Recommended tank test procedure of Open type Ducted Propeller （Gate Rudder System）

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It is a well-known fact that the accurate power prediction of the new concept vessel is challenging because of the shortage of full-scale data. Following the successful installation of the world's first gate rudder on a 400TEU container ship, "Shigenobu", three different vessels with the gate rudder system (GRS) were delivered, and another three ships are under construction (Fig 1). Therefore, comparing the full-scale data obtained from these four vessels with their model test data and so-called model-ship correlations are slowly being unravelled.

In this paper, some remarkable differences in the model ship correlation of the gate rudder system with the conventional rudder system will be discussed based on the investigation of the associated tank test data, full-scale data and numerical analyses related to each vessel.

Through the model tests carried out at several major model basins, some problems were also clarified. In order to solve these problems, the recommended tank test procedure has been discussed among the researchers of not only the model test experts but also the CFD experts. Nevertheless, we still have uncertainty about why we can see the remarkable discrepancy between the model tests and full-scale data, which is extremely better than the model tests. However, the more significant part of this uncertainty was revealed by our efforts mentioned above.

The analyses of the model and full-scale data and the support from the CFD can propose a recommended tank test procedure for ship models with GRS that may be considered to be the best at the moment.

	Sakura	Shigenobu
Loa (m)	111.4	
B (m)	17.8	
d (m)	5.24	
Main Engine	3309kW x 220rpm	
Rudder	Flap Rudder	Gate Rudder
Delivery	August 2016	December 2017

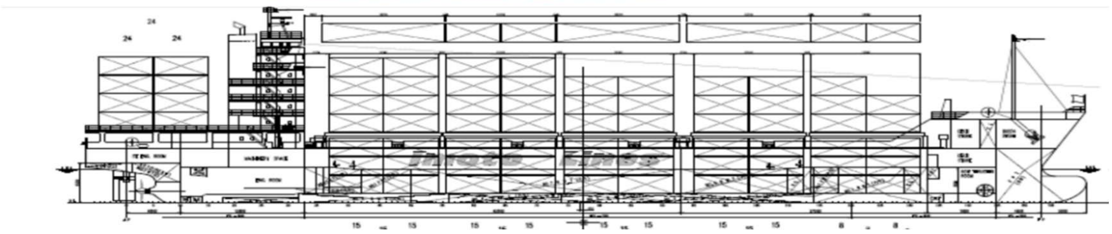

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Figure 1 The first gate rudder application to 400TEU container ship 'Shigenobu'

1 INTRODUCTION

The Gate Rudder System (GRS) is a rather novel but straightforward arrangement of the ship rudder and propeller to act as an attractive and sound Energy-Saving propulsion and Manoeuvring Device (ESMD), e.g. Sasaki et al. (2015), The Naval Architect (2019), The Motorship (2019). In this system, the classical single-rudder behind the propeller arrangement is replaced by twin-rudder blades with asymmetric cross-sections on either side of the propeller. Hence, the two rudder blades encircle the propeller at the upper half, and two sides of the propeller, like a semi-duct, split into two parts with no bottom part, and each blade can be controlled independently (See Figs 1 and 2).

Two gate rudder cargo ships were delivered in 2021, as shown in Fig 2, Shinmon maru (left) and Koshin maru (right). Following these two ships, the maximum size of the domestic container ship 'Nogami' was delivered in May 2022 (Fig 3), and the GRS was installed again by the same ship owner 'Imoto Line', who was well-satisfied with the performance of Shigenobu.

Figure 2 Shinmon maru (left) and Koshin maru (right)

Figure 3 The largest domestic container 'Nogami'

During last four years, a lot of tank test and full-scale data was obtained and compared involving these vessels. Owing to these valuable data, the discrepancy between the model tests and full-scale data has been unravelling gradually. Especially the model tests and CFD studies conducted in the EC-sponsored GATERS project under the H2020 programme (GATERS, 2020) contributed to this development. The main objective of GATERS is to develop a procedure to retrofit GRS on a vessel and demonstrate its pros and cons by applying it to an existing target vessel, which is a 90m coastal general cargo ship MV Erge, as shown in Fig 4. The types and performance data for the four Japanese ships and MV Erge are presented in Table 4. The experimental and CFD activities in work package (WP)1 of the GATERS project showed remarkable evidence, which will contribute to the development of accurate tank test procedures for the power prediction of ship models equipped with a GRS and their extrapolation methods for the full-scale power prediction.

In this paper, the presentation of the recommended tank test procedure for the power prediction of ship models with GRS, developed by the GATERS project partners and their external collaborators, is presented and discussed to contribute to the development of the GRS technology.

Figure 4 The target ship "Erge" of GATERS

Table 1 The ship type and performance data

Ship name	***type***	***Sea trial***	***Voyage***
Shigenobu	Container	Yes	3 years
Koshin maru	Cargo	Yes	No
Shinmon maru	Cargo	Yes	1 year
Nogami	Container	Yes	4 months
Ohshima	Training ship	Jan.2023-	2023-
MV Erge	Cargo	Feb.2023	2023-

2 THE PROBLEMS OBSERVED IN MODEL TESTS

2.1 is – GRS an appendage or propulsor ?

As described earlier, a GRS has two main components; a

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propeller and two rudder blades aside from the propeller that can be controlled independently. The rudder blades have asymmetric blade sections with a camber toward the ship's centre line. This configuration is similar to the ducted propellers, as shown in Figure 5, by red circle

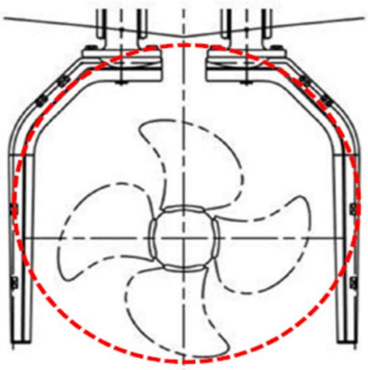

Figure 5 The similarity of GRS to the ducted propeller

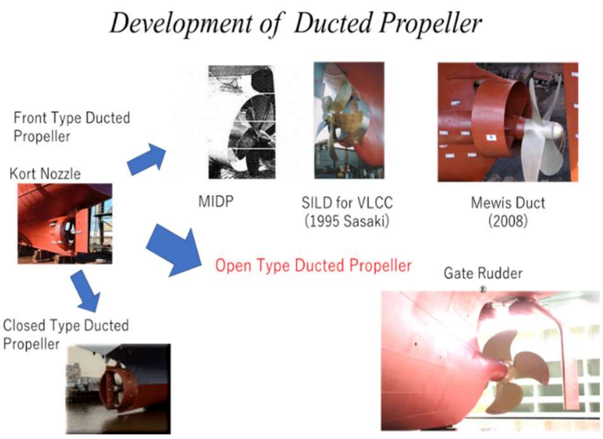

Figure 6 The history of the duct type ESD

Figure 6 shows the historical development of Energy Saving Devices (ESD) involving various duct arrangements (Sasaki ****). Among these ESDs, the GRS is the closest type to a classical accelerating type ducted propeller, and hence we may describe a GRS as an "open-type ducted propeller". 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 where the rudder is considered an “appendage”.

Considering the GRS is a mid-way arrangement between the classical ducted propeller and conventional rudder-propeller systems (CRS), it will be appropriate to analyse model tests results of a GRS by treating it both as a “propulsor” and "appendage" and compare the results. Therefore, in the following, these two procedures are explored, and the results are compared:

- Procedure A (Propulsor-base)
- Procedure B (Appendage-base)

The basic principles of these procedures are summarised in Table 2 for further information.

Table 2 Two model test procedures for GRS

Tests	***Procedure A*** *(Propulsor-base)*	***Procedure B*** *(Appendage-base)*
Resistance test	Naked hull	With rudders
Propeller open water test	Propeller with rudders	Propeller without rudder
Self-propulsion test	With propeller and rudders	With propeller and rudders
Scale effect	similar to conventional ship	different from a conventional ship

In the GATERS project, an approximately 11m long model of the 110m container vessel was tested in the HSVA towing tank. One of the main objectives of these tests was the development of an adequately accurate model test procedure for a ship featuring a Gate Rudder system. The two procedures mentioned above are in mind; the test scope consisted of calm water resistance and propulsion tests at two draughts of the model equipped with a conventional flap-type rudder system (CRS) and the gate rudder system (GRS) to compare the test results. In addition, the naked hull resistance test and the propeller open water tests with the gate rudder were also conducted to satisfy procedure A.

HSVA conducted the model tests with the CRS and GRS and analysed the results using the above-mentioned two procedures. Figure 7 shows the difference in the propeller-hull interaction coefficients and related efficiencies based on the two procedures.

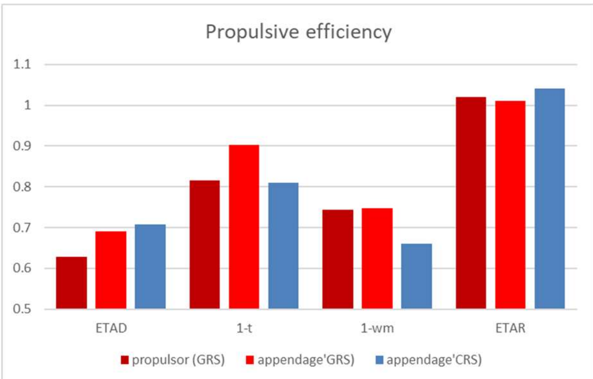

Figure 7 The difference in propeller-hull interaction coefficients and efficiencies between CRS and GRS using two different procedures (Propulsor-base vs Appendage-base)

Based on these analyses, we can conclude that:

1. The difference of (1-t) values between the GRS and CRS obtained from Procedure B (Appendage-base) is abt. 10% and this can be explained by the thrust of

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GRS, while CRS shows only resistance.

2. No difference of (1-w) was observed between the results from Procedure A and B for the model with GRS. However, one should expect the value from Procedure A (Propulsor-base) of the GRS treatment should be lower than the Procedure B treatment because the flow velocity at the propeller plane is accelerated by the presence of the gate rudder blades.
3. The difference in the relative rotative efficiency between GRS and CRS is 2-3%, and we will discuss this in Section 2.5.

Another container ship was delivered in May 2022, and the performance can be compared with her sistership, which was fitted with a conventional twin rudder system. The model tests of these ships (Ship A and B) were conducted at SRC Japan using the 6m large model. The data available for these two vessels are summarised in Table 3.

Table 3 Ship dimensions

Particulars	***Ship A***	***Ship B***
Loa (m)	111.4	136.25
B (m)	17.8	21.0
D (m)		9.2
d (m)	5.24	6.0
M/E (kW)	3309	5220
Rudder	GRS	GRS

2.2 Accuracy of the rudder models

In general, the resistance of a typical conventional rudder is less than 5%, and the accuracy of the rudder geometry is not so important as far as the main parameters such as rudder area, outline profile, maximum thickness and the distance from the propeller are kept as they are. However, one needs to pay attention to the difference in the flow speed and Reynolds number between two different rudders, which may affect the viscous resistance considerably. Two different rudder shapes for both rudder system were investigated, as shown in Figure 8. The outcome of the study will be introduced in Section 3.2.

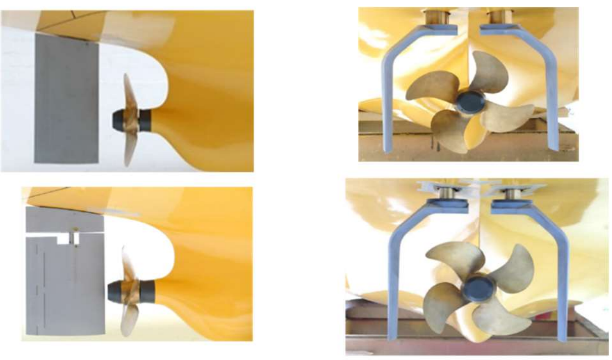

Figure 8 The rudder geometries studied by HSVA
(Left column: CRS; Right column: GRS;
Upper row: simplified models; Lower row: accurate models)

2.3 Resistance extrapolation

In the course of predicting the full-scale power based on the model tests, not only propulsion tests but also resistance tests are carried out. Usually, the resistance test is carried out by fitting the model with the same appendages as during the propulsion tests except for the propulsion devices. In the case of testing a Gate Rudder, it needs to be defined if the Gate Rudder is considered as part of the propulsion device (i.e. Procedure A) or if it shall be treated as a 'regular' appendage (i.e. Procedure B) as described in the previous section.

As soon as the rudder is treated as a regular appendage, it needs to be discussed if the resistance component of the rudder is to be scaled in the same manner as the ship's hull or if it is to be scaled and corrected differently. There are several ways of considering the resistance of the vessel's appendages, described in the following:

i) Determination of appendage resistance coefficient C_{APP} and scaling separately from the hull resistance
ii) Using the same scaling for the hull and appendage resistance
iii) Determination of form factor for the vessel, including or excluding the appendages

For the resistance extrapolation, it is preferable to use the ITTC form factor procedure because the appendage drag can be categorised as the viscous resistance as long as the appendage is deeply submerged.

Figure 9 shows the difference in the form factor (K) values obtained from the resistance tests of several model tests with the CRS and GRS. The difference in K values (ΔK) between GRS and CRS can be averaged around 0.02, correspondings to less than 1% hull resistance. The decrease in K values can be observed in the higher K values of the vessels. The largest deviation was found in the case of Ship A.

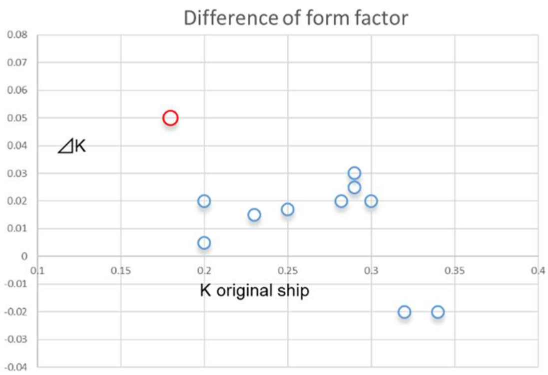

Figure 9 The difference in form factor (K) values between CRS and GRS obtained from model tests

HSVA, in the GATERS project, experimentally explored and cooperated to find the reason for this large deviation.

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The main difference in resistance between the GRS and CRS is not originated from the rudder blades because the GRS blades can produce the thrust even in the towing condition. It was revealed that the dominant resistance originated from the rudder stocks. A detailed investigation is given in Section 3.2.

2.4 **Wake scaling**

The wake scaling procedure for single screw vessels with symmetric wake and single propellers is quite well elaborated, established and verified in the literature, especially by ITTC. Various test institutes may use different wake scaling procedures, which are part of their entire prediction process chain and are well correlated with further correction factors.

However, the correction of the wake parameter in case a Gate Rudder is applied does not seem straightforward. In the GRS case, the wake field that the propeller is operating in is decisively affected by the rudder blades, which are partially surrounding the propeller. This, in turn, affects the velocity components of the inflow to the propeller and, thus, the effective wake parameter. The additional component on the model wake, which GRS contributes, is not considered in the CRS wake scaling procedures; thus, such correction methods may mislead. In order to establish and verify a wake scaling procedure for the GRS application, further research is required, which may cover the following, among others:

i) Full-scale Particle Image Velocimetry (PIV)
ii) CFD investigations in model scale and full scale
iii) Determination of the full-scale wake parameter based on sea trial measurement analyses

2.5 Questionable relative rotative efficiency

The relative rotative efficiency is the difference between the propeller efficiency in behind and open water conditions. It is generally recognised that the relative rotative efficiency could be increased in a non-uniform flow, whereas the ship flow at the aft end can be disturbed or regulated.

Despite the recent progress in CFD, the relative rotative efficiency is still the most difficult to predict accurately due to the simple turbulence models used to simulate the stern flow. Through the hundreds of model tests with the GRS, the relative rotative efficiency predictions for the ships with GRS are relatively poor.

Norbert et al. (Refs) investigated the laminar flow separation which occurred on the propeller blade surface during the model tests. The combined flow characteristics of the laminar and turbulent flow were investigated. This investigation may help to explain this discrepancy between the experiments and CFD which can be seen in Figures 10 and 11 for the models with the GRS and CRS.

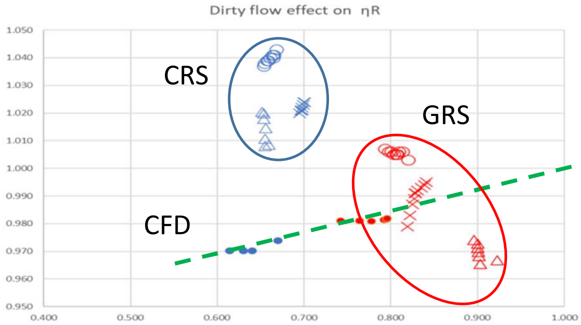

Figure 10 The opposite trend of η_R of CRS and GRS against wake fraction

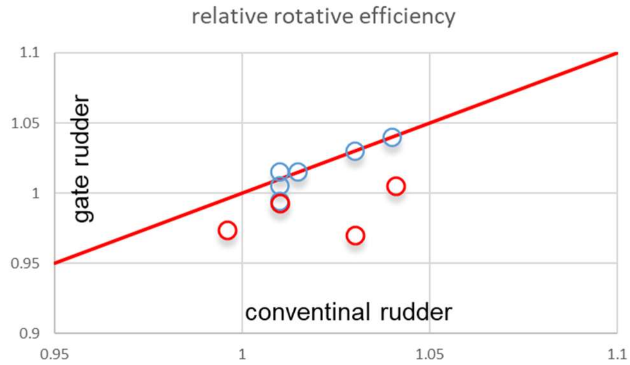

Figure 11 The comparison of η_R between CRS and GRS installed on the same model ship

The remarkable laminar separation effect on the relative rotative efficiency can be seen when the self-propulsion test was conducted at very low ship speeds conditions as shown in Figure 12.

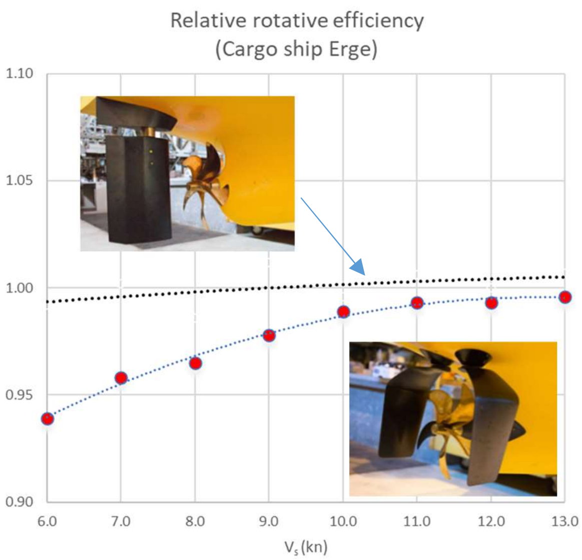

Figure 12 Remarkable trend of relative rotative efficiency of gate rudder ship affected by the flow characteristics

This separation phenomenon can be prevented by a

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turbulent stimulator applied to the inner radii of the model propeller blades. This countermeasure should be considered when the Reynolds number at the blade root is lower than $6 * 10^4$, i.e.:

$$Rnk = V_T * C_{0.3} / \gamma \quad < 6 * 10^4$$

$$V_T = ((2 \pi n r)^2 + V_A^2) **0.5$$

$V_A = V_S * (1 – w)$
$r = 0.3 * R$
$C_{0.3}$: chord length at 0.3 R (m)
R : propeller radius (m)
w : wake fraction at propeller root position
γ : kinematic viscosity (m^2/s)

It is also effective to apply the special wing section as shown in Figure 13. This wing section is effective, especially in the inner radii of CPP (Controllable pitch propeller) blades because of the restriction of chord length.

Figure 13 Application of open-type trailing edge for CPP

3. The investigation conducted in GATERS

3.1 The difference between the propulsor and the appendage

In the GATERS project, the difference between the two procedures (A&B) described in Section 2.1 was investigated by HSVA using the data in Ship A of Table 3.

Each method has pros and cons, as explained in Table 4.

Figure 14 shows the image of the power prediction errors in the process of two methods.

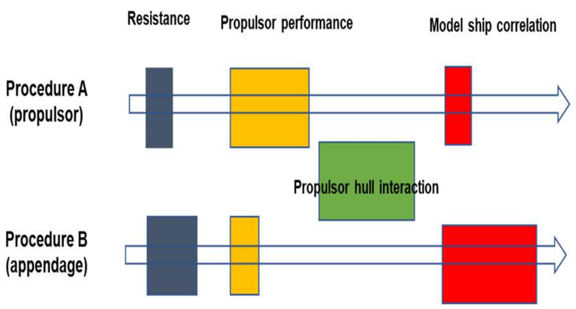

Figure 14 Error distribution in each procedure

Table 4 Pros and Cons of two procedures

	Procedure A (Propulsor-base)	**Procedure B** (Appendage-base)
Pros	The obtained propulsive coefficients are similar to the data obtained from existing ships and the model ship correlation can be well recognized	The model test can be conducted as same as other ESDs. The ITTC recommended procedure for the appendage, i.e. for the rudder blades can be applied
Cons	The propeller open water test should be conducted with rudder blades. This measurement may have a significant error due to flow separation. The treatment of the surface piercing rudder stock is difficult	The scale effects on the propulsive factors are not clear because the data of GRS is very limited.

As shown in Figure 14, both procedures offer a good agreement with each other when all errors are minimised.

However, we still need to select a procedure which should include more minor risks to deter the accuracy of the model test results. In this context, procedure B is superior to procedure A.

3.2 The effect of rudder geometry

The Reynolds number of the gate rudder blades and rudder stocks is rather low compared with the main hull, while the conventional rudder is under the effect of not only the turbulent stimulator but also the propeller slipstream in the model scale.

The paint test and CFD studies were conducted by the HSVA and Strathclyde university, respectively, and results are shown in Figure 15..

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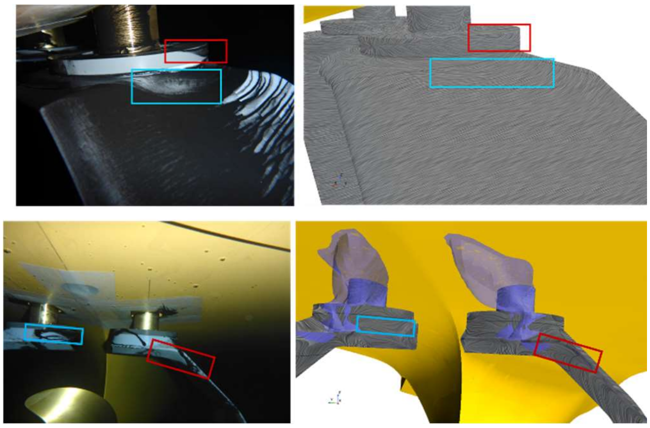

Figure 15 Paint test results (on the left column) **and CFD predictions** (on the right column)

3.3 The model ship correlation

In general, the model-ship correlation manifests itself through two parameters, C_A and w_S, which are the hull roughness allowance and full-scale wake fraction, respectively.

At the first stage, the full-scale wake (w_S) is analysed by following equations assuming the same thrust deduction fraction (t) and the same relative rotative efficiency (η_R) as the model ship data.

$$ei = (1 - w_S) / (1 - w_M)$$
$$w_S = 1 - nDJ/Vs$$
$$J = f(K_Q)$$
$$K_Q = P_B \, \eta_R / \rho \, (2 \pi n^3 D^5)$$

After determining w_S, the power difference between the measured and re-calculated values (replacing the initial w_S with the determined w_S) can be explained by the difference in C_A.

Figure 16 shows the comparison of the "ei" values between predicted and measured, which is not the same as conventional ships, as mentioned in Section 2.4.

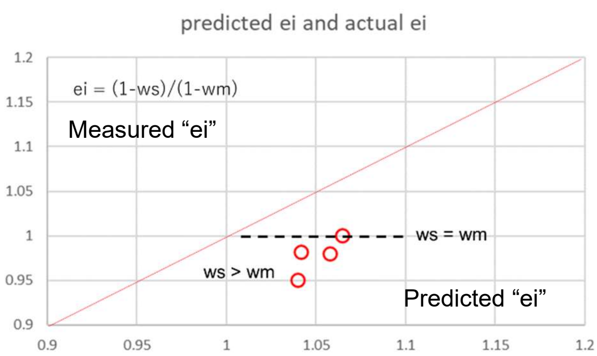

Figure 16 Predicted and measured "ei" in full scale

3.4 Important additional tests

3.4.1 Propeller overload tests at normal ship speed

As the tank test can demonstrate the ship's performance at calm sea condition, different model tests should be conducted to demonstrate the real ship performance which is experienced during the in-service condition where the wind and waves co-existed. This will require testing the models, at least in waves at ocean basins.

In order to simulate the "in-service" conditions, which demand higher propeller loading, in a simple way in the towing tank, HSVA conducted propulsion tests by loading the GRS and CRS propeller gradually and compared the measured rudder force results, as shown in Figure 17.

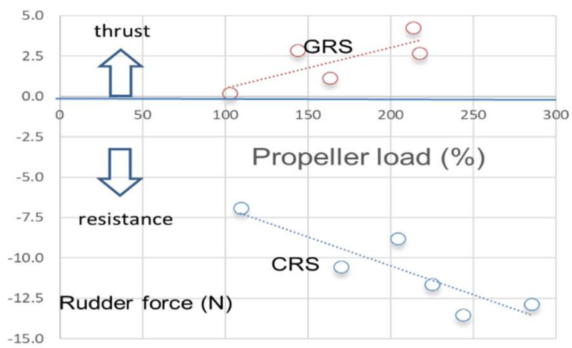

Figure 17 Rudder forces (longitudinal) on GRS and CRS under increased propeller loading

As shown in Figure 17, it is clear that the longidutinal force, i.e. thrust and resistance, produced by the GRS and CRS, respectively, increase with the increasing propeller loading, indicating that the ship with GRS will outperform the ship with CRS.

We can also see a good correlation between the trends observed in these test results and the full-scale voyage data of the 400 and 600TEU containers vessel, collected by 5 min. average and plotted based on the wind speed (5 min. average) as shown in Figure 18.

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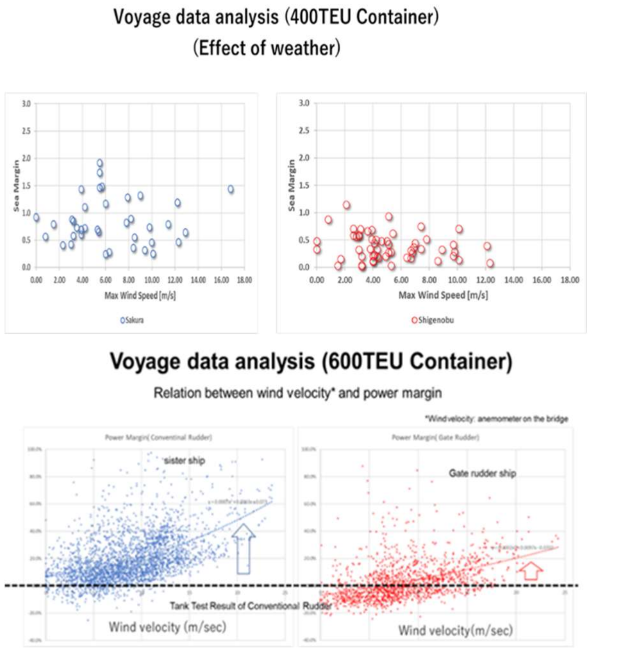

Figure 18 Sea margin obtained from the voyage monitoring data

3.4.2 Propeller overload tests at dead slow

The minimum Power Requirement (MPR) Regulation Level 2 requires the ship's performance in adverse sea conditions, as described in Table 5.

Regarding this requirement, Figure 19 shows the trend of (1-t) values based on the propeller loading factor (K_T/J**2) used in the application process of the MPR. It is clear that the (1-t) value of two rudder systems will keep the deviation even if the propeller loading factor will be changing.

Table 5 The data required for the calculation of MPR

Ship speed	2 kts	
Added wind resistance	Vw = 19.0 m/s	Less than 200m Lpp
Added wave resistance	Hw=4.5m T = 7.7 sec	Less than 200m Lpp
Added rudder resistance	3% of Ter	Ter = T - Xr
Torque limit	Engine Maker	
Power limit	Based on Torque limit	

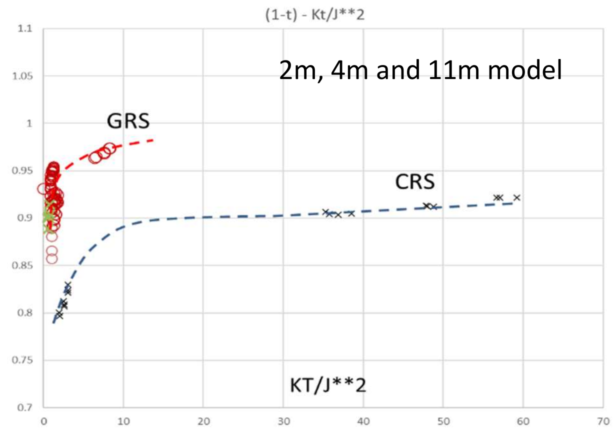

Figure 19 (1-t) values at extremely high propeller loading

4 Recommended Tank Test Procedures

Based on the model tests conducted in different facilities and limited full-scale data analyses, one can recommend the best tank test procedures for models with the GRS as summarised in Table 6

Table 6 Recommended tank test procedure for GRS

Tests	Details	Pros and Cons
Resist' tests	• Resistance test with rudder • ITTC form factor method is recommended • Keep the same wave resistance at the design ship speed	• The same procedure as the conventional rudder • The turbulent stimulator should be considered
Props' Open Water tests	• Propeller without a rudder • The turbulent stimulator will be needed	• The propeller open water test is very common and the accuracy will be guaranteed
Self-Pro' Tests	• With propeller and rudder	• No difference except scale effect of wake fraction • Pay attention to the relative rotative efficiency which may be deteriorated by uniform inflow
Powering	the similar to the conventional ship except wake scaling	

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