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Experimental Powering Performance Analysis of M/V ERGE in Calm Water and Waves

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Abstract: The study is on the details and results of the resistance, propulsion and seakeeping (at a yaw angle) tests conducted with a scaled model of the GATERS target ship (M/V ERGE) made to a scale of 1/27.1. The comparative tests are conducted at the trial (ballast) loading condition of the ship appended with the conventional rudder system (CRS) and the Gate Rudder System (GRS) both in the calm water and waves at the Kelvin Hydrodynamics Laboratory's towing tank of the University of Strathclyde (UoS). The main objective of these tests is to contribute toward the establishment of the best procedure to estimate the powering prediction of a ship retrofitted with a GRS in calm water and waves using experimental methods. The resistance and propulsion tests were conducted in calm water to establish the accurate performance prediction methodologies for the prediction of Gate Rudder performance using traditional model test techniques. Furthermore, seakeeping tests at a yaw angle were conducted to evaluate the effect of waves on the comparative powering performance of the hull with the GRS and CRS to simulate the in-service operations of commercial ships at sea. These tests are conducted in regular waves and the hull at a yaw angle (to simulate an oblique wave condition) with a significant wave height of 1.25 m in full scale (corresponding to Beaufort 4) for a range of different wavelengths.

Keywords: Gate Rudder System (GRS); Resistance, Propulsion and Seakeeping Tests.

1 INTRODUCTION

As part of the EU H2020 Project GATERS activities (The EC - H2020 Project "GATERS": GATE Rudder System as a Retrofit for the Next Generation Propulsion and Steering of Ships. (Project ID: 860337), 2021), this experimental investigation presents the details and results of the resistance, propulsion and seakeeping (at a yaw angle) tests conducted with a scaled model of the GATERS target ship (M/V ERGE, (a 90m and 7421 DWT general cargo vessel) made to a scale of 1/27.1 (LPP = 3.9m). The comparative tests are conducted at the trial (ballast) loading condition of the ship (3585 DWT) appended with the conventional rudder system (CRS) and the Gate Rudder System (GRS) both in the calm water and waves at the Kelvin Hydrodynamics Laboratory (KHL)'s towing tank of the University of Strathclyde.

The main objective of these tests is to contribute to the establishment of the best procedure to estimate the powering prediction of a ship retrofitted with a GRS in calm water and waves using experimental methods within the activities of T1.3 of WP1 of the GATERS project.

In achieving the objectives of the experimental investigations, the paper presents the experimental facility and equipment in Section 2. The information on the model preparations, experimental setup, and test matrix is given in Section 3. While Section 4 presents the results and their discussions regarding the resistance, propulsions and seakeeping (at a yaw angle) tests, Section 5 draws some concluding remarks from these investigations.

2 EXPERIMENTAL FACILITIES

2.1 Kelvin Hydrodynamics Laboratory Towing Tank

Experiments were carried out in the towing tank of KHL of the University of Strathclyde, as shown in Figure 1, which has the following specifications and features;

- Tank dimensions ($L \times W \times D$): 76×4.6×2.5 (m)
- Carriage: Driven along rails by a computer-controlled (digital) DC motor (Max speed 5 m/s).
- Wave-Maker: Variable water depth and computer-controlled four-flap absorbing wave-maker. Capable of generating regular and irregular waves of up to approximately 0.5 m.
- Beach: At the opposite end of the wave-maker, there is a beach for absorbing the waves and reducing wave reflections.

Figure 1 Kelvin Hydrodynamics Laboratory Towing Tank Carriage.

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2.2 Rudder Load Measurement System

A dedicated rudder load measurement system was specifically designed and tailor-made for the target vessel model to accurately measure forces and moments acting on both CRS and GRS. The load cells can measure the horizontal (yawing) moment (or torque) and longitudinal (surge) and horizontal (side) forces acting on the rudder blade to enable an accurate interpretation of the cause of the potential savings provided by the GRS (Figure 2).

Figure 2 Rudder load measurement system.

2.3 Propeller load measurement System

The self-propulsion dynamometer for the system was also commissioned with the remaining parts of the system. The specially designed dynamometer has 250N thrust and 10Nm torque measurement range with up to 150% permitted overload. Self-propulsion dynamometer also has driving motor and shafting system that has a speed range up to 3000RPM at 1.5kW rated power.

3 EXPERIMENTAL SETUP & TEST MATRIX

3.1 Component Specification and Manufacture

The ship and propeller models were designed and manufactured following ITTC (2017) recommended guidelines. The scale factor of 21.7 was chosen to prevent blockage effects and consider the capacity of towing tank carriage, following ITTC (2011a). The ship model incorporated an interchangeable stern part (encircled on the model picture as shown in Figure 3) that enabled interchanging the CRS and GRS aft end configurations.

A single model propeller with parameters shown in Table 1 was used for both conventional and gate rudder tests. The model propeller was scaled from the newly designed propeller for M/V ERGE, which will be installed as part of the GRS retrofit on this vessel. The diameter of the model propeller is 165.9 mm (ITTC, 2011b). The model was manufactured from brass with a manufacturing tolerance of ±0.027 mm under a scale factor of 21.7 following ITTC guidelines (ITTC, 2017). In addition, the propeller open water characteristics were measured to be used for the self-propulsion analysis.

Figure 3 Appended model used for the tests.

Table 1 Gate rudder propeller parameters and characteristics.

Parameters	Index
Number of Blades	5
BAR (A_E/A_0)	0.4551
Diameter, D (m)	0.1659
Pitch Ratio ($P_{0.7}/D$)	0.83
Material	Brass
Direction	Left-Handed

3.2 Test Conditions

The model tests were carried out corresponding to the ballast (trials) load condition of MV ERGE (T_{MEAN}=3.3 m) due to weight limitations of the Kelvin Hydrodynamics Laboratory towing tank carriage. The corresponding ship and model characteristics for the ballast load condition are provided in Table 2.

Table 2 Model and ship characteristics for the ballast loading condition.

Parameters	Units	Model	Ship
L_{OA}	(m)	4.145	89.95
L_{BP}	(m)	3.915	84.95
B	(m)	0.710	15.4
T	(m)	0.152	3.30
T_A	(m)	0.175	3.80
T_F	(m)	0.129	2.80
Δ	(ton)	0.363	3585
C_B	(-)	0.806	0.806
C_P	(-)	0.823	0.823
C_M	(-)	0.994	0.994
C_{WP}	(-)	0.854	0.854

3.3 Test Matrix

The test matrix in the ballast (trials) load condition for the resistance and the self-propulsion tests is given in Table 3.

Table 2 Resistance and self-propulsion test matrix.

Test Type	Condition	V_S (knot)
Resistance	Bare Hull	7-13
Resistance	CRS	7-13
Resistance	GRS	7-13
Propulsion	CRS	11-13
Propulsion	GRS	11-13

The seakeeping tests were conducted with the ship model oriented in the towing carriage at a mean yaw angle of 5° oblique to the regular head waves for a range of different periods corresponding to Beaufort 4, as shown in Table 4.

Table 4 Seakeeping test matrix.

V_S (knot)	H_S	T_S	λ/L_{WL}
10	1.25	4.316	0.33 (BF4)
10	1.25	5.273	0.50
10	1.25	6.458	0.75
10	1.25	7.457	1.00

4 RESULTS AND DISCUSSIONS

4.1 Resistance Tests

The resistance tests were conducted in the ballast (trial) load condition without rudder (s) for the CRS and GRS configurations. The ship model was free to trim and sinkage whilst she was fixed to heel, sway and yaw motions. Form factor analysis and the extrapolation of the model test results to the full scale were carried out by Prohaska and the ITTC'78 methods, respectively (ITTC, 2011b). The effect of the appendages was calculated using the beta factor (β=0.70). The CRS and GRS were considered appendages and extrapolated to the full scale accordingly.

The comparison of the full-scale effective power predictions for the CRS and GRS configurations is shown in Figure 4. As one can notice, there is a 4.3% effective power reduction at ~13 knots for the hull with the GRS.

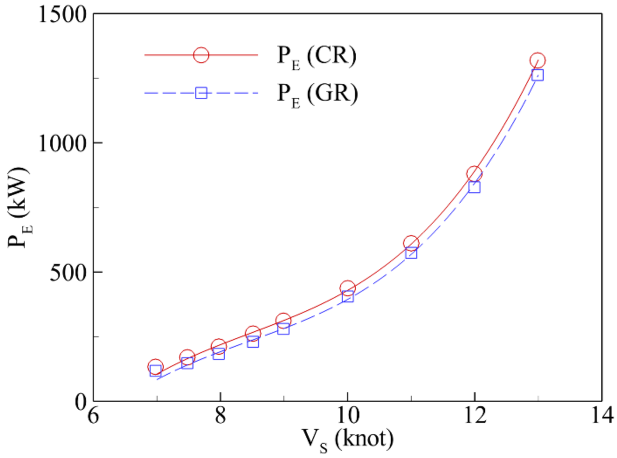

Figure 4 Comparison of the effective power results for conventional rudder (CR) and gate rudder (GR) configurations.

4.2 Propulsion Tests and Powering Calculations

The self-propulsion test results obtained in the ballast load condition for the hull with the CRS (rudder amidship) and the GRS rudder angles at 0° configuration are given in Table 5 and Table 6, respectively. During the self-propulsion tests, an additional towing force should be applied to consider the frictional drag correction for the full-scale ship propulsion point. This external force F_D also called the Skin Friction Correction (SFC) takes into account the Reynolds effect of the model test and ship trial conditions. Therefore, F_D can be calculated according to (ITTC, 2011b) Procedure.

Table 5 Power requirement of the ship with CRS.

V_S (knot)	10.996	11.990	12.987
P_E (kW)	608.887	875.599	1313.476
ω_{TS}	0.377	0.387	0.43
t	0.193	0.204	0.259
η_H	1.294	1.298	1.299
η_0	0.514	0.521	0.527
η_R	0.904	0.875	0.807
η_D	0.601	0.592	0.552
P_D (kW)	1013.252	1480.026	2378.349

Table 6 Power requirement of the ship with GRS (0°).

V_S (knot)	10.997	11.99	12.986
P_E (kW)	573.817	830.413	1263.687
ω_{TS}	0.279	0.275	0.273
t	0.134	0.119	0.167
η_H	1.201	1.215	1.145
η_0	0.475	0.483	0.505
η_R	1.222	1.23	1.152
η_D	0.697	0.721	0.666
P_D (kW)	823.424	1151.682	1897.064

In order to analyse the self-propulsion test results and predict the delivered power in the full-scale for the ship with the CRS and GRS, the ITTC 1978 Performance prediction method is used with a slight modification to the full-scale wake correction for the GRS, which is described in the following.

The characteristics of the full-scale propeller are calculated from the model propeller characteristics in open water, which are corrected for the scale effect according to the 1978 ITTC (2011c). The model wake fraction is converted to the full-scale wake fraction, as in the procedure for the CRS. However, for the GRS, the wake fraction of the model and ship is assumed to be the same (i.e. $1-\omega_M = 1-\omega_S$) based on the recent experience with the limited number of ships with the GRS. The comparison of the delivered power predictions for the CRS (rudder amidship) and the GRS at 0° configurations are presented in Figure 5. As shown in this figure, the GRS results in an approximate 20% saving in the delivered power compared to the CRS.

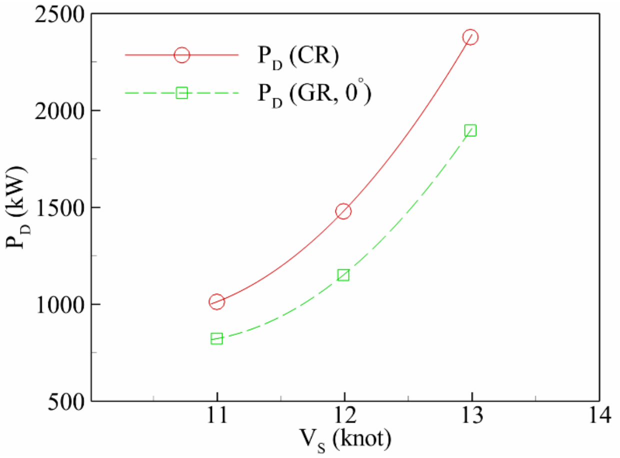

Figure 5 Comparison of the delivered power results for conventional rudder and gate rudder configurations.

4.3 Seakeeping Test (Powering in Waves) at a Yaw Angle

Upon completion of the resistance and self-propulsion tests in calm water, the ship model towing point attachment was modified to allow for the yaw and roll motions, in addition to the heave and pitch. Following the modification, a series of seakeeping tests was conducted in regular waves at the propeller shaft speeds, n_{CRS} and n_{GRS}, corresponding to the self-propulsion points of the CRS and GRS configurations, respectively.

In order to avoid excessive yaw angles that may cause damage to the load cell, the rudder angle of both rudder systems (δ_{Rudder}) was measured at a critical regular wave condition (i.e. λ/L_{WL}=1.00) for varying GRS, and CRS rudder angles to achieve a 5° of mean yaw angle with the model hull (i.e. 5° oblique to the incoming waves). A steady 5° yaw angle of the hull was achieved when the CRS' rudder angle was 1.25°, while the GRS' rudder angles (both Port and STB) were at 5°, as shown in Figure 6.

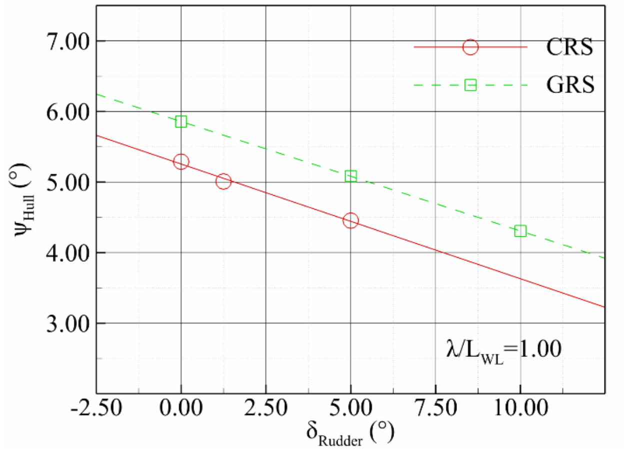

Figure 6 Rudder angles of CRS, GRS versus hull yaw angles at (λ/L_{WL}=1.00).

As shown in Figure 7, the mean yaw angle of the ship model was found to follow a similar pattern in each wave condition tested (i.e. λ/L_{WL}=0.33, 0.50, 0.75, 1.00) to remain around a steady 5° yaw angle of the hull for both the CRS and GRS configurations.

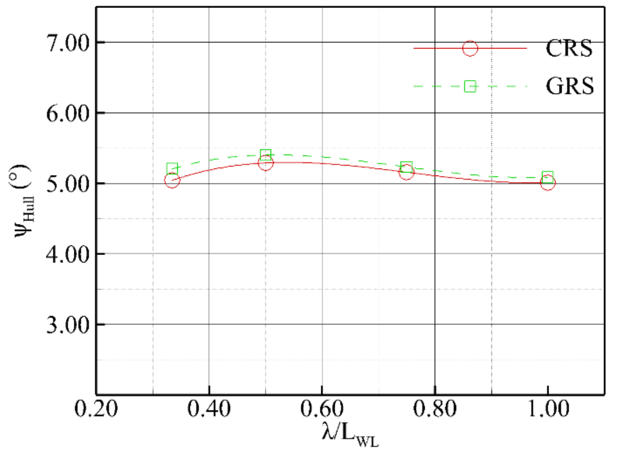

Figure 7 Yaw angle variations of the hull (Ψ_{Hull}) with the CRS and GRS configurations in different wave conditions tested.

In order to present the propulsion test results in waves relative to the results in calm water, the following non-dimensional coefficients are used for the ship model's performance (both with the CRS and GRS as appropriate):

$$C_1 = F\Big/\left(0.5\times\rho\times S_M\times V_M^2\right),\ \ F = F_R + T \qquad (1)$$

$$C_2 = D_R\Big/\left(0.5\times\rho\times S_M\times V_M^2\right) \qquad (2)$$

$$\Delta C_{1,2} = \left[\left(C_{1,2_{WAVES}} - C_{1,2_{CALM}}\right)\Big/C_{1,2_{CALM}}\right]\times 100 \qquad (3)$$

$$\Delta K_{T,Q} = \left[\left(K_{T,Q_{WAVES}} - K_{T,Q_{CALM}}\right)\Big/K_{T,Q_{CALM}}\right]\times 100 \qquad (4)$$

In Eq. 1 and Eq. 2, F_R (resultant force) is measured force on towing load cell during the tests, T is propeller thrust, D_R is rudder drag, ρ is density, S_M is model wetted surface area and V_M is model speed. In Eq. 3 and Eq. 4, K_T is thrust coefficient, and K_Q is torque coefficient, whilst subscript *WAVES* and *CALM* denote the results in waves and calm water, respectively. As one can see in Figure 8, the difference in the total force measured on the hull model in waves (ΔC_1) is almost similar with both rudder systems in each wave condition tested (i.e., λ/L_{WL}=0.33, 0.50, 0.75, 1.00). However, the relative thrust and torque variations in waves and hence the loading on the propeller with the GRS are relatively lower, as shown in Figure 9 and Figure 10, for the relative thrust and torque, respectively.

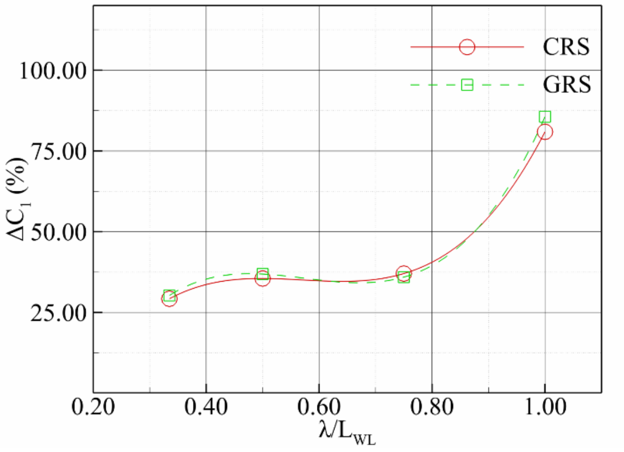

Figure 8 The force coefficient difference (self-propulsion tests in waves) of CRS and GRS.

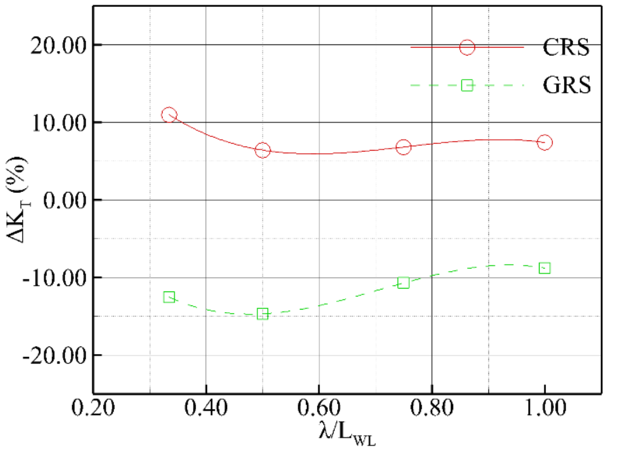

Figure 9 The thrust coefficient difference (self-propulsion in waves) of CRS and GRS.

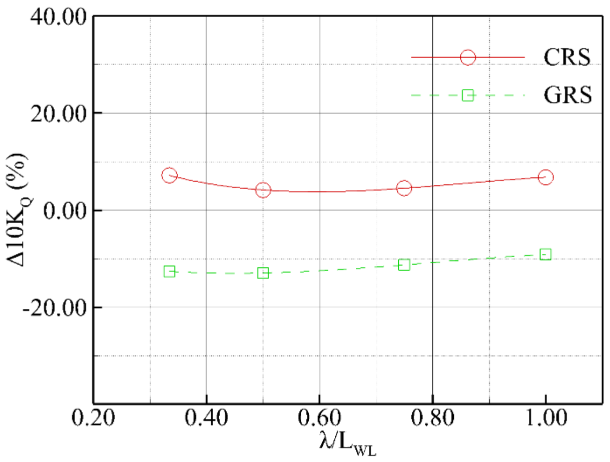

Figure 10 The torque coefficient difference (self-propulsion and seakeeping tests) of CRS and GRS.

The most prominent finding from the propulsion tests in waves at a yaw angle has been the significant decrease in the power requirement with the GRS compared to the CRS. Furthermore, decreasing loading of the propeller with the GRS arrangement can be associated with the differences in the increasing drag on each rudder system, as shown in Figure 11, where the rudder drag increase of the CRS and GRS in waves were compared with reference to their calm water drag values. As one can see, in the wave conditions tested, the rudder drag increase in the CRS is almost five times compared to its calm water drag values, whilst the increase in the drag of the GRS in waves is virtually negligible.

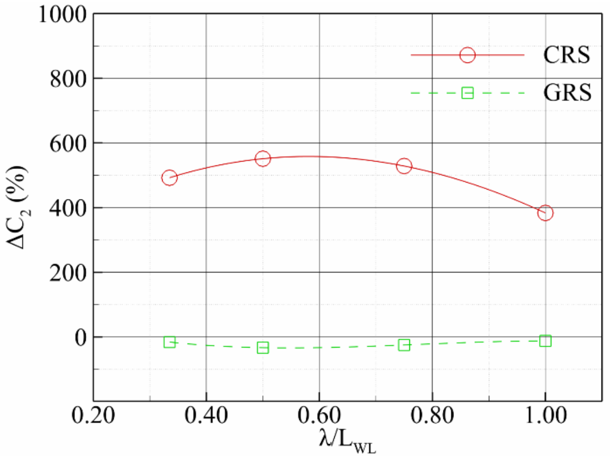

Figure 11 The rudder force coefficient difference (self-propulsion and seakeeping tests) of CRS and GRS.

5 CONCLUDING REMARKS

As part of the experimental activities of the GATERS Project, this study presented the powering performance prediction and analysis of the project target vessel through model tests in calm water and waves. The resistance, propulsion and seakeeping (at a yaw angle) tests were conducted with a model made to a 1/21.7 scale (3.9m LPP) of the target vessel (M/V ERGE) at the University of Strathclyde's Kelvin Hydrodynamics Laboratory towing tank. The resistance and propulsion tests in cam water were conducted to establish accurate performance prediction methodologies for the powering performance of a ship retrofitted with a GRS using traditional model test techniques. In addition, the seakeeping tests were conducted in waves to investigate the comparative powering performance of the ship with the CRS and GRS to simulate the in-service conditions.

The calm water resistance tests of M/V ERGE were first conducted with her bare hull, and then the hull was appended with the CRS and GRS configurations. The comparative resistance tests of the hull displayed up to a 4% reduction in the hull resistance with the GRS configuration over the CRS one.

The self-propulsion tests in calm water were also conducted for the model with the CRS and GRS configurations for the corresponding full-scale speeds of 10, 11 and 13-knots; while the CRS rudder was kept amidship, and the GRS rudder angles were set at 0°. The comparison of the delivered power requirements measured for these conditions showed a 22% benefit for the GRS configuration.

The seakeeping tests were conducted to assess the effect of waves on the comparative powering performance of M/V ERGE with the CRS and GRS. These tests were conducted in regular waves in the towing tank with the ship model fixed at a small yaw angle to simulate the oblique wave condition and with a significant wave height of 1.25m in full-scale (corresponding to Beaufort 4) for a range of different wavelengths. The rudder angles of both rudder systems were preset at the appropriate values to produce a mean hull yaw angle of 5° to avoid high yaw angles that could damage the load cell.

The comparison of the powering performance of the hull with the CRS and GRS indicated that the thrust and torque increase in waves for the model with the GRS was 20% less than those with the CRS. However, the additional resistance and ship motions in waves were comparable for the model with both rudder configurations. This was primarily due to the increase in the CRS' drag for almost five folds of the drag in calm water when maintaining a 5^0 yaw angle. For the equivalent condition, GRS has provided more thrust than calm water conditions. This combined effect has resulted in power savings of up to 20%.

ACKNOWLEDEGEMENTS

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