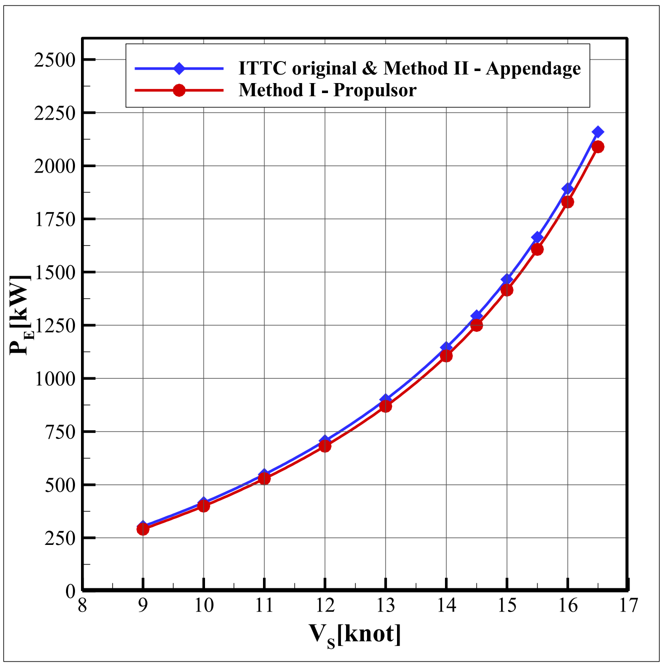

Fig. 6. Comparison of P_E predictions by Method I and Method II for SHIGENOBU.

the procedure outlined in Section 2.2, along with the extrapolation methods presented in Section 3. The thrust deduction, wake fraction, and the type of open water data have significant roles in defining the other self-propulsion characteristics, including η_H, η_R, η_D, P_D. In order to observe the variations in these characteristics, the results for SHIGENOBU at her service speed (15 knots) are graphically represented in Fig. 7 and listed in Table 4. In Fig. 7, the relative differences between Method I and Method II are presented with respect to the ITTC 1978 method, which serves as a baseline for the SHIGENOBU across the characteristics listed in Table 4. Each bar represents the percentage change, with red bars corresponding to Method I and blue bars to Method II. Positive values indicate that the method yields higher results than the ITTC 1978 method, while negative values represent lower results. Here, the η_H calculated by Method II (appendage treatment) exhibited a slight increase when compared to those determined by both the ITTC 1978 method and Method I (propulsor treatment), which resulted in improved η_D. The η_O of the GRS (in Method I) at the self-propulsion point was significantly lower than the η_O of the propeller's open water data (in Method II) for the same condition. The values of calculated propulsive efficiencies (η_D), from the highest to the lowest, are as follows: Method II, ITTC 1978, and Method I. In other words, the appendage treatment of the GRS blades presented higher propulsive efficiency, mainly due to the favourable propeller efficiency.

Finally, the predicted brake power results are shown in Fig. 8, over a ship speed range of 15–16.5 knots, along with the sea trials data conducted in 2017 (GATERS, 2024). The comparison of the predictions with the sea trials data indicates that while all three methods tend to overpredict the sea trial data, Method II is the closest to the trial data, and the ITTC 1978 original method is the second closest prediction. This suggests that treating the GRS blades as an appendage appears to be a more realistic approach than treating the GRS as a propulsor unit, which presented significant overprediction of the trial data.

Based on the SHIGENOBU experience, the powering predictions for M/V ERGE were performed only using ITTC 1978 and Method II, both of which treat the GRS blades as appendages. In order to observe the variations in these characteristics, the results for M/V ERGE at her service speed (12 knots) are shown in Fig. 9 as a chart and listed in Table 5. In Fig. 9, the relative differences of Method II are presented concerning the ITTC 1978 method, where P_E, t, and η_R are omitted, as these are assumed to be the same at both model and full scales in both approaches. The comparison of results for the M/V ERGE, as shown in Fig. 10, reveals a correlation with the findings of the SHIGENOBU. In both cases, all methods tend to overpredict the sea trial results, but the degree of discrepancy varies among them. Method II provides the closest predictions to the sea trials, indicating its consistency across different ship types. The ITTC 1978 original method ranks second in accuracy concerning the sea trials, demonstrating that its empirical basis remains relevant, though it shows more significant deviations compared to Method II. The consistency of these trends across both cases suggests that the observed patterns are not specific to a single vessel but reflect

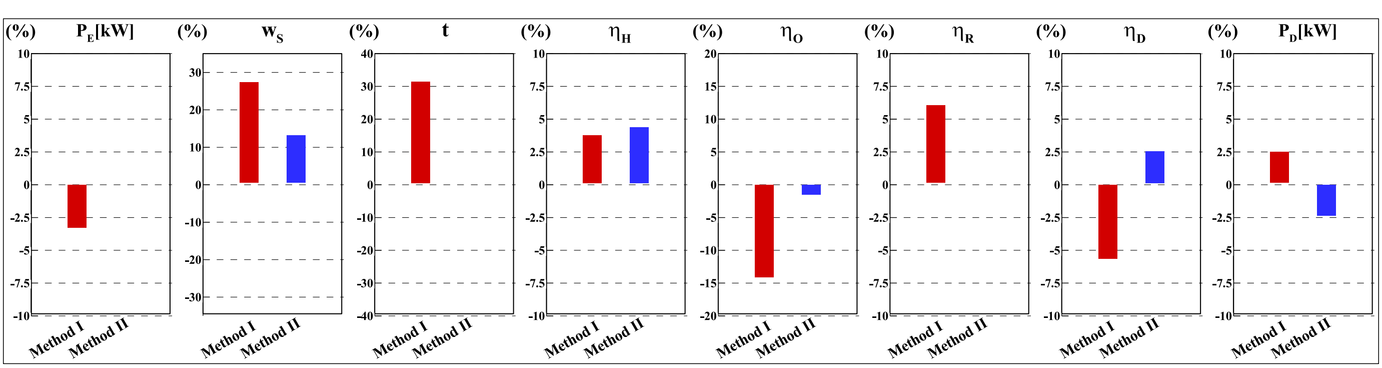

Fig. 7. Comparison of the methods relative to ITTC's original method for SHIGENOBU.

Table 4
Comparison of the self-propulsion characteristics for SHIGENOBU.

Method	V_s [kn]	C_{TS}	R_{TS} [kN]	P_E [kW]	w_S	t	η_H	η_O	η_R	η_D	P_D [kW]	P_{Bmin} [kW]
ITTC original	15	3.15E-03	189.92	1465.44	0.243	0.144	1.130	0.610	0.925	0.638	2297.03	2350.54
Method I	15	3.05E-03	183.43	1415.31	0.309	0.190	1.173	0.523	0.981	0.601	2354.39	2452.54
Method II	15	3.15E-03	189.92	1465.44	0.275	0.144	1.180	0.599	0.925	0.654	2240.01	2292.41

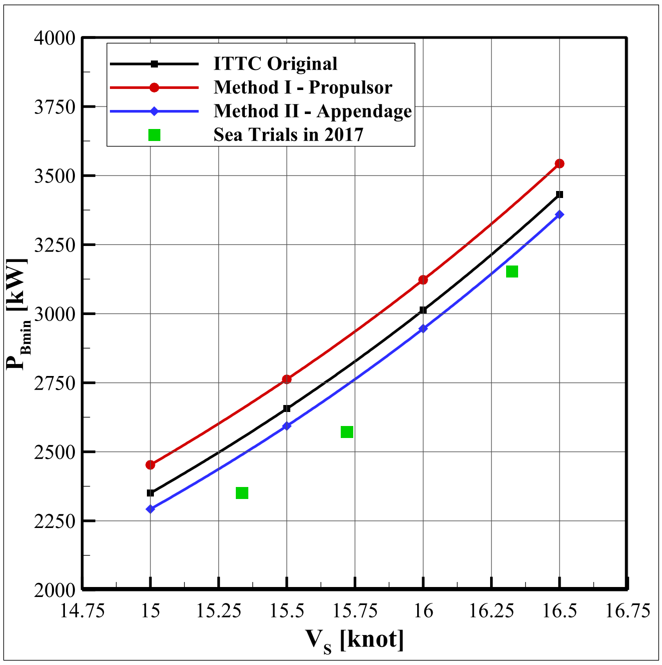

Fig. 8. Comparison of P_{Bmin} predictions by various extrapolation methods with sea trials for SHIGENOBU.

broader predictive tendencies in evaluating the GRS' performance. However, this finding further justified the treatment of the GRS blades as the appendages as well as the pragmatic wake assumption made in Method II based on the limited data and experiences with the vessels fitted with the GRS. However, there is still some gap to close for further accurate power predictions of ships with the GRS, as well as the need for more full-scale data for ships with the GRS.

5. Further discussion on the propeller-hull-rudder interaction with the GRS

In the introductory section, we mentioned some resemblance between the working principles of the GRS and accelerating ducted propulsor due to the accelerating and thrust-generating ability of the rudder blades (Turkmen et al., 2015). However, there are also significant differences between the geometry of the two propulsion systems in terms of the massive clearances between the gate rudder blades and the propeller, the removed bottom parts of the rudders, etc.

Although the duct is an appendage to a ship hull, because of its close integration with the propeller as a compact unit, a classical ducted propeller has been categorised as a "propulsor" by many naval architects for a long time. This is opposed to a conventional rudder and propeller system (CRS) where the rudder is considered an 'appendage'. Considering the GRS is a mid-way arrangement between the classical ducted propeller and CRS, in this paper, we decided to extrapolate the model test results of the GRS by treating it both as a 'propulsor' and 'appendage' and to compare the results (GATERS, 2023; Çelik et al., 2022).

Having conducted the analysis in Section 3, one can notice the difference in thrust deduction fraction between the propulsor treatment (Method I) and the appendage treatment (ITTC 1978; Method II) approaches. The former approach yields a higher fraction and hence drag

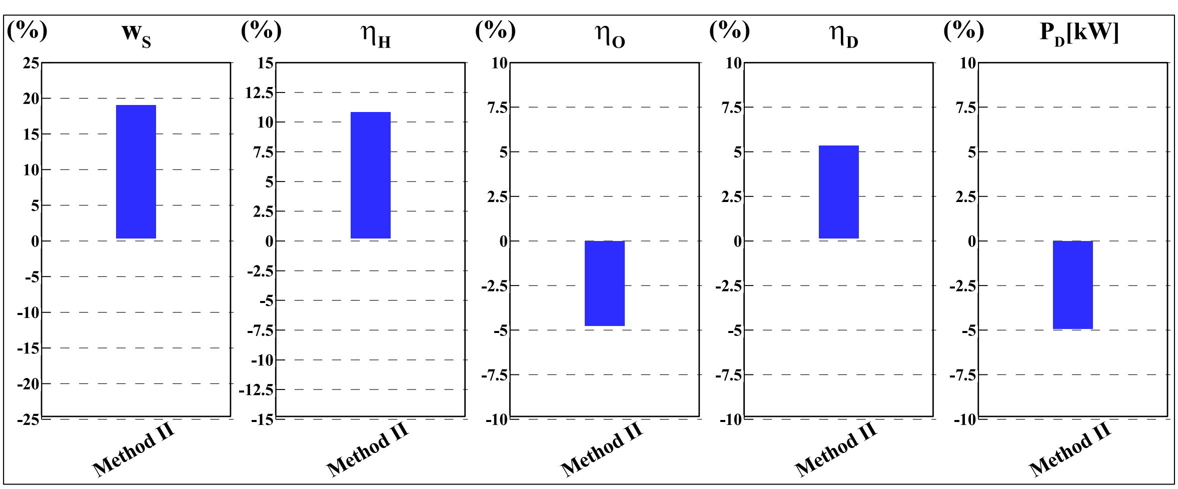

Fig. 9. Relative difference of Method II compared to ITTC original method for M/V ERGE.

Table 5
Comparison of the self-propulsion characteristics for M/V ERGE.

Method	V_s [kn]	C_{TS}	R_{TS} [kN]	P_E [kW]	w_S	t	η_H	η_O	η_R	η_D	P_D [kW]	P_{Bmin} [kW]
ITTC original	12	4.48E-03	139.63	861.94	0.340	0.156	1.279	0.573	0.958	0.702	1228.26	1261.96
Method II	12	4.45E-03	139.63	861.94	0.405	0.157	1.417	0.545	0.958	0.739	1165.90	1190.34

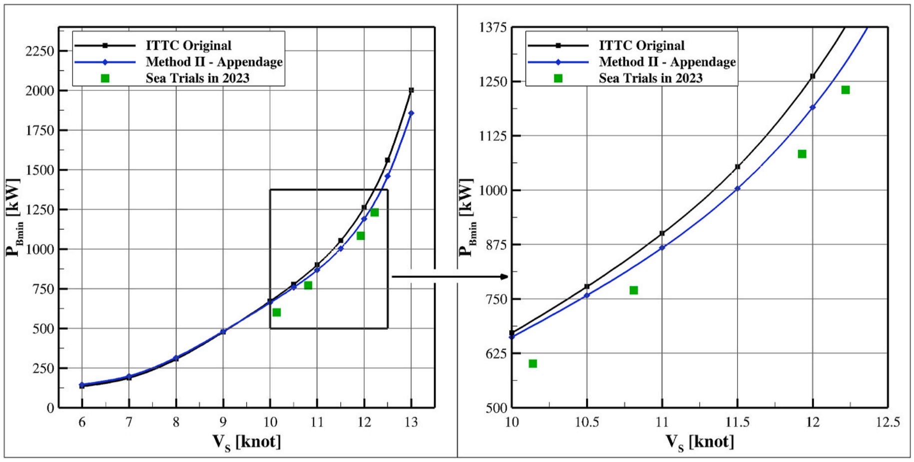

Fig. 10. Comparison of P_{Bmin} predictions by proposed extrapolation methods with sea trials M/V ERGE.

penalty than the latter one. Similarly, the wake fraction analysis also presented a difference, as the propulsor-based wake fraction prediction was larger than the appendage-based one. However, the scaling issue in the wake analysis is important and using the standard conventional rudder scaling method cannot be justified, although we have used the ITTC 1978 method as the reference. However, in Method II, which is appendage-based, we had to modify it by assuming that the wake fraction for the model and full-scale are the same. This was based on the verification and validation of the model and full-scale data analyses in the GATERS project and private communications with the gate rudder inventors based on the full-scale data available on the four recent coastal vessels built in Japan (GATERS, 2023; Köksal et al., 2024b). In fact, the correction of the wake parameter with the GRS is not straightforward since the wake field, where the propeller operates, is affected by the gate rudder blades, partially surrounding the propeller. This, in turn, affects the propeller inflow and, thus, the effective wake parameter. The additional component on the model wake, which the gate rudder blades contribute, is not considered in the CRS wake scaling procedures; thus, the use of conventional rudder-based correction methods may be misleading (Sasaki et al., 2019). In order to establish an appropriate wake scaling for the GRS applications, further research is required, involving dedicated wake flow analysis using PIV/LDA-based measurements supported by the CFD in the model and full-scale, as well as the full-scale data to validate the analyses. On the other hand, there is also a difference between the relative-rotative efficiency terms predicted by the appendage and propulsor-based approaches, as the former is smaller than the latter. Again, the challenge here is the uncertainty associated with the flow regime around the gate rudder blades in the model scale; while the conventional rudder operates in the turbulent propeller slipstream, this is not the case for the gate rudder blades which can operate in the laminar regime which can suffer from the laminar flow separation in model scale, hence bringing further uncertainty, especially at slower speeds.

6. Conclusions

This study presented an experimental investigation to bridge the gap in the literature regarding the full-scale powering extrapolation of ships, which can be purpose-built or retrofitted with the GRS, including the sea trials data. Therefore, the model scale propulsion tests of two coastal vessels, a purpose-built container ship (SHIGENOBU) with the GRS and an existing dry-cargo ship (M/VERGE) retrofitted with the GRS, were conducted. The test results were extrapolated to full-scale for the trial power predictions of these ships using the ITTC 1978 and its two variations of extrapolation methods (i.e., Method I and Method II) that were proposed in this investigation. Subsequently, the prediction results were compared with the results of the sea trials conducted with SHIGENOBU in 2017 and M/V ERGE in 2023.

While the above discussions highlight the complexities and current issues with the propeller-rudder-hull interaction with the GRS, one may think that the propulsor-based approach may be preferred. However, this will require open water tests in the presence of the gate rudder blades, which may suffer from significant error due to flow separation on the propeller blades in model tests, Bulten and Stoltenkamp (2017), especially at low speeds. Also, the treatment of surface-piercing rudder stocks and related flow disturbances in the open water tests is difficult. On the counter-argument, the appendage-based approach may be preferred to build on the experience with the current analysis procedures (e.g., ITTC 1978) with careful handling of the scale effects based on the full-scale validations as followed in this investigation by the time being.

Based on the investigation presented in the paper, the following conclusions can be drawn.

- The main difference between Method I and Method II lies in the treatment of the GRS. Method I considers the GRS as a propulsor unit, integrating the rudder blades with the propeller, whereas Method II treats the GRS blades as appendages. In Method II, the model-scale wake fraction is assumed to represent the full-scale wake fraction, a pragmatic approach justified by the limited availability of full-scale data for ships equipped with the GRS.
- The comparative analysis showed that treating the GRS as a propulsor unit in Method I led to overpredictions compared to the sea trials. In contrast, Method II provided less discrepancy with the sea trials. The ITTC 1978 method also yielded reasonable predictions but with further overpredictions compared to Method II. These findings further support treating the GRS blades as appendages rather than as an integral part of the propulsion unit.
- The complexities associated with propeller-hull-rudder interaction in the GRS remain challenging, especially due to scale effects and the limited availability of full-scale data. This study highlights that the appendage-based treatment (Method II) appears more practical given the existing data. However, further research is required, including advanced CFD analyses, wake flow measurements, and additional full-scale validations, to propose a modified approach not only for the wake fraction but also for thrust deduction and skin friction correction, thereby refining the extrapolation procedure and improving accuracy.

CRediT authorship contribution statement

Cihad Çelik: Writing – original draft, Validation, Methodology, Formal analysis, Conceptualization. **Selahattin Özsayan:** Writing – original draft, Validation, Methodology, Investigation, Formal analysis. **Çağatay Sabri Köksal:** Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Devrim Bülent Danışman:** Writing – review & editing, Validation, Formal analysis. **Mehmet Atlar:** Writing – review & editing, Project administration, Funding acquisition. **Emin Korkut:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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