GATE RUDDER® PERFORMANCE

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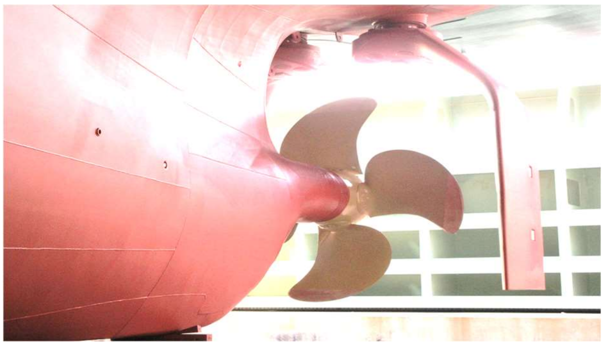
The world first gate rudder was installed on a 2400 DWT container ship "Shigenobu" at the end of 2017, and the vessel is showing her extraordinary superior performance for not only trial conditions but also service conditions. Shigenobu has a sistership "Sakura" built in 2016, and the design is exactly the same except the gate rudder system. Two vessels were built by Yamanaka shipyard and have been operated by Imoto line. Both companies are the leader company for the market of coaster shipbuilding and shipping respectively. It was very lucky for the Authors that Imoto line decided to operate two vessels in the same navigation route on the same day. Addition to these operation conditions, Imoto line has swapped the captain and the chief engineer of Sakura for Shigenobu when Shigenbu was delivered. This has provided an opportunity to share the comparative experiences of the vessel crew with both ships as reported in this paper.

The paper presents an investigation on the performance of the gate rudder system based on the sea trial data and navigation data which have been collected by the same performance monitoring system "e-navigation" installed on the two vessels. The remarkable difference between two vessels is being investigated using CFD methods at several places such as Istanbul Technical University (ITU) and Kamome Propeller.

In addition to the above Shigenobu data, two scaled model test data of Japanese coastal cargo ship are introduced in the paper to explain the scale effect issue of the gate rudder system



1. Introduction

It is a well-known fact that the rudder placed behind a propeller at the stern is a part of ship resistance. Therefore, a lot of energy-saving devices are invented to reduce this resistance contribution by fitting the bulb or fins on the rudder. It is also well-known fact that duct of a ducted propeller can generate a thrust instead of resistance due to propeller action. Addition to these two facts, we know that the duct located in front of a propeller generates thrust or reduce hull pressure resistance due to the mutual interaction of the duct-hull-propeller.

There are many ideas to improve ship energy efficiency and manoeuvring performance at the same time. However, we know that we have to sacrifice others if we want to improve one aspect of efficiency. The high-lift type of rudders such as flap type and fishtail type is a good example. These rudders showed less energy efficiency when we compared service conditions where the ship is running straight, and the vessel speed with these high lift rudders is slightly low.

On the other hand, the pre-swirl fins and post-swirl fins have been utilised to improve the energy efficiency, while this needs a careful design by taking the manoeuvring performance into account because we may have a possibility of large separation and hence higher resistance originated from these fins.

The steerable duct is an idea to use the axisymmetric circular duct as a rudder blade while the circular duct of the steerable duct will not work well as a conventional rudder because of unfavourable flow fields inside of the duct at a high helm angle.

Within the above context, there is an old rudder concept known as "Kitchen rudder" which was invented by J.G. Kitchen and has been used for a small boat. The aim of this rudder is to guide the propeller flow by two rudder blades which are connected at the top and bottom in the centre of the ship. The flow direction can be changed by these two rudder blades, and the user can get directional thrust force quickly. The reason why we cannot see any application to the large ship is due to its lower efficiency due to the high resistance at the top and bottom connection parts. Because of the same reason as the steerable duct, it is easy to show a large separation flow when the blade has large rudder angle due to the 2-dimensional flows without any blade tips. Another reason is the difficulty of the structural design for the bottom part because the larger ship is designed as a mariner type stern to install a larger diameter propeller to obtain higher propeller efficiency.

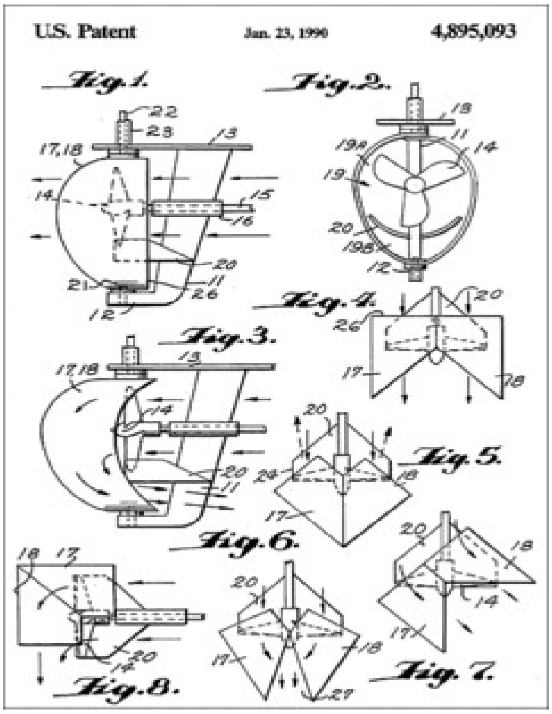
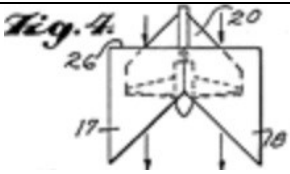
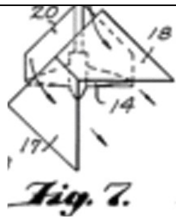
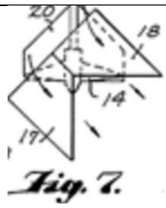
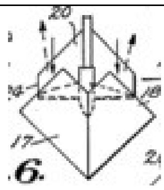


Fig. 1 - Kitchen Rudder

However, the Kitchen rudder is a good hint to create a new concept for an entirely new propulsion system which contains both a propeller and rudder. Table 1 shows the difference between the gate rudder and Kitchen rudder system from the operational modes points of view.

Table 1 - Kitchen Rudder and Gate Rudder

mode	Gate rudder	Kitchen rudder	difference
Normal Ahead			The blades are not parallel and wing section is cambered.
Course Keeping			Similar operation
Turning			Similar operation
Stopping			The blades interrupt water flow into the propeller to avoid sever vibration and noise
Crabbing			Two blades will work as a single large blade and use their lift forces instead of drag

Before discussing the new type of propulsion system, we need to investigate the reason why the conventional rudder is arranged behind the propeller and why nobody tries to locate the rudder blade outside of the propeller slipstream

There are several reasons to answer the above question. The main reason is to obtain an additional rudder force at slower speed where the ship needs frequent manoeuvring such as berthing. However, the ship's rudder is one of the sources contributing to higher ship resistance when it is located behind the propeller. Within this context, the main purpose of the Gate Rudder System is to remove this drag source and replace it with a thrust source (like a duct of a ducted propeller) to reduce the required main propeller thrust and hence reduce the required main engine power. With this idea, the rudder may become an Energy Saving Device by being placed around the propeller, instead of behind the propeller, thus simulating the beneficial duct effect of a ducted propeller system.

The Gate Rudder has two rudder blades with asymmetric sections, which are located around 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 similar to the ducted propeller system and hence produce additional thrust, as opposed to the additional drag of a conventional rudder behind the propeller. Owing to this extra thrust by the Gate Rudder, the required thrust of the propeller as the main propulsor can be reduced by more than 10%. By introducing this ESD based on the above simple idea, the interaction among the propeller, hull and conventional rudder can be replaced by a completely different interaction scheme.

The Gate Rudder can be categorised as a new type of the ducted propeller, which can be called as "Open Type Ducted Propeller" as distinct from a conventional "Closed Type Ducted Propeller" and a "Front Type Ducted Propeller". The Mewis Duct, for example, is a very good example of the "Front Type Ducted Propeller" systems as is the SILD (Sumitomo Integrated Lammeren Duct) which is the original front type ESD. Schematic history and the classification of the ducted propeller systems is shown in Figure 2.

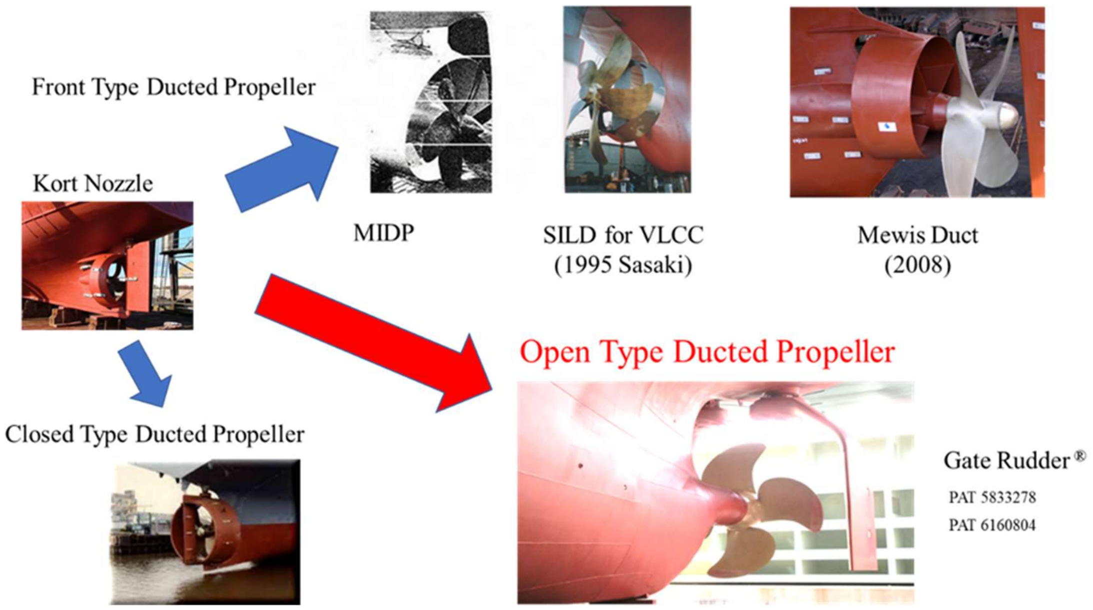


Fig. 2 - History of Ducted Propeller Systems

2. Gate Rudder System - Design Philosophy

2.1 Elementary Propulsive Efficiency

It is well- known that the bottom part of the front type duct shows a poor performance compared with the upper part of the duct behind a ship. Sometimes this part shows negative thrust (resistance) due to the adverse flow for the duct section. By opening this part and moving it to the side of the propeller, this invention has a rudder function and can avoid the risks for cavitation erosion which may occur on the inner surface of the duct. It is also well-known that the minimum clearance between the propeller tip and the inner surface of the duct guarantees the best open water efficiency of the ducted propeller system because of minimising the tip vortex leakage which normally introduces 2-3% energy loss.

However, the new concept "Gate Rudder " revealed that the duct (rudder blades) located in the high wake zone behind the ship shows best propulsive efficiency instead of the best open water efficiency This means the minimum clearance between the propeller tip and the inner rudder surface is not required to establish the best propulsion system. This new concept is termed "Elementary Propulsive Efficiency" which can be represented by the following equations;

$$\eta_D = \frac{T_P * V_S + T_{GR} * V_S}{DHP}$$

This equation implies that the propulsive efficiency will be increased by the gate rudder thrust if T_P and DHP is the same as the those of the conventional rudder system. However, this is not the case, and we need to investigate what will happen to those figures.

The thrust deduction factor can be represented using the increased resistance of the hull as follows:

$$t_{GR} = \Delta R/(T_P + T_{GR})$$
$$T_P + T_{GR} = R + \Delta R$$

From our database, thrust deduction with the gate rudder, t_{GR} is 0.05-0.11 while with the conventional rudder, t_C is 0.15-0.22. This means the interaction between hull and propeller is extremely low compared with a conventional rudder system.This implies that only propeller is generating the resistance on the hull surface by increasing the flow velocity and decrease the surface pressure while the interaction between rudder blades and hull is negligibly small.

From the painstakingly detailed, special model tests in cavitation tunnel with the gate segmented rudder/hull system and the CFD investigations, it has been revealed that the increased resistance of the stern part for the gate rudder system is small compared with the conventional rudder system due to less propeller action (less accelerated flow ΔV_P) which corresponds the propeller thrust directly. This smaller interaction resistance will contribute the total resistance - thrust balance and hence the "favourable circle" will start.

On the contrary, the interaction between the propeller and stern of the conventional rudder system is larger than the gate rudder system as shown in Figure 3. Also, the interaction between the propeller and the stern, the increased accelerated flow of the conventional rudder system will increase the rudder resistance behind the propeller. This is the so-called "vicious circle".

The calculation was made for the typical ships listed in Table 2. The results can be seen in the table as ΔR(kN).

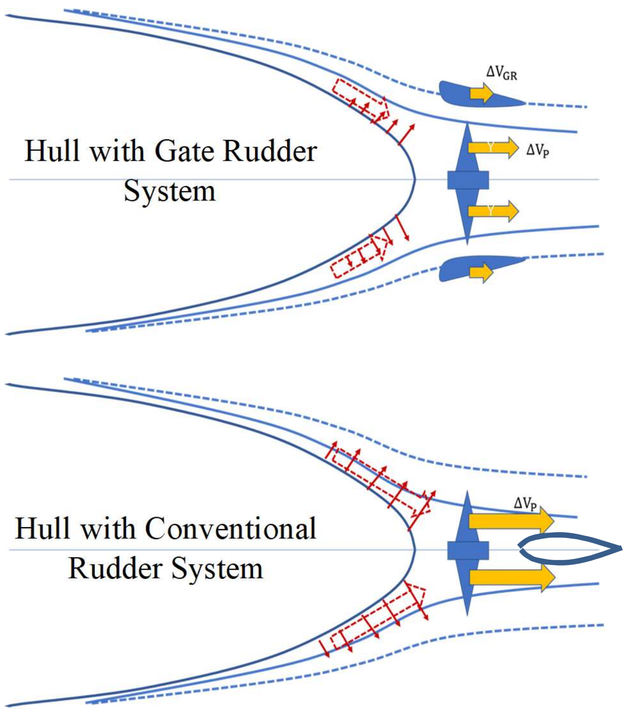


Figure 3 Thrust deduction factor of Gate Rudder (above) and Conventional Rudder (below) systems

From the previous discussion, it will be a useful idea to calculate the fuel savings by the gate rudder for several cases.

Although the description of the effective wake for a vessel with the Gate Rudder System can be subjected to further discussion, by following the standard terminologies, it may be helpful if we can identify how the Gate Rudder should be regarded as an appendage; or a propulsor. Within this context, by considering its overall functioning a whole system or unit, and the analysis and discussions conducted so far, it is more correct to regard as a propulsor. Having said that this treatment would have its own complexities, e.g. conducting an open water test with the Gate Rudder unit is not so easy with the two large surface piercing struts and the flat plate of the rudder top which may generate surface wave easily etc. However, these can be circumvented by some tailor-made testing arrangements and analysis procedures, as we experienced with other special propulsors, e.g. ducted propulsors, pods, thrusters etc.

Regarding the effective wake description, which manifests itself in the propeller advance speed behind the hull mainly by the contraction effect of the viscous boundary layer due to the action of the propeller, it is best to evaluate at a location behind the hull where the induced velocities due to propeller are negligible. For this purpose a sketch which shows the representation of the effective wake due to the Gate Rudder and Conventional rudder is included in Figure 4. As it can be appreciated by sketches in this figure the Gate Rudder configuration will not be affecting the hull boundary layer structure and hence the resulting wake field compared to that field with the conventional rudder arrangement which will be similar or slightly slower.

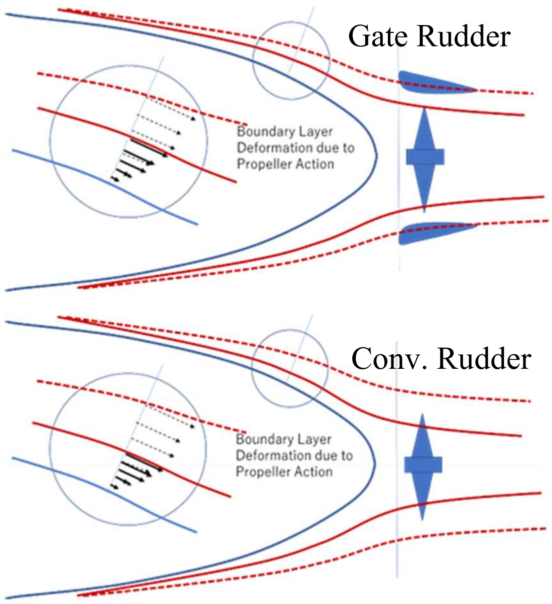


Figure 4 Effective wake of GR

2.2 Balanced design of the gate rudder system

The propeller efficiency of the conventional propeller can be represented by the following formula using a simple axial momentum theory.

$$\eta_D = \kappa \frac{2}{1 + (1 + C_T)^{0.5}}$$

where κ is correction factor from the ideal efficiency to actual propeller efficiency and C_T can be calculated using water density, ρ and propeller disc area S_P,

$$C_T = \frac{T_P}{0.5\rho(V(1 - w_T))^2 S_p}$$

From these equations, it is obvious that C_T is very important for the evaluation of ESD performance.

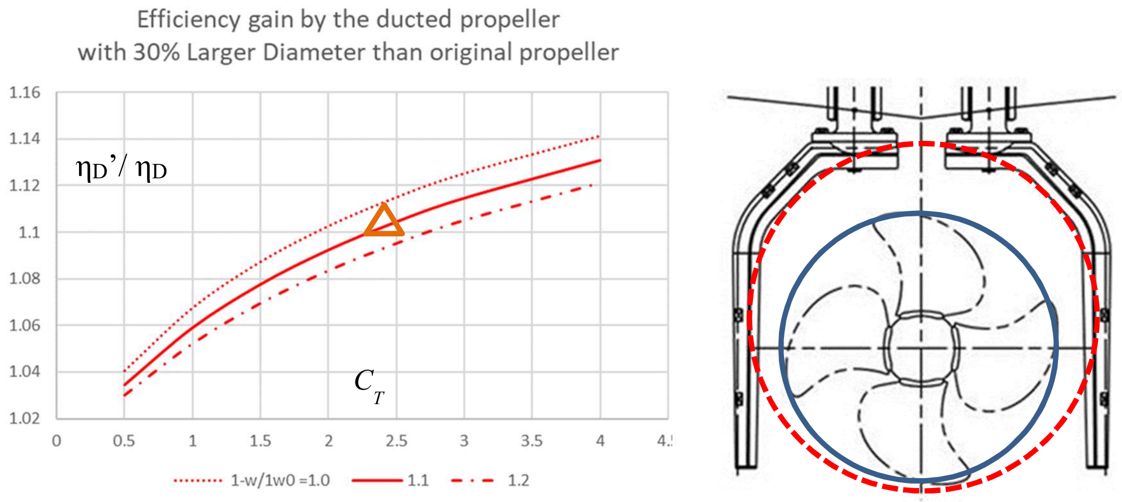


Fig. 5 - Expected gain by G.R system from the duct size

The Gate Rudder is a huge Ducted Propeller, and its efficiency gain can be estimated based on the propeller loading factors $C_T = T_P / (1/2 \rho V_A^2 A_P)$

The Gate Rudder system is also a strong manoeuvring device with the two rudder blades with asymmetric sections, which are located alongside the propeller, and each blade can be controlled independently. The two rudder blades, encircling the propeller at the top and sides as shown in Figure 5, different rudder control modes can be obtained by using this independent twin rudder system at her slow speed as shown in Table 1 .

When the Gate Rudder is used with a bow thruster, the crabbing mode can be established. This mode is very useful for positioning the ship in any direction by a combination of the bow thrust and the Gate Rudder propulsion system.

By replacing the stern thruster and conventional rudder system by the Gate Rudder system, the vessel's design capability will be much improved from the aspect of not only the cost but also the operation, EEDI/EEOI and the life cycle cost. From this point of view, it is very substantial to design the Gate Rudder System which will give us the best performance taking both aspects (energy saving and manoeuvring) into account. This can be called as a balanced design.

3. Power Prediction

In this context, the major reasons for power saving can be summarized as follows:

- Smaller propeller thrust due to assisted rudder thrust and smaller propeller-hull-rudder interaction
- Better propeller design conditions due to the lower thrust density and more uniform wake

3.1 Thrust base powering

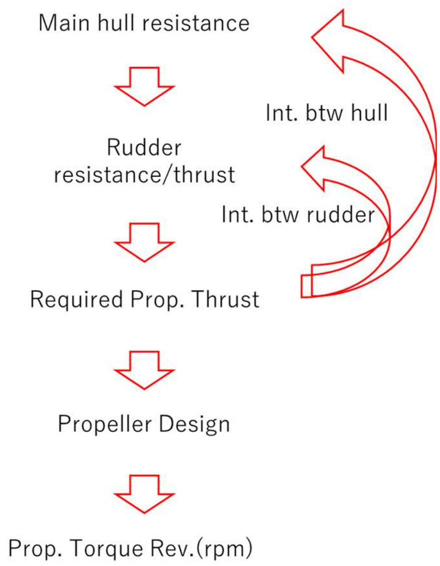


Fig. 6 - Powering procedure of G.R. system

When we noticed that the main difference between the gate rudder system and the conventional rudder system was the extremely small propeller thrust, we could focus on the maximum propeller efficiency and hence the associated propeller design by which we can achieve it.

It is not difficult that we can expect the initial optimum propeller design can be conducted by the conventional propeller design procedure which is based on the experimental/empirical database of the propellers. The final propeller design of the gate rudder system can be favoured by uniform wake, and it will allow us to apply smaller blade area ratio compared with the conventional propeller design which we need to consider for the non-uniform wake affected by the rudder potential wake.

Following examples in Table 2 show the result of the thrust base powering which reflects the above advantages of the gate rudder system while Figur 6 shows the flow chart of the thrust base powering calculations. As can be seen from these examples, the power can be calculated by the propeller torque and revolutions which is designed to generate the required thrust of the gate rudder system.

Table 2 - Examples of powering for three ships investigated by tank test

	2400DW Container		High-Speed RORO		499GT Cargo	
Dimensions	101.9m (15.5kts)		162m (22kts)		69m (13kts)	
	Conv. R	Gate R.	Conv. R	Gate R.	Conv. R	Gate R.
T_P (kN)	261.7	216.5	905.7	772.1	123.7	101.7
η_D	0.708	0.755	0.777	0.827	0.637	0.727
ΔR(kN)	55.0	26.0	181.1	84.9	27.2	7.6
BHP(kW)	2400	2074	10548	9404	1045	893

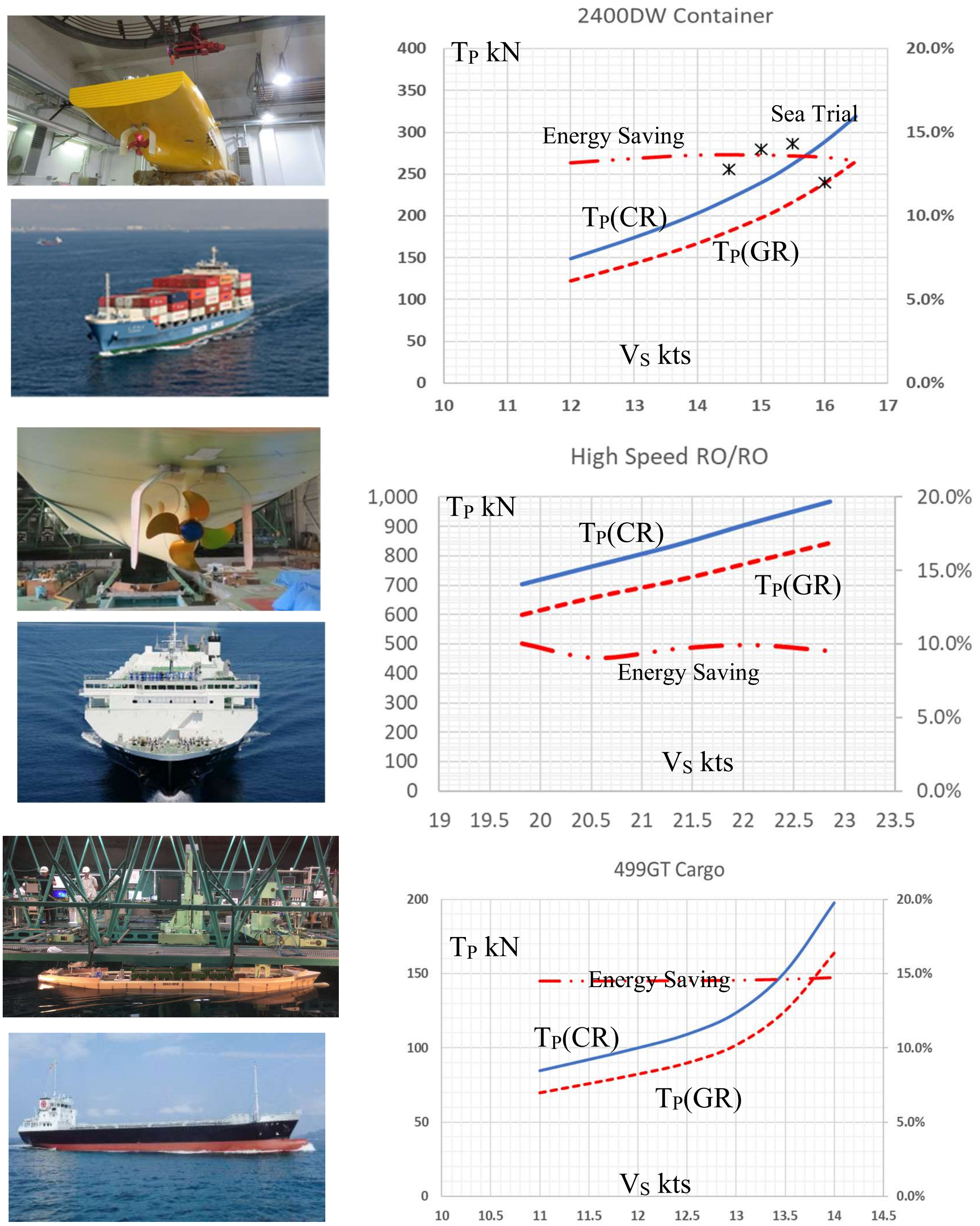


Fig. 7 - Energy saving predicted by the model test with a large model

The interacted resistance was derived by following equations.

$$\Delta R = t * T_P$$

$$t = \frac{R - F}{T_P}$$

The thrust deduction facor t can be measured by the self propulsion test of the tank test according to the ITTC standard procedure.

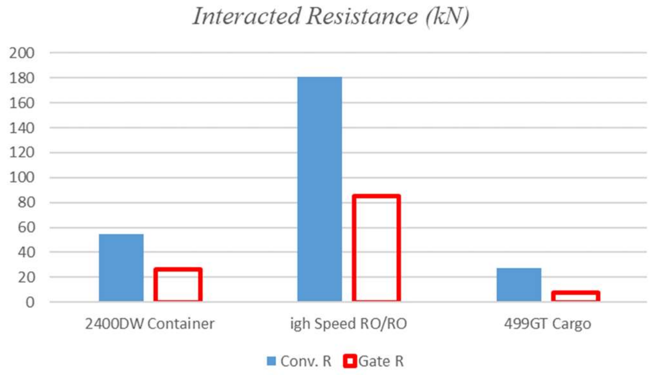


Figure 8 Interacted resistance of CR and GR systems

As shown in Figure 8, the interacted resistance of the Gate Rudder System is rather small and 35%-55% of that of the conventional rudder system.

3.2 Sea Trial Results

The first full-scale Gate Rudder System was manufactured by the financial support received from the Nippon Foundation utilising the technologies developed by the University of Strathclyde, Key Seven Co, Yamanaka Zosen Co. Ltd., and Kamome Propeller Co. Ltd since 2012. The speed trial of the world's first container ship equipped with the Gate Rudder System "Shigenobu" was conducted on Nov.12th and 13th of 2017. The results were compared with the sister ship "Sakura" which was delivered in August 2016. These two vessels have the same hull form and the same engine. The difference is only their rudder systems including the propellers. 14% power difference of speed performance was found for these speed trial based on both raw data and corrected data according to ISO standard procedure, as shown in Figure 9.

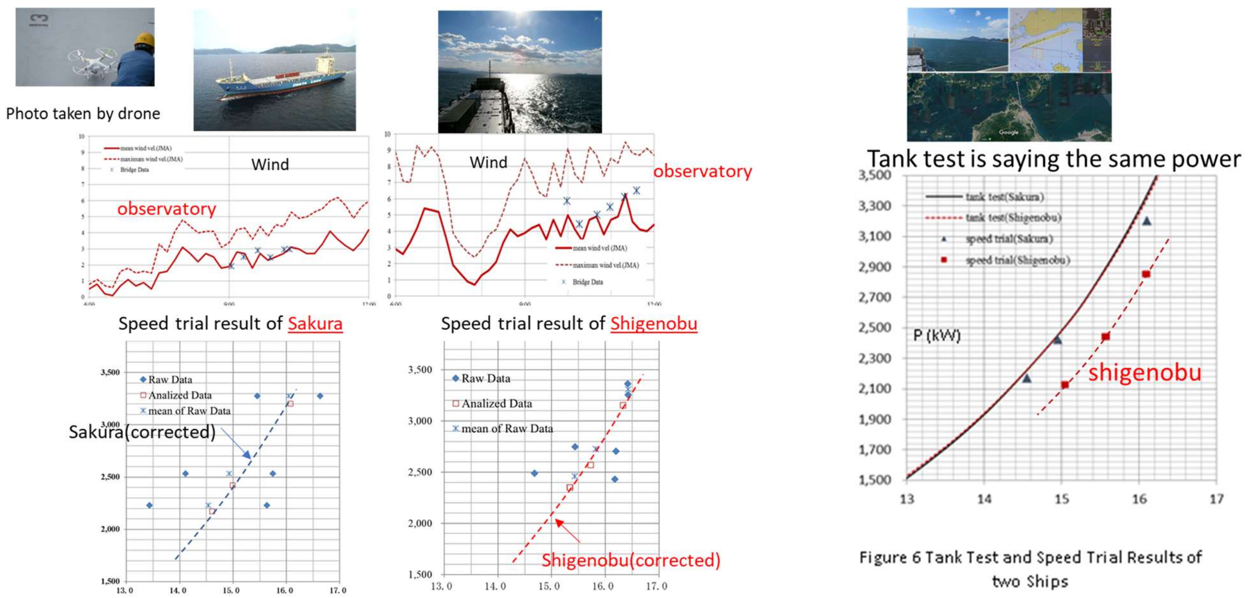


Fig. 9 - Speed trial results of "Shigenobu" with gate rudder system and "Sakura" with conventional Ruddder system

3.3 Performance in-service at actual sea

After the delivery of Shigenobu, luckily both vessels run the same coastal route on the same day. This enabled us to evaluate the two ships' performance without the effect of different routes which may bring differences in weather and current. Around 30% fuel saving was found from the voyage data reported from both vessels every day using the same monitoring system installed on each vessel as shown in Figure 10.

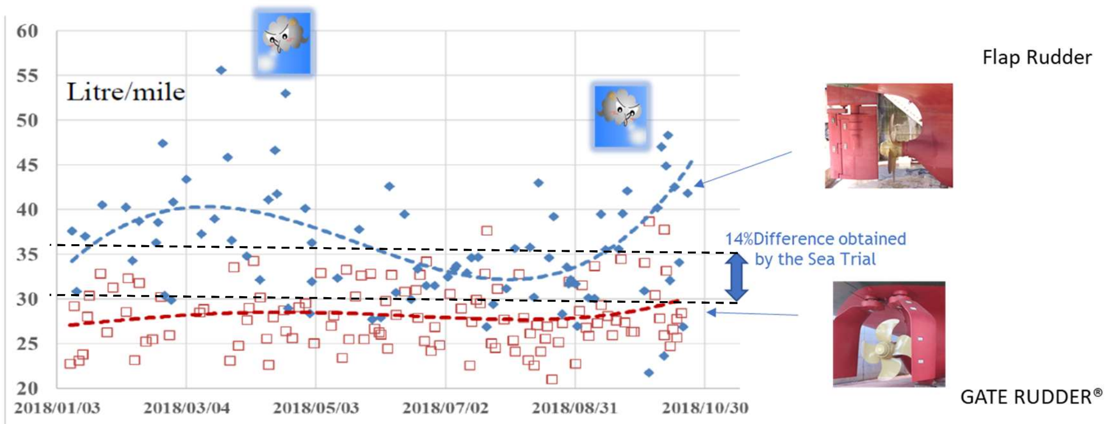


Figure 10 - Performance data comparisons in-service at actual sea

The voyage data was compared with the predicted power curve obtained from the tank test. The averaged power curve of the Shigenobu predicted from the voyage data indicates lower (even negative) sea margin while the Sakura shows 25% which is normal for the coastal vessel running a north-east coast route.

The mechanism of the above difference can be explained as follows:

- the propeller of the gate rudder system requires much smaller thrust than that of the conventional rudder system because the rudder is changed from a resistance device to a thrust-generating device. This also reduces the interactive hull resistance which is known as the thrust deduction factor.

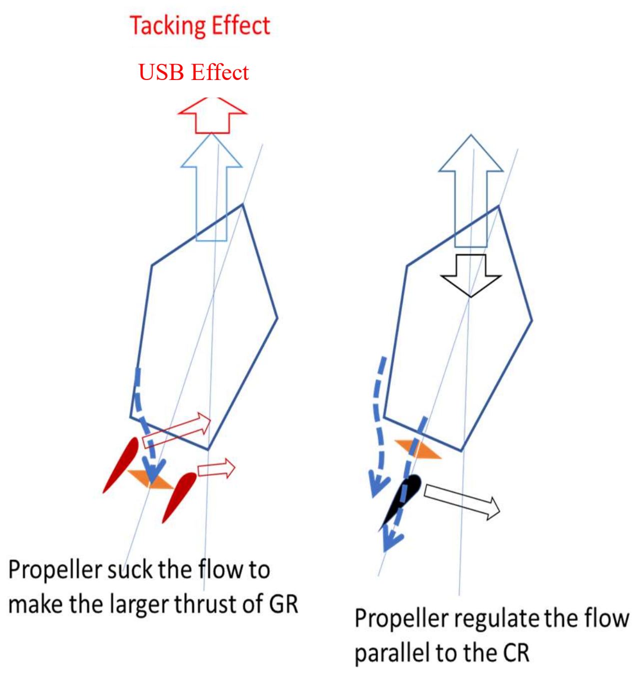


Figure 11 Gate rudder thrust at actual sea

- A second factor is also at play as depicted in Figure 11. The gate rudder also works like the sails of a sailing vessel in the water. The propeller increases this sail performance by means of the so-called USB (Upper Surface Blowing) technology like an aero-plane wing, while the conventional rudder works in the deflected flow of a propeller slipstream which deteriorates the sail performance. The same effect of the gate rudder on rolling motion can be also expected.

Recently, it was also revealed that the gate rudder can improve the course keeping ability for the vessel with unstable characteristics which can be seen in beamy ships or slender ships with the extremely flat and wide stern. The modern energy-saving container has a large open stern and high superstructure for the visibility, hence it can easily sacrifice the course keeping ability.

The gate rudder is so effective that the manoeuvrability of such kind of ships in adverse conditions can be improved remarkably by supporting those mentioned above as the superior hydrodynamic features of this system as summarised in Figure 12.

Finally, there are serious concerns regarding the sufficiency of propulsion power and steering devices to maintain manoeuvrability of ships in adverse conditions, hence regarding the safety of ships if the EEDI requirements are achieved by simply reducing the installed engine power. The gate rudder is the most efficient and promising measure for this conflict between the EEDI and MPR (minimum power requirement).

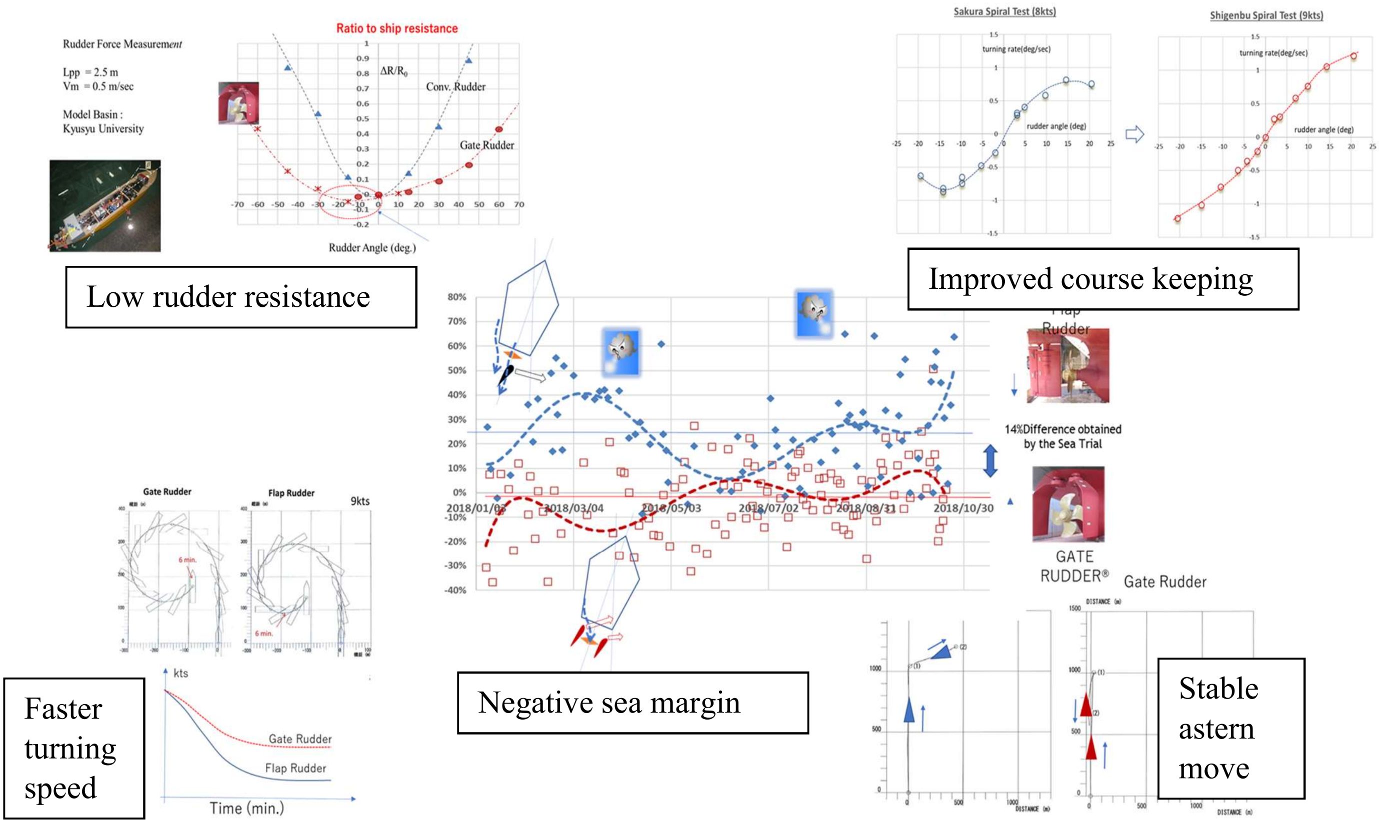


Fig. 12- Superior hydrodynamic features of the gate rudder system

4. Conclusions

22 months have passed after the delivery of Shigenobu, the world first vessel equipped with the gate rudder system. A lot of full-scale data from not only the sea trial but also performance in-service condition has been accumulated and evaluated. The fuel-saving more than 20%

which is superior to the result of the speed trial during the sea trial is the most remarkable fact, however it was also revealed that the difference between the calm sea performance and actual sea performance is originated from the very interesting characteristics of the gate rudder system, which can be summarized as follows:

- Gate rudder blades are working as twin sails of a yacht which can generate thrust in the against wind conditions (tacking). The thrust is huge because the thrust of the gate rudder is 828 times larger than the sail in the air when when compared them at the same speed and same area because of the ratio of fluid density (at 20 deg.).
- The propeller position to the rudder blade(s) has an important role. The rudder blade behind the propeller will not work as the gate rudder blades because of deflected flow due to the propeller's action. There is a similarity to the USB (upper surface blowing) function of an aeroplane so that the vessel with the gate rudder system takes the advantage of this function.
- The strong thrust force generated by the gate rudder system at the stormy condition will assist the manoeuvrability and hence the system can be the best solution for MPR (minimum power requirement) of ships in-service as required by the regulations

5. Nomenclature

A_P	*Propeller disc area (m^2)*	A_R	*Rudder area (m^2)*
F	*Towing Force (N)*	C_T	*Prop. loading coefficient*
DHP	*Delivered horsepower (kW)*	EHP	*Effective horsepower (kW)*
GR	*suffix of Gate Rudder*	J	*Propeller_advanced ratio*
N	*Propeller revolutions (rps)*	R	*Resistance (kN)*
T	*Thrust (kN)*	T_P	*Propeller thrust (kN)*
T_{GR}	*Gate Rudder thrust (kN)*	V_A	*Propeller advanced speed (m/s)*
V_S	*Ship speed (m/s)*	ρ	*Water density (kg/m^{-3})*
κ	*Correction factor*	η_D	*Propulsive efficiency*

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