Full-Scale GATE RUDDER Performance obtained from Voyage Data

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Abstract: GATE RUDDER® system is a novel propulsion arrangement or Energy Saving Device (ESD) inspired by the new concept of elementary propulsive efficiency and its optimization in a ship's wake to recover more energy. The performance of a GATE RUDDER® system in the hull wake, therefore, is important not only for the efficiency but also from the cavitation, noise and vibration point of view. The world's first GATE RUDDER® was installed on a 2500GT container ship (Lpp=102m) built by Yamanaka Shipyard of Japan and delivered later in 2017. Excellent manoeuvring performance was reported with a significant fuel saving over her sister ship fitted with a conventional rudder. The comparative full-scale manoeuvring trials of the two sister ships with two different rudder configurations revealed that the resistance increase of the GATE RUDDER® during steering was extremely low compared to that of the conventional rudder. After some in-service experiences with both vessels, two important performance advantages with the GATE RUDDER® system have been observed. One of these advantages is the reduced sea margin requirement for the GATE RUDDER® fitted vessel while the other advantage is the improved speed-drop for the same vessel during manoeuvring in ports which makes the vessel's berthing operations very easy and more efficient.

This paper investigates the reasons for the above-mentioned two important performance advantages of the vessel fitted with the GATE RUDDER® system, based on the performance data obtained not only from model tests, but also from the voyage data collected over the 7 months after the delivery of this vessel

1 INTRODUCTION

GATE RUDDER® system is a new and innovative ESD technology for ships to propel and steer them more efficiently. As opposed to a conventional rudder, which is usually behind a propeller, the GATE RUDDER® has two rudder blades with asymmetric sections, which are located aside the propeller, and each blade can be controlled independently. The two rudder blades, encircling the propeller at the top and sides, provide a duct effect and hence produce additional thrust, as opposed to the additional drag of a conventional rudder behind the propeller. See Figure 1 for comparison of the conventional rudder and GATE RUDDER® system on two sister vessels which are the subject of this paper. The independent control of the two rudder blades also provides effective control of the propeller slipstream and hence steering, Sasaki et al (2015). Thus the GATE RUDDER® system presents not only more propulsive efficiency but also higher manoeuvrability. In addition to these two major advantages of the GATE RUDDER® system, there are other performance superiorities, which are noticed based upon the further analysis of the voyage data, including reduced resistance during manoeuvring motion.

To shed a light on the further performance advantages of the GATE RUDDER® system, which are associated with the induced resistance during manoeuvring as well as the performance in waves, this paper investigates the details and sources of these performance improvements based on not only the model tests, but also the log book data obtained from the two sister container vessels shown in Figure 1 and detailed in Table 1. In the table Vessel A is fitted with a conventional flap rudder-propeller system while her sister Ship B is fitted with the GATE RUDDER® system.

Table 1 Principal dimensions of S Shigenobu & Sister Ship

	Ship A	Ship B
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

2 GATE RUDDER CONCEPT

A ship's rudder is one of the sources in contributing to the ship's resistance. Within this context, the main purpose of the GATE RUDDER® system is to remove this source or

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rather replace with a thrust source (like a duct) to achieve higher thrust and hence improved propulsive efficiency. With this idea, the rudder may become an ESD by being placed aside the propeller, instead of behind the propeller, to simulate the duct effect of a ducted propeller, but with additional manoeuvring capability by independently moving the two rudder blades to control the propeller slipstream, in contrast to the fixed nozzle of the ducted propellers. The GATE RUDDER® arrangement also reduces the viscous energy losses created by the hull boundary layer and utilise the wake flow more effectively than the traditional rudder-propeller arrangement, Sasaki et al (2018).

In a similar way, although many ideas and applications exist to combine a rudder and a propeller, such as podded propulsion systems, steerable ducted propellers and so on (e.g. Carlton, 2012), these propulsion systems generally work with limited applications in the full scale without fully exploiting their propulsive performances and manoeuvring abilities. In contrast, the GATE RUDDER® propulsion system has a flexibility that can be applied to a new design as well as a retrofit system to many types of conventional vessels where the conventional rudder-propeller system can be used.

As reported in Sasaki et al (2018) the GATE RUDDER® propulsion system was originated in Japan and has been further developed in UK through CFD and EFD studies since 2014. Based on these developments, the first GATE RUDDER® system was applied to a 2400 GT container ship and the full-scale sea trials were carried out in November 2017 in Japan. The performance gain expected from the application of this novel ESD was demonstrated by the comparison of these trial results with those of her sister container vessel of the same design, except the rudder system, which is a conventional flap rudder-propeller system and this vessel was delivered one year before in 2016 as shown in Figure 1. Both vessels currently operate on the same route in Japan between Hokkaido and Yokohama.

The analysis of the sea trials data conducted in the same geographic region with the two vessels with about one year interval and those of the voyage data on the same service routes indicated that the container vessel with the GATE RUDDER® system can save abt. 14% more fuel over the vessel with the conventional rudder-propeller system.

Based on the experiences during the sea trials and following on-board experiences of both vessels' captains during service, it was noticed that the vessel with the GATE RUDDER® experienced less power demand (hence reduced sea margin) during the winter season when the wind and waves are relatively high compared with other seasons. Based on these observations, as the main objective of this paper, it has been decided to explore the resistance characteristics of both vessels associated with the manoeuvring motions during their navigations. However, these manoeuvring motions are not the motions imposed by large rudder helm angles but by rather small helm angles (within 20 degrees) which can be adopted by the auto pilot system in order to keep the same heading course in navigation

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Figure 1. Conventional Flap-Rudder (Top) vs. GATE RUDDER® (Bottom)

3 MANOEVRING TESTS

3.1 Model test and test set-up

In order to investigate huge energy saving during her navigation period, test data obtained from the manoeuvring tests with 2.5 m wooden model equipped with GATE RUDDER® was reanalysed. This main particulars of this model, which represented a general cargo vessel, was slightly different from the container ship model since the latter has a superior manoeuvrability in course keeping compared to a cargo ship with larger fullness parameters such as C_B and L/B etc.

The main particulars of the vessel selected here are compared with the container ship as listed in Table 2. Figures 2 through 4 show the general view, aft end details with the conventional flap rudder and GATE RUDDER® arrangements as well as the measurement system arrangement during the tests.

Table 2 Ship Model for the Test

	Cargo	Container
L/B	5.717	5.725
B/d	2.892	3.397
CB	0.73	0.67
Vs (kts)	13	14.5

Figure 2 2.5 m Wooden Model

Figure 3. Fish Tail Rudder arrangement

3.2 Measurement system

Captive model tests and free running test were conducted in the Kyushu University model basin by following their standard procedures. During these tests, the forces and moments on the starboard rudder blade of the GATE RUDDER® were measured. These measurements were complemented by the propeller thrust and torque as well as the ship motions and hull hydrodynamic force/moments (only captive tests) measurements. Table 3 lists the measured parameters during the model test

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Table 3 Conducted Manoeving Model Test

Kind of tests	Ship speed	Measured items
Speed trial	0 – max.	V, F, n, T, Q
Cartive Test	Design Vs	β ,V, F, n, T, Q, F_X, F_Y N_Z, F_{RX}, F_{RY}, N_{RZ}
Free Runing	Design Vs	V, n, ϕ , ϕ ’, X,Y, X’,X’’,Y’,Y’’
Rudder Force Test	Design Vs Port Vs	β ,V, F, n, T, Q, F_X, F_Y N_Z, F_{RX}, F_{RY}, N_{RZ}
Bollard Test	0	n. T, Q, F, F_{RX},F_{RY},N_{RZ}
V:model speed(m/s), F:towing force(N), n:rps, T: thrust(N), Q(N-m), Fx: ship X direction force(N), Fy: ship Y direction force(N), Nz: ship moment at Z axis(N-m), X: ship position X in thr tank, Y: ship position Y,F_{RX}: rudder x direction force (N), F_{RY}: rudder y direction force(N), N_{RZ}: rudder moment at z axis (N-m), ϕ : ship heading angle (deg.) β : shp oblique angle (deg.)		

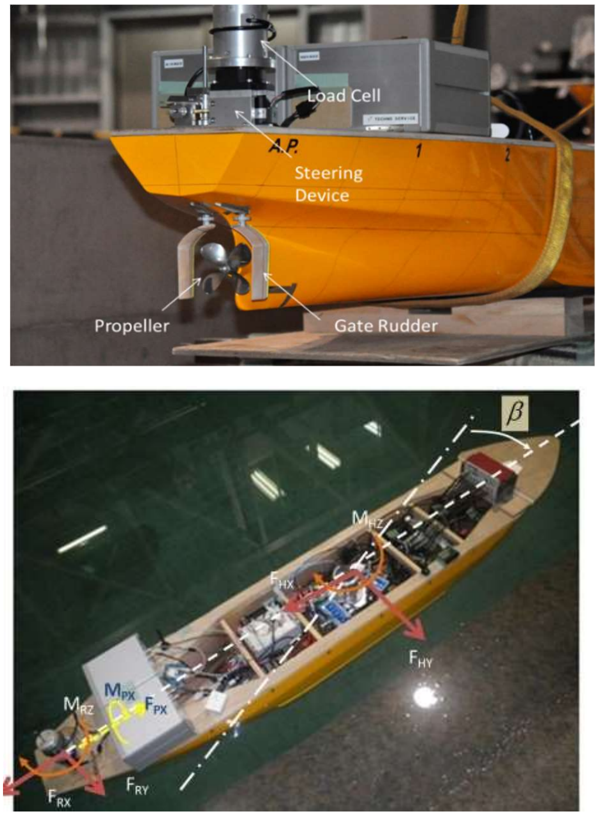

Figure 4 GATE RUDDER® arrangement and measurement System installed on the model

3.3 Test Conditions

The test conditions used for the captive and free running tests were decided from the speed trials prior to the manoeuvring tests. The test conditions for the captive tests and rudder force measurements (during free running tests) are shown in Table 4 and Table 5, respectively.

Although comprehensive data collected during the manoeuvring test campaign, here in this study, only some parts of the captive tests and free running tests involving the measured rudder forces and moments are used.

It is also noted that the required thrust for the GATE RUDDER® case was much smaller than that of the conventional rudder case due to the additional thrust originated from the GATE RUDDER® blades.

Table 4. Test Conditions Captive Test

Kind of Rudder	***V***	***n***	β	δ	*T*
	m/s	rpm	deg.	deg	N
Fish Tail	0.5	11.22	0	0	156
			10	0	133
			-10	0	158
GATE RUDDE R	0.5	11.46	0	0	146
			10	0	130
			-10	0	148

Table 5. Test Conditions Rudder Force Measurement

Kind of Rudder	***V***	***n***	δ	
	m/s	rpm	deg	
Fish Tail	0.5	11.22	-45,-30,-15, 0,15,30,45	
GATE RUDDER	0.5	11.46	port -30 -15 0 15 30 45 60	starboard -30 -15 0 15 30 45 60

3.4 Test results

Captive model tests and free running test were conducted in the Kyushu University model basin by following their standard procedures. During these tests, the forces and moments on the starboard rudder blade of the GATE RUDDER® were measured. These measurements were complemented by the propeller thrust and torque as well as the ship motions and hull hydrodynamic force/moments (only captive tests) measurements. Table 2 lists the measured parameters during the model test.

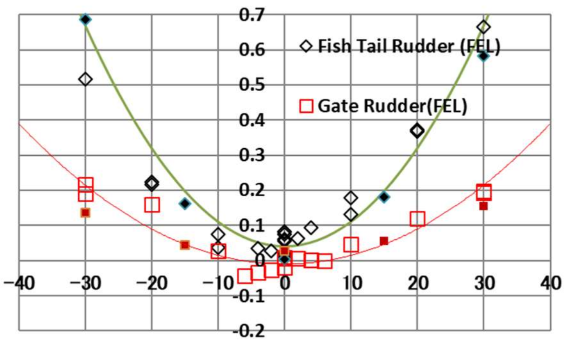

Figure 5 Resistance of rudder due to helm

(fraction of ship resistance)

5 VOYAGE DATA AND DISCUSSION

From the model test, it is quite obvious that the resistance of the GATE RUDDER® is rather small compared with that of conventional rudders. This implies that the vessel equipped with the GATE RUDDER® should require a smaller sea margin than the vessel with the conventional rudder. In order to investigate this attractive feature, it has been decided to analyse the full-scale data collected with the two sister ships. This was because the owner of the both vessels routinely collects the data in their logbook as part of their standard operation and management tasks.

After the delivery of the vessel with the GATE RUDDER®, 7 months of very interesting data were obtained from the logbook of the two ships. There was nothing special with these data but they were collected according to the owner's long term practice and experience. Also the data quality was the same as for other vessels , however it is very important and fortitious that two vesselas are running on the same route, almost the same day and in the same loading conditions (draught).

Apart form the logbook data, some special data collection were conducted by the onboard measuremets, e.g. accurate power monitoring by the newly fitted torque meter and conducting optimum rudder angle tests during voyage and recording the data. The full analysis results of these data and tests will be reported by the end of the ongoing GATE RUDDER® project which is supported by the Nippon Fundation.

Figure 6 presents the average wind speed data collected over the 7 months of onboard monitoring including the trend line. Year 2018, which covered the part of the onboard data monitoring and collection, was extraordinarily different from the last 10 years in Japan. Many typhoons attacked Japan and they might have affected the performance of the two vessels after August 2018.

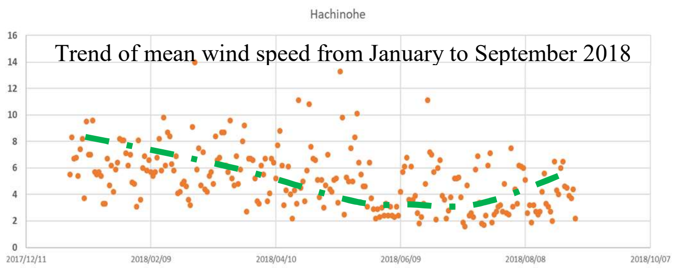

Figure 6 Trend of mean wind speeds (m/s) at Hachinohe from Jan. to Sept. 2018

Based upon the analysis of the two vessels' log book data, Figure 7 shows the comparison of the Admiralty

Coefficients (C_{adm}) for both vessels over the 7 months of on board data collection campaign.

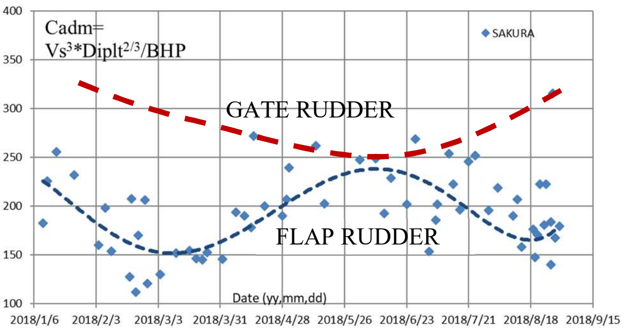

Figure 7. Trend of Admiralty coefficients based on logbook data of two sister ships (Jan. –Sept.2018)

As one can see from the trend lines plotted in Figure 7 the vessel with the GATE RUDDER® has clear powering performance superiority over her sister with the conventional rudder and this is particularly higher over the winter period.

The latter finding, i.e. better powering performance of the ship with the GATE RUDDER®, is most interesting and attractive that requires further investigation. In relation to this interesting finding, it is worthy to re-analyse the results of the seakeeping tests conducted with a container ship model with the GATE RUDDER® at the towing tank of the Newcastle University as part of an MSc study.

As shown in Figure 8, these tests involved the added wave resistance measurements with a 2.1m container model which was equipped with actively controlled GATE RUDDER® and its counter-part conventional rudder. These tests demonstrated the wave absorbing behaviour of the vessel under the effect of actively controlled GATE RUDDER® with small helm angles synchronized with the encounter wave frequency in head seas.

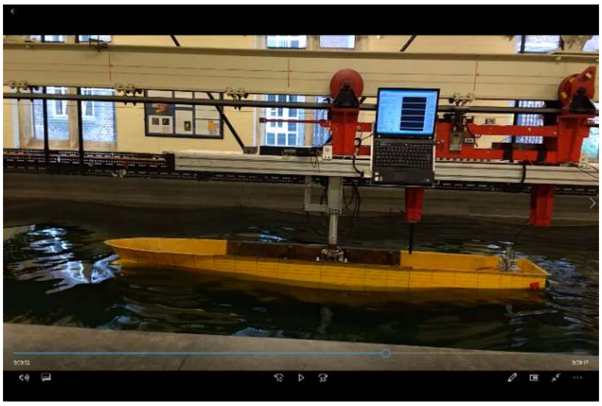

Figure 8 Active GATE RUDDER® Control Tests in waves

In order to investigate the rudder resistance further, the simulation program, which was developed by Newcastle University by Carchen et al. (2018), was used. The software was used to simulate the data collected during the model tests conducted at the Kyushu University manoeuvring basin, and presented in Figure 5.

Figure 9 shows the simulation results for the zig-zag tests from the same initial ship speed. In this figure time history of ship speed (m/s) and propeller thrust (kN) for the GATE RUDDER® and conventional rudder case, respectively. The rudder resistances were calculated according to the data measured during the model tests (Figure 5). The resistance curves of two data sets (for Fish Tail rudder and GATE RUDDER®) were interpolated with parabolic curves, which were implemented in the simulation programme developed by Carchen et.al.(2016).

For both Fish Tail and GATE RUDDER®, three points of the relative parabola were taken (at helm angle = -30°, 0°, 30°) and the resistance increment was measured. From these values, it was possible to obtain the coefficients of the curves to embed in the simulation programme.

According to the obtained measurements, and taking into account the ship motion effect, the two parabolas were embedded as follows:

Conventional rudder: $X_{Rud}/R = 2.261(0.6 \cdot \delta)^2 + 0.05$

GATE RUDDER®: $X_{Rud}/R = 0.776(0.6 \cdot \delta)^2 - 0.04$

where X_{Rud}/R is the resistance increment ratio to hull resistance due to the rudder, and δ is the helm angle.

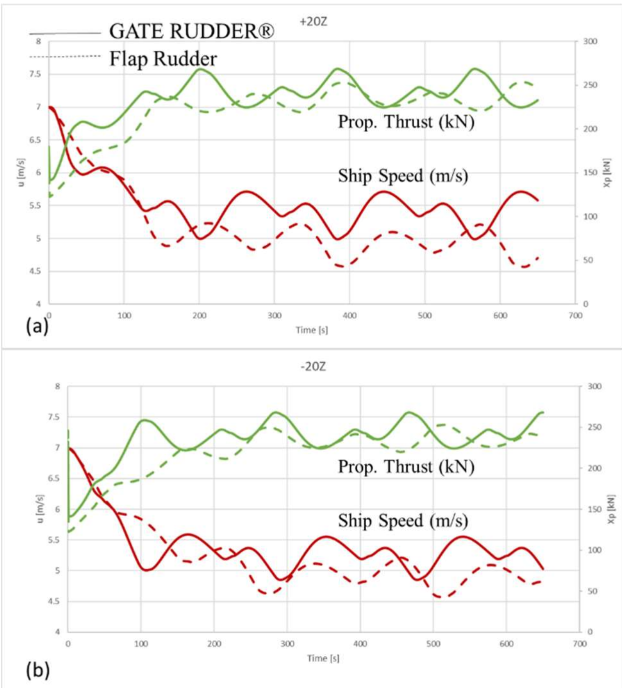

Figure 9 Propeller Thrust and Ship Speeds for two Ships

The rudder angle in the simulations shown in Figure 9 ranges from +20° and -20° (a), and from -20° and +20° (b), i.e. with the ship heading starboard and port at the beginning of the manoeuvre, respectively. The graphs show that, at the same propeller thrust, the GATE RUDDER® allows the ship to keep a higher speed. It is also visible that the velocity oscillations have a higher frequency when the GATE RUDDER® is used, which implies a higher manoeuvrability, compared to the conventional rudder (Figure 10). Another word the vessel with the GATE RUDDER® is more responsive to the helm actions. Based on these simulation results one can conclude that the rudder resistance has an important role for the power savings during the navigation and the GATE RUDDER® can save considerable energy during navigation. Since the power is proportional to V^3, the difference in ship speed indicated by Figure 9 corresponds 30% of power difference if we need to keep the same speed for both ships.

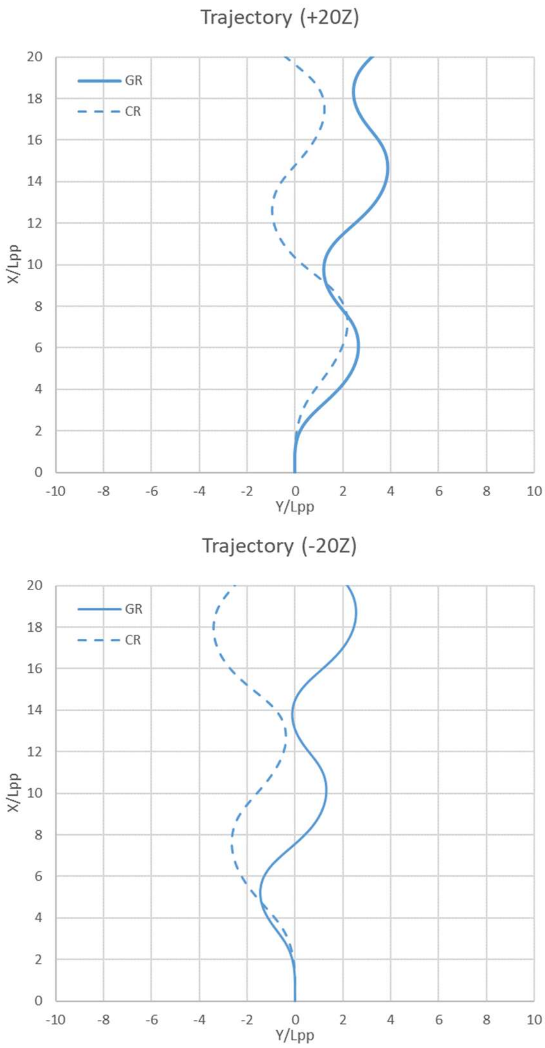

Figure 10 Trajectory during zig-zag test starboard (top) and portside (bottom)

6 CONCLUDING REMARKS

This paper investigated the reasons for the different tendencies in the energy saving performances of two sister ships (Figure 7), which are equipped with two different rudder systems, based on their voyage data.

The difference in the tendency was found during the winter season and typhoon season where the wind and wave was extremely high. Except these periods deviation of the powering performance of the two vessels is around 15% which is very close to the results obtained during the speed trials.

By investigating the model test manoeuvring data and conducting the simulation reflecting these data, it was concluded that the difference in rudder resistance during manoeuvring is the most likely reason for this.

The rudder resistance of the GATE RUDDER® is extremely low compared to that of a conventional rudder. This fact affects the voyage data for both ships in a different way.

It may require further study to conclude that the difference of the rudder resistance is the main cause. However, there is no doubt that the GATE RUDDER® has the big advantage of having smaller resistance during the manoeuvring motion.

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