GATE RUDDER

Noriyuki Sasaki*, Sadatomo Kuribayashi, Mehmet Atlar***
***University of Strathclyde, Scotland, UK,**
noriyuki.sasaki@strath.ac.uk, mehmet.atlar@strath.ac.uk
****Kuribayashi Steam Co., Japan**
kuribayashi@kuribayashi.co.jp

Abstract

This paper introduces an innovative propulsion system which may not be categorized as a conventional energy saving device and it has not been even fully explored so far. Yet this system, which is called "GATE RUDDER ", has been already applied for the first time on a 2400 GT container ship and full-scale sea trials were conducted successfully in November 2017 in Japan. The new concept stemmed from a new idea of propulsive efficiency, called "Elementary Propulsive Efficiency", that may be exploited by any arbitrary shape and arrangement of propulsor system apart from a conventional propeller-rudder system. The recent full-scale trials with 110m Japanese domestic container vessel have confirmed the superior performance of the GATE RUDDER system which is not only a remarkable energy saving (~14%) achieved over her sister ship fitted with a conventional (flap) rudder-propeller system but also it has other favourable performance characteristics (e.g. superior manoeuvrability, quieter aft end etc.) as discussed in the paper. The Authors believe the innovative GATE RUDDER system might eventually take place of the conventional high lift rudders for steering ships.

Keywords: GATE RUDDER, duct effect, two bladed rudder, energy saving, elementary propulsive efficiency

1. Concept Definition

There is no doubt that a rudder is one of the appendages more significantly contributing to the resistance of a ship during her navigation (see Fig. 1). This has been largely accepted because no one can expect that the rudder could be a most powerful energy saving device exceeding the common expectations. Naval architects also long believed that a rudder with strong maneuverability in a port tends to have rather unfavorable characteristics for propulsive performance because of its higher resistance due to the special section or a flap behind the rudder blade. There have been a lot of ideas to combine a rudder and a propeller as one unit such as a steerable ducted propeller and a podded propulsion system (Carlton, 2012), however these propulsion systems work for limited applications and they are compromised systems which is not delivering the best for the propulsive and maneuverability performances.

In this paper, a new concept of propeller-rudder arrangement, called “GATE RUDDER” (Sasaki et. al. 2015) is introduced. This innovative rudder system has two rudder blades with asymmetric sections located aside the propeller (see Fig. 2). The blades can be controlled independently via an independent rudder stock for each blade. Owing to a duct effect of the two rudder blades, the system can achieve excellent performance for not only maneuverability but also for superior propulsive performance.

Fig. 1. Wave generation by a rudder of the most up-to date container ship and cargo liner

Fig. 2. Installation of GATE RUDDER on a container ship built by Yamanaka Ship Yard

The Authors believe that the idea behind the GATE RUDDER system is the recovery of viscous energy loss by the propulsion system, which is a phenomenon not well-known even to experts. In the following section of the paper this energy loss component and its recovery is explored further.

2. Recovery of Viscous Energy Loss

2.1. Improvement of Propulsive Efficiency

It is not obvious that a ship's propeller absorbs the waste energy caused by the hull surface and its wake which manifest itself as the viscous hull resistance (Sasaki 2011). The hull form designer therefore always tries to collect and guide all the stream lines into the propeller plane as much as possible. The viscous resistance loss is transported by each stream line as the momentum loss. If the propeller with diameter D_P is working in the flow region exposed to this momentum loss, the propulsive efficiency increase of the vessel with speed V_S can be estimated according to following formula:

$$\frac{\eta'}{\eta} = \frac{1-w_P}{1-w_P-w_V} \cdot \frac{1+\{1+C_T(w_P)\}^{0.5}}{1+\{1+C_T(w_P)+\Delta C_T(w_V)\}^{0.5}} \tag{1}$$

with

$$C_T = \frac{8 \cdot R(V_S)}{(1-t)\rho V_S{}^2 (1-w_P-w_V)^2 D_P{}^2} \tag{2}$$

where η is the propulsive efficiency. w and C_T are the wake fraction and the propeller thrust loading coefficient respectively. C_T can be calculated by equation (2) using water density ρ and the ship resistance R at the ship speed V_S. The wake fraction w can be divided into w_P and w_V as the potential part and viscous part, respectively.

Fig. 3 shows the actual data of C_T and w for existing vessels. A clear relationship between the two parameters can be found.

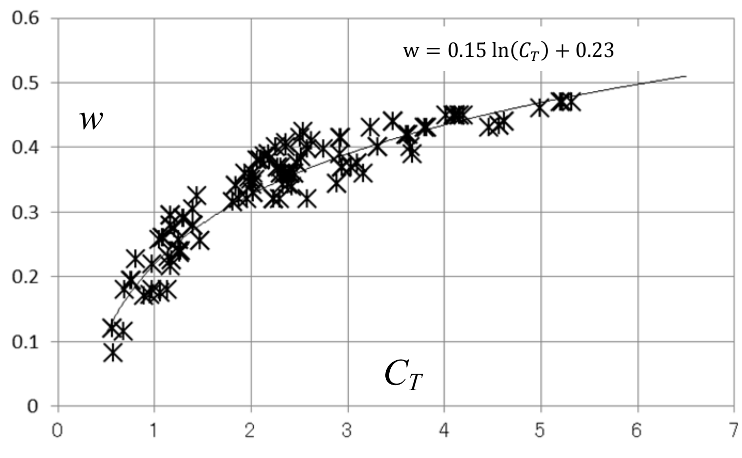

Fig. 3. Relationship between propeller thrust loading coefficient and wake fraction

Fig. 4 shows the improvement of propulsive efficiency $\frac{\eta'}{\eta}$ for increment of propeller diameter (10%, 20% and 30%) and wake fraction respectively

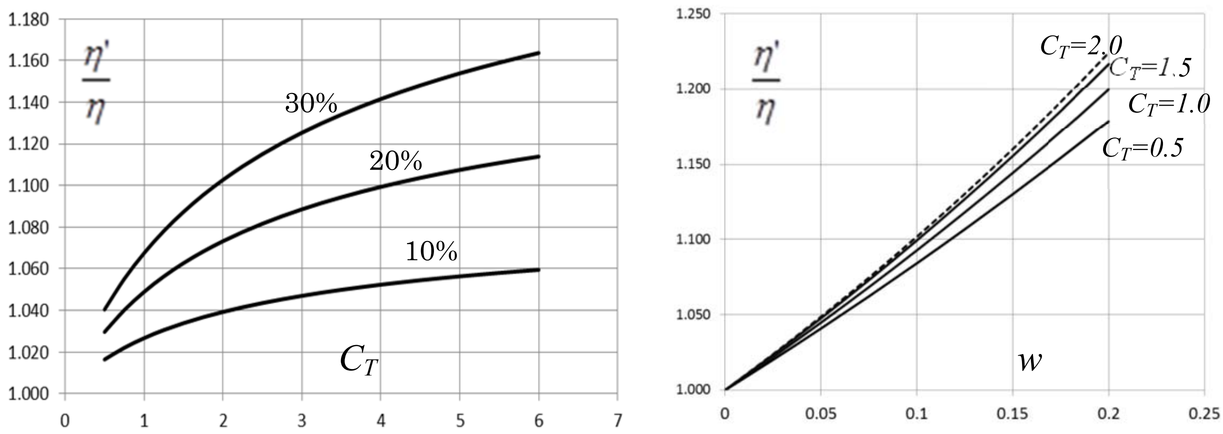

Fig.4. Effect of enlarged propeller (left) and wake gain (right) on better propulsive efficiency

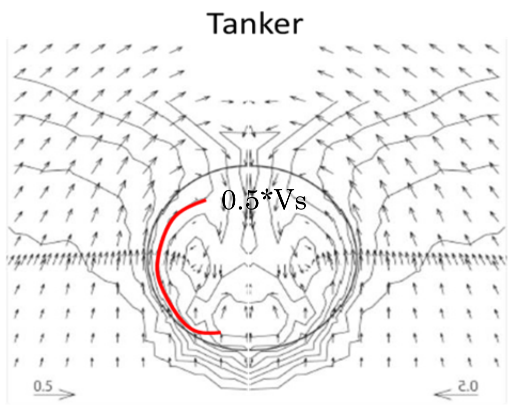

Fig. 5. Wake distribution of Tanker

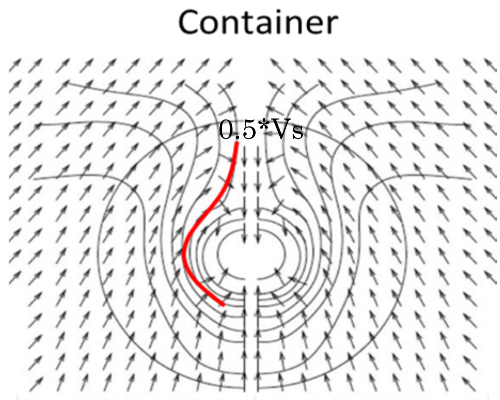

Fig. 6. Wake distribution of Container

Fig. 5 and Fig. 6 show wake distributions on a propeller plane for a tanker and container respectively (Suzuki et al. 2015). It can be seen there are two groups of dominant wake flows. The first group is a pair of wake flows at the lower part of the propeller plane while the second is upper part outside of the propeller plane. The first group is formed by the bilge vortices three dimensionally separated from both bilge corners while the second group of wake is generated by the boundary layer growth on the hull surface at the upper part.

2.2. Elementary Propulsive Efficiency

According to the propulsion theory, the definition of propulsive efficiency can be as follows:

$$\eta = \eta_P \cdot \frac{1-t}{1-w} = \frac{2\kappa}{1+(1+C_T)^{0.5}} \cdot \frac{1-t}{1-w} \quad (3)$$

Fig. 5 and Fig. 6 lead to a good idea to form the propulsor as large as possible to reduce the thrust density and each thrust element should be located in the lowest velocity field and far from the hull surface in travel (x axis) direction. By introducing a wing section with an attack of angle α in the most efficient way, an elementary propulsive efficiency η_i can be represented as in the following formula as function of the angle of attack α and local wake fraction w_i .

$$\eta = \frac{TVs}{DHP} \quad (4)$$

$$\eta = \frac{\sum SPi\alpha^2(1-\mathrm{t})(1-wi)^2}{\sum \quad DHPi}\pi\gamma\rho Vs^3 \quad (5)$$

where S_{Pi} is the projected area of elementary propulsion producing thrust T. γ and ρ are the lift slope correction and the density of the water, respectively.

Fig. 7 shows an example of ideal propulsor which will give the best propulsive efficiency for a ship if the thrust element can be established in this special form.

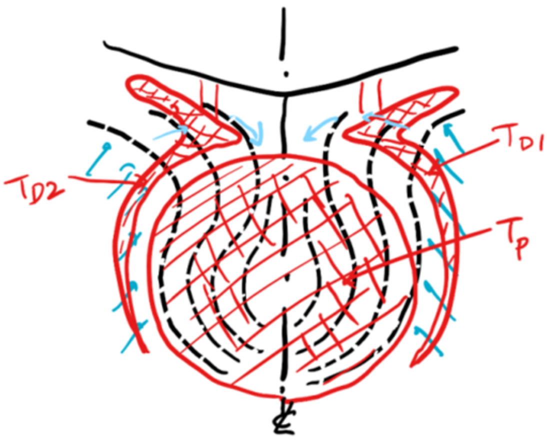

Fig. 7. Ideal shape of propulsor with the best propulsive efficiency

3. Idea of GATE RUDDER

According to the above analogy, an extremely large square duct with a propeller was designed so as to catch both groups of the above mentioned wake flow. The differences between this ducted propeller arrangement (ie. GATE RUDDER) and a conventional ducted propeller can be listed as follows:

(1) The size of the duct is extremely large (120%-140% of a propeller diameter)
(2) The duct shape is not circular as regular ducted propeller to obtain the best elementary propulsive efficiency
(3) The duct is split into two parts at the center and the each part can work as a single rudder independently
(4) The bottom part of the duct was removed because the elementary propulsive efficiency is rather low

In addition, the replacement of the conventional rudder with the GATE RUDDER can provide an attractive ship stern design and easy maintenance opportunities that can be exploited in different ways as follows:

(5) The overhang part of the stern which was occupied by the conventional rudder can be saved and the ship length can be shortened.
(6) The propeller can be placed further aft with the removal of the conventional rudder and the engine room can be moved towards the stern, which can improve the cargo capacity for the same ship length
(7) It is also possible to apply a better streamlined stern in front of the propeller to improve propulsive performance for the same ship length
(8) The replacement of the conventional rudder with the GATE RUDDER will provide a better access to the propeller and shafts for maintenance purposes.

4. First Full-Scale Application of GATE RUDDER on a Container Ship

4.1. General

It has been believed that the performance of container ships can be expected to improve but with difficulty by using energy saving devices (ESD). The level of energy savings has been 3-5% using existing types of ESDs because of the recovery method, which is very simple and it states that it is not possible to save energy more than energy loss in the target zone. In the above case, the target zone is the propeller disc and the swirling loss of fluid due to the propeller rotation which remains the only energy source left to be recovered.

As discussed earlier, the duct type of energy saving devices aims to recover viscous resistance loss by collecting the streamlines distorted by the hull surface with viscosity. It is notorious that these types of energy saving devices are the most efficient compared to other ESDs. However, the duct type of ESDs have not been applied to the fine forms of ships, like container vessels, as it is hard to find a distorted viscous layer near the propeller plane except the upper part farther from the propeller disc, as shown in Fig. 6.

4.2 Main Particulars of the Container Ship

Table 1 shows the main particulars of the container ship which is fitted with the GATE RUDDER. Her sister vessel has exactly the same dimensions but was fitted with a conventional flap rudder and she was launched one year before. Fig.8shows photos of both configurations. It was therefore thought to be a good opportunity to compare these two vessels performances based on the sea trial results and their voyage data by selecting the same route and period.

Table 1. Principal dimensions of two sister ships with different rudders

	Ship A (Flap Rudder)	**Ship B (GATE RUDDER)**
Loa (m)	111.4	111.4
Lpp (m)	101.9	101.9
B (m)	17.8	17.8
d (m)	5.24	5.24
Main Engine	3309kW/220rpm	3309kW/220rpm
Prop. Dia. (m)	3.48(CPP)	3.30(CPP)
Rudder Type	Flap rudder	GATE RUDDER
Draft at Sea Trials (m)	4.30	4.30

Fig. 8. Flap Rudder (Ship A) on the left and GATE RUDDER (Ship B) on the right

4.3. Sea Trials

Sea trials were conducted at Seto-uchi Sea of Japan according to a standard procedure including the double run method, in the same direction and same position, as shown in Fig. 9. Speed trials of ship A (Flap Rudder) and ship B (GATE RUDDER) were conducted at the same place with the same procedure on 27th July 2016 and 16th Nov 2017 respectively. The test conditions of both vessels were exactly the same as shown in Table 1. Fig.10 shows the weather conditions for the two vessels. The weather condition of ship B (GATE RUDDER) was rather worse compared with the weather condition of ship A (Flap Rudder) as can be seen from Fig. 10. It was concluded that the measured data should be corrected by taking the wind and wave effect into account addition to the correction of current.

Fig. 9. Sea Trials Site and Weather Observatory Point of Japan Meteorological Agency

The wind velocity was measured with the instruments at the bridge. The measured data was compared with the official weather records measured by JMA (Japan Meteorological Agency) for a location 11 miles away. Fig. 10 shows the comparison of the two data. The measured data seems reasonable, being very close to the JMA mean data. The wave height was decided based on eye sight judgement and video films were used for on-shore evaluation purposes by an expert following the trials.

Fig.11 shows the measured power in kW both raw data and analyzed data. From this figure, it was concluded that the power saving of GATE RUDDER is around 14%.

The engine performance data of two vessels were examined and it was confirmed that the two engines were showing almost the same measured engine performance (SFC). It is well known that the measured power at sea trial could be very low if the SFC was very poor. For the ship owner, the relationship between fuel consumption and ship speed is more important than relationship between power and ship speed.

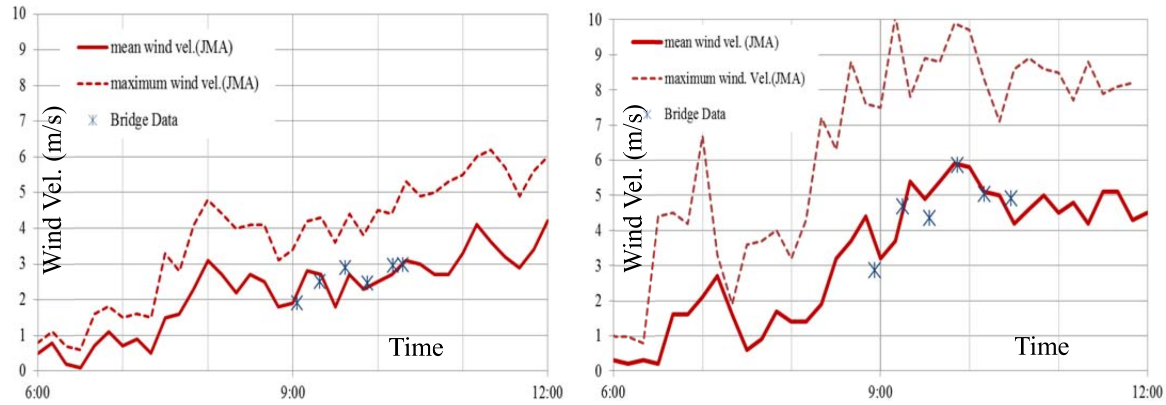

Fig. 10. Wind force records for Ship A (left) and Ship B (right)

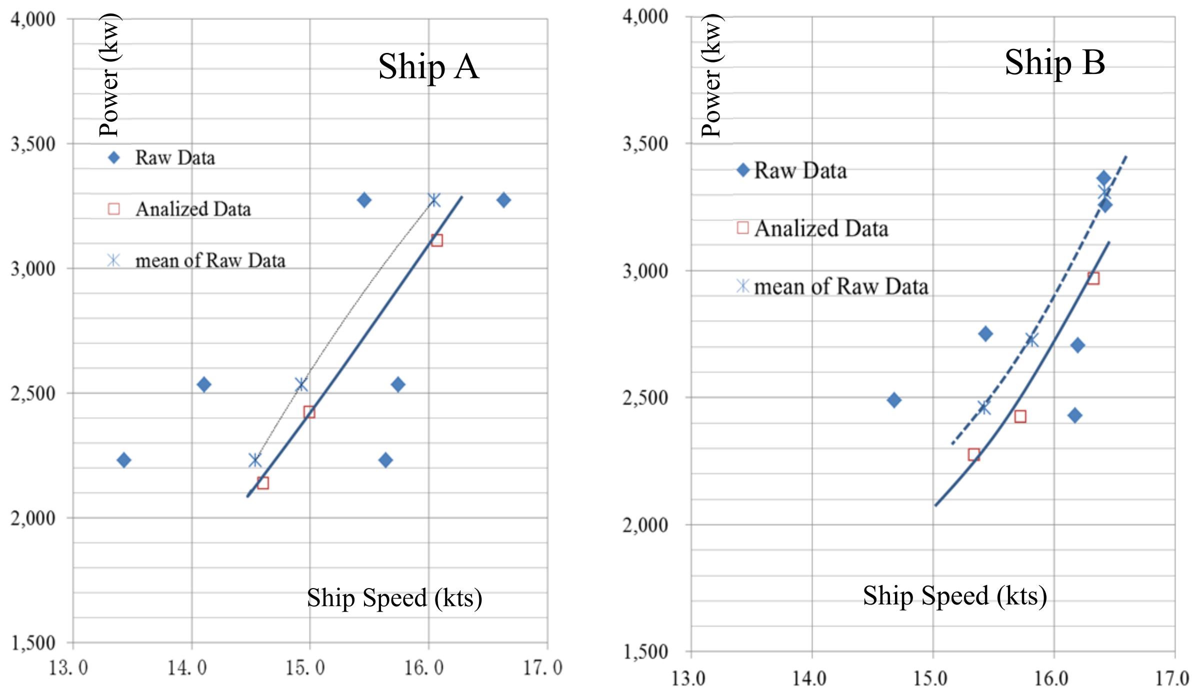

Fig. 11. Speed trial results of Ship A (Flap Rudder) and Ship B (GATE RUDDER)

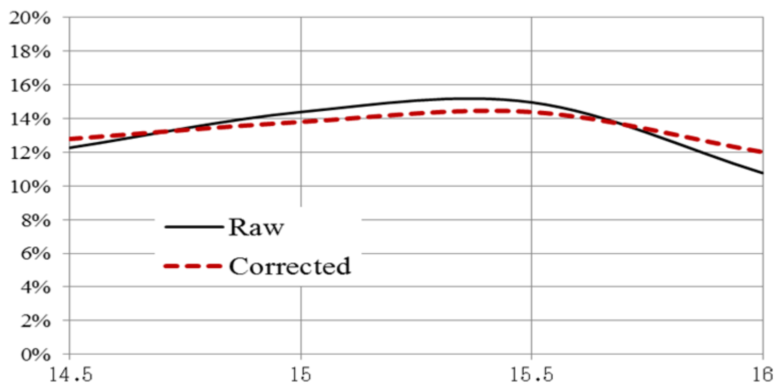

Fig. 12. Power saving by GATE RUDDER obtained from speed trial data

As the domestic vessels have the same feature, which is ship/engine size and propeller rudder configuration, it seems that the obtained power saving can be applied to all existing vessels. Based on this assumption, Fig. 13 is presented to show the impact of the GATE RUDDER on the environmental from the GHG emission point of view and on the economical market of domestic vessels.

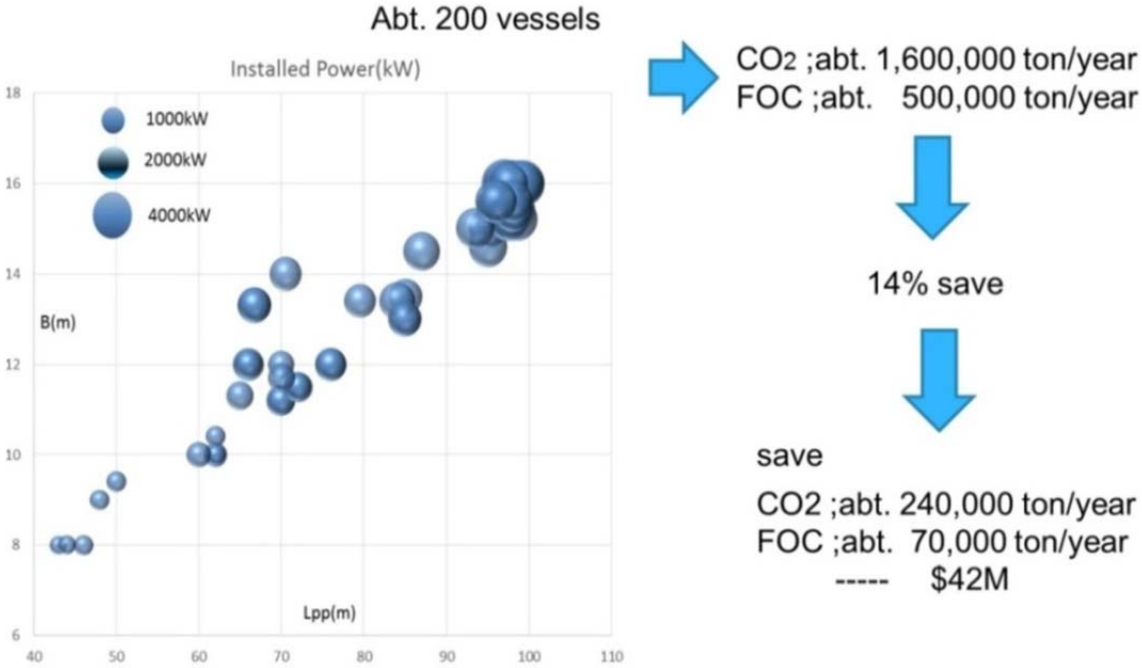

Fig. 13. Environmental and economic impact of GATE RUDDER on domestic vessel market

4.4. Maneuvering

In order to predict the motion of the ship with GATE RUDDER, several model tests were conducted, a maneuvering simulation program was developed by Newcastle University and Kamome Propeller (Turkmen et al. 2016, Carchen et. al. 2017) based on these model test data and several other investigations.

A modified Maneuvering Modelling Group (MMG) model was used for the prediction of a ship motion with GATE RUDDER as shown in Fig. 14. The main difference from the original MMG model is a prediction procedure of the rudder forces. Major modification is the rudder force of the GATE RUDDER which varies depending on the rudder position around the propeller. Axial velocity u_R and lateral velocity v_R are investigated not only by captive model tests (see Fig.15), but also by CFD calculations and following new equations are introduced:

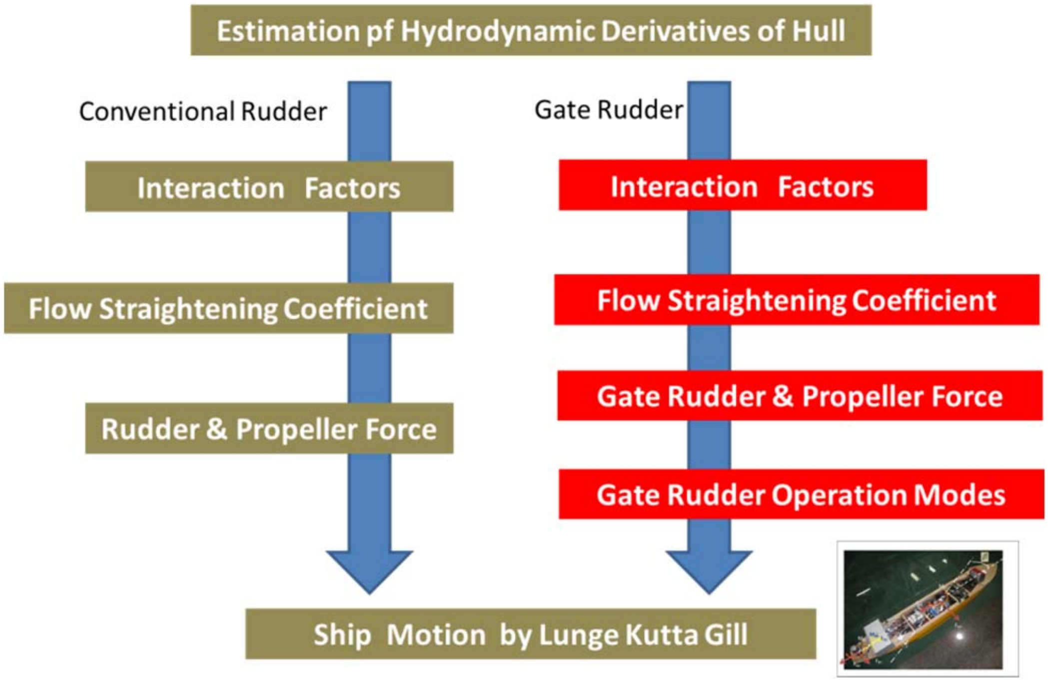

Fig. 14. Simulation flow of maneuvering motion of a ship with GATE RUDDER

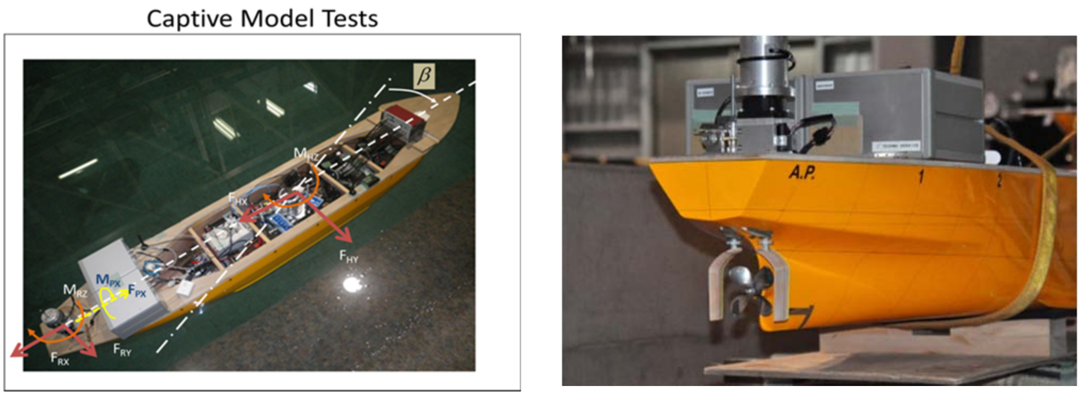

Fig. 15. Captive model test at Kyushu University

for the area behind the propeller

$$u_R = \varepsilon(1-wp)(1+\kappa(1+C_T)^{0.5}) \tag{6}$$

for the area outside of the propeller slip stream

$$(v_R)_P = 0.15 - 0.001\delta_P + 0.01\beta \quad \cdots \quad \text{for port side rudder} \tag{7}$$

$$(v_R)_S = -0.15 - 0.005\delta_S + 0.005\beta \quad \cdots \quad \text{for starboard side rudder} \tag{8}$$

Here, rudder angles δ and yaw angles β are given in degrees and the velocities components are non-dimensionalized by the ship's speed U. In order to predict the rudder force under the condition of partially covered by the propeller slip stream, the following new equations were introduced;

$$
\begin{aligned}
u_{R1} &= 0.85 - 0.0015\delta \\
u_{R2} &= \varepsilon(1-wp)(1+\kappa(1+C_T)^{0.5}) \\
\mu &= \frac{A_{CV}}{A_R \cdot \eta} \\
F_N &= F_{N1}\cdot(1-\mu) + \mu \cdot F_{N2} \\
F_{N1} &= \frac{1}{2}\rho u_{R1}{}^2 A_R C_{L1}\cos(\delta - \frac{v_{R1}}{u_{R1}}) \\
F_{N2} &= \frac{1}{2}\rho u_{R2}{}^2 A_R C_{L2}\cos(\delta - \frac{v_{R2}}{u_{R2}}) \\
C_{L1} &= \frac{6.23}{2.25+\lambda}\sin(\delta - \frac{v_{R1}}{u_{R1}}) \\
C_{L2} &= \frac{6.23}{2.23+\lambda}\sin(\delta - \frac{v_{R2}}{u_{R2}})
\end{aligned}
\tag{9}
$$

where F_N is the rudder normal force and C_L is the lift coefficient.

$$
\begin{aligned}
A_{CV} &= A_{TE} - A_{LE} \\
A_{TE} &= \theta_T \cdot \frac{D_P{}^2}{4} - \frac{R \cdot L_{TE}}{2} \\
\theta_T &= \sin^{-1}(\frac{L_{TE}}{2R}) \\
A_{LE} &= \theta_E \frac{D_P{}^2}{4} - \frac{E \cdot L_{TE}}{2} \\
\theta_E &= \sin^{-1}(\frac{L_{LE}}{2R})
\end{aligned}
\tag{10}
$$

where, L_{LE} and L_{TE} are the projected length of the leading edge and the trailing edge of the rudder blade, respectively. R and E are the transverse distance from the ship center line of the rudder trailing edge and the rudder leading edge respectively.

Fig. 17 and Fig. 18 show the simulation results of 35 deg. circle test for a model scale and a full scale, respectively. The simulation program was developed based on the captive test of a 2.5m similar model (see Fig. 15) however, the full scale flow field of GATE RUDDER is quite different from the model ship. The reason is that the flow surrounding the GATE RUDDER is almost outside of the boundary layer while the flow field of the conventional rudder is still inside. According to the paper presented by Kuribayashi et al. (2015), the rudder force can be modified in order to predict full scale maneuverability. The difference can be seen clearly in Fig. 17 and Fig. 18

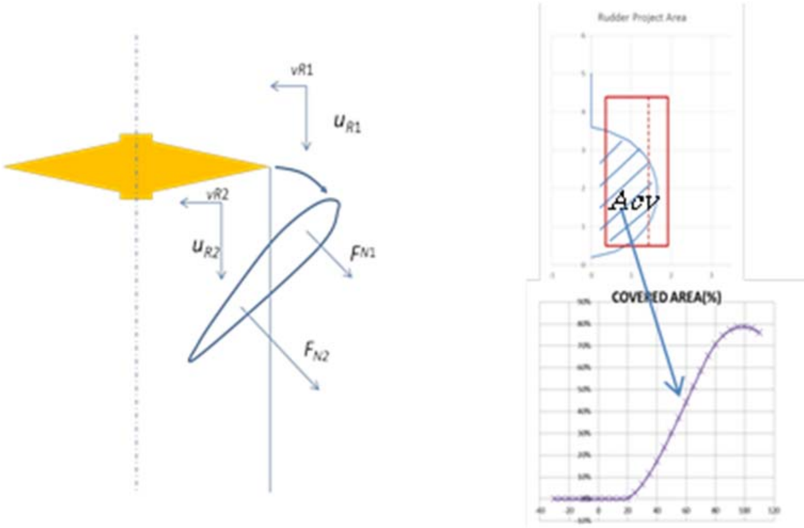

Fig.16. Illustrations related to Equation 9 and Equation 10

.

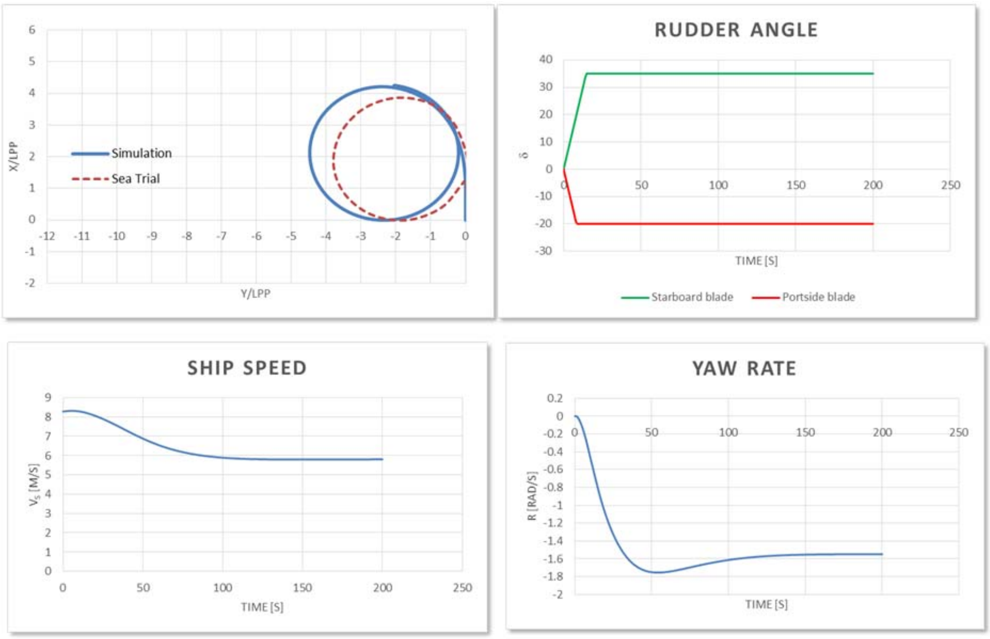

Fig. 17. An example of simulation results for steady turning (Model Scale)

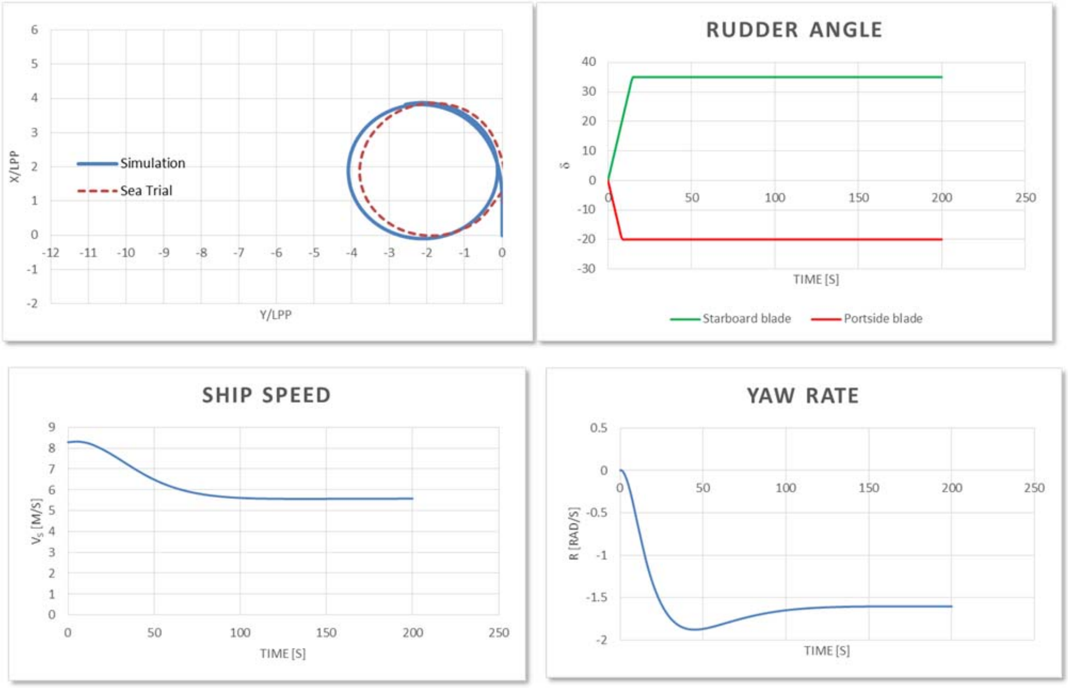

Fig. 18. An example of simulation results for steady turning (Full Scale)

The full scale sea trial for the spiral test was conducted on 14th November 2017 prior to the official sea trial and the result is shown in Fig. 19 with the simulation result previously explained.

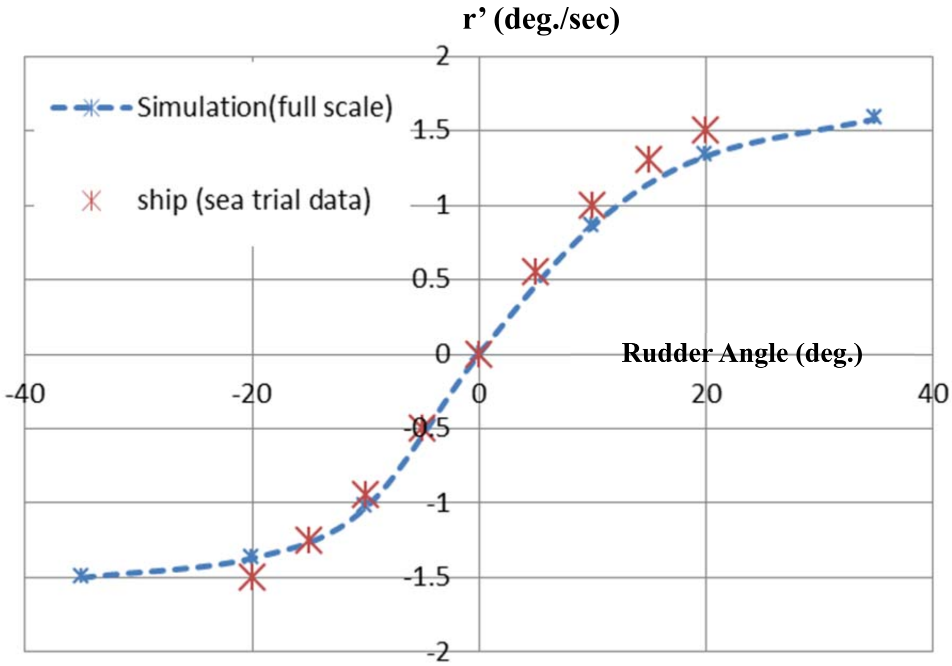

Fig. 19. Result of full scale spiral test and simulation results

The GATE RUDDER has very high lift to drag ratio compared with a conventional high lift rudder. The resistance of the GATE RUDDER shown in Fig.20 is lower than 50% of the conventional high lift rudder. This remarkable feature fosters the following advantages;

(1) The speed drop due to helm angle is very small and this contributes to both energy saving and safety in stormy weather condition, because a ship without enough speed will bring risks of loss of controllability.
(2) Circular motion is very quick and steady.

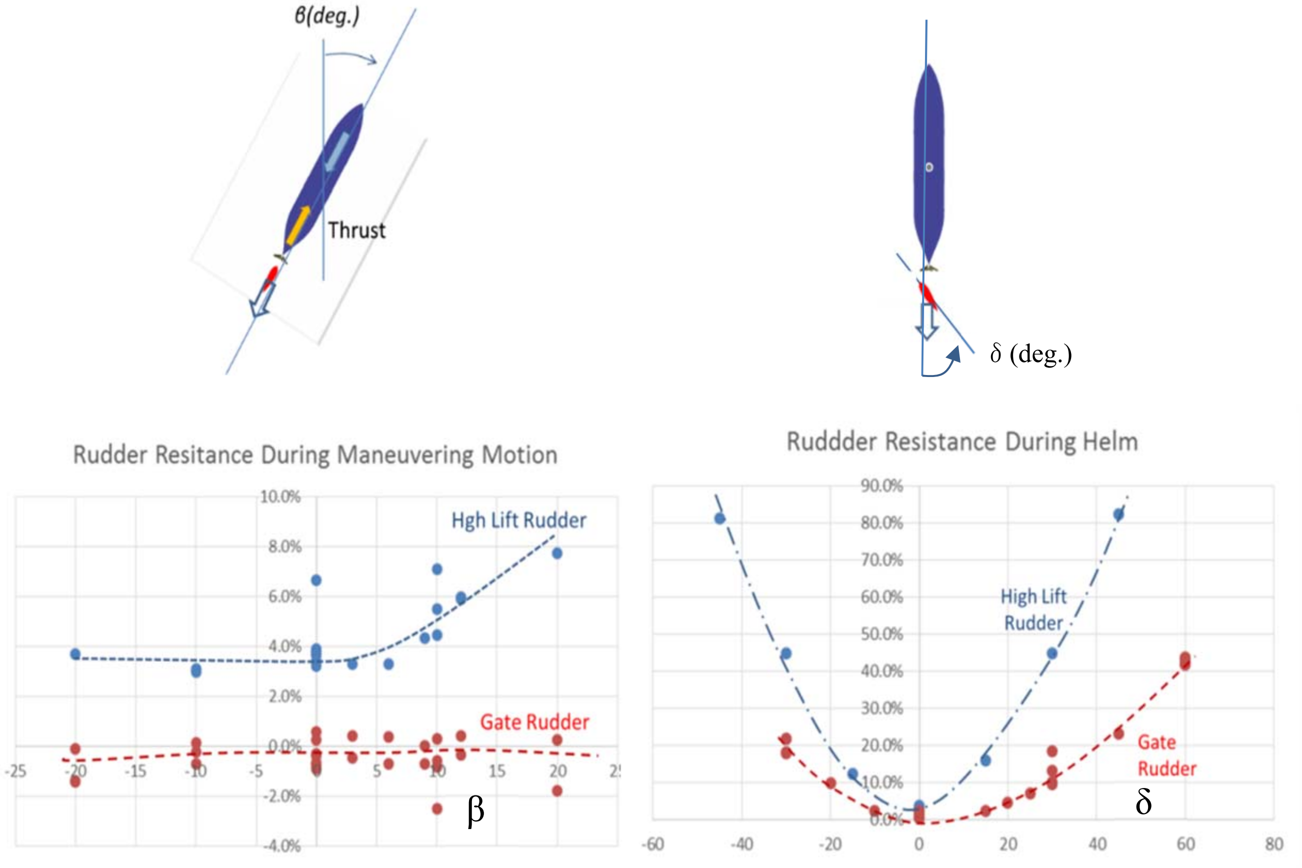

Fig. 20. Variation of rudder resistance (% of Thrust) due to maneuvering motion

The difference of rudder resistance during the maneuvering motion can be seen clearly in the low speed circle tests shown in Fig. 21 which were obtained from sea trials of both vessels. The ship with GATE RUDDER shows the quicker circle motion than the ship with flap rudder.

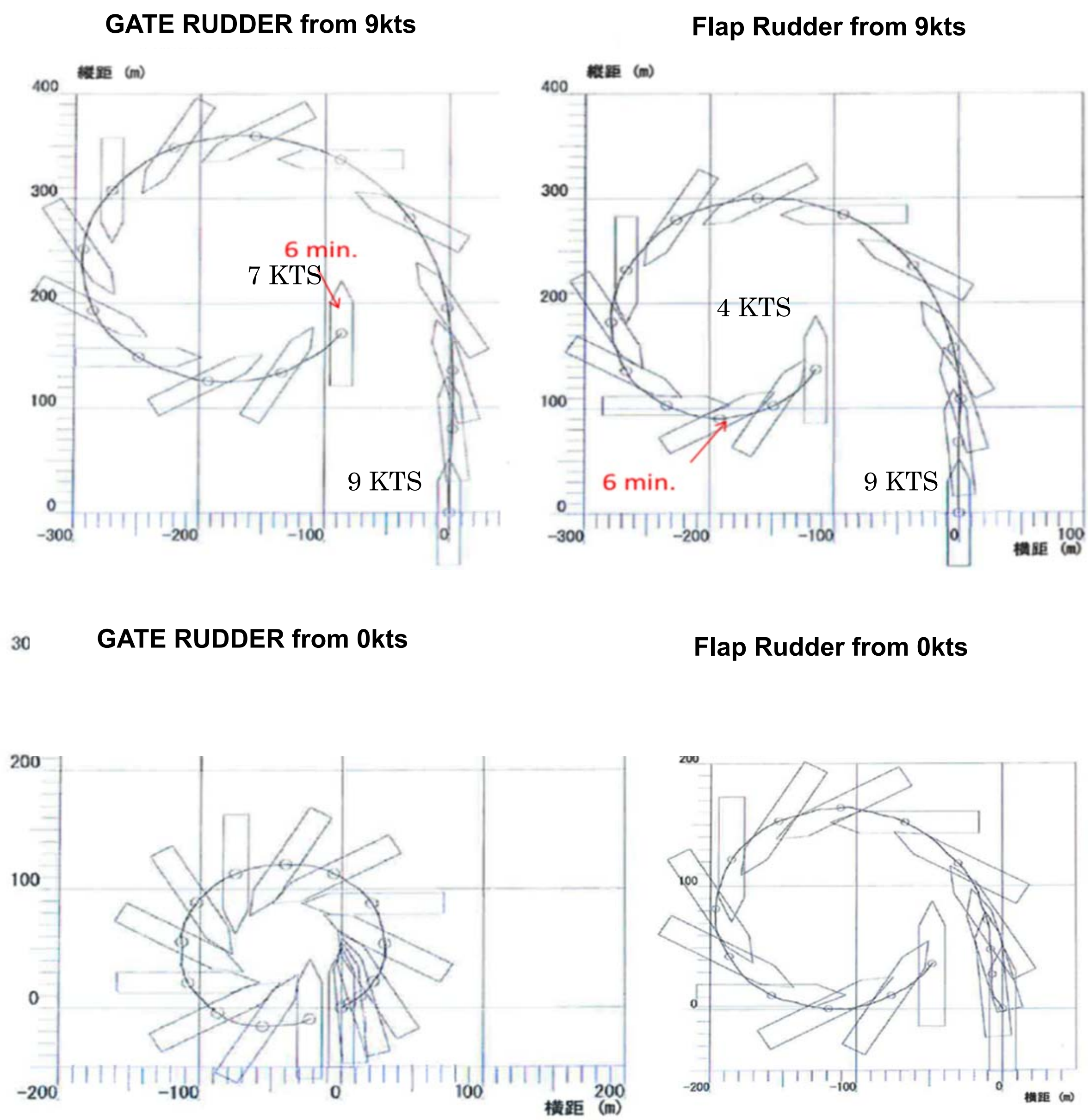

Fig. 21. Full scale Circle Tests for Ship A and B (Flap Rudder/GATE RUDDER)

The maneuvering test was conducted during two days and summarized in the Table 2.

Table 2. Summary of Steering and Maneuvering Tests

		Portside	Starboard	mean
Circle (35deg.)	Tactical Dia./L	3.19	3.26	3.23
Vs0=16.1kts	Advance/L	3.85	3.55	3.70
Circle (70deg)	Tactical Dia./L	2.69	2.59	2.65
Vs0=9.0kts	Advance/L	3.35	3.40	3.38
Stopping	15.3kts→0kts	-	-	6.7
Distance/L	0kts →16.1kts	-	-	16.3
10 Z maneuver	1 st OSA	11.1	11.1	11.1
(O.S.A in deg.)	2nd OSA	26.7	26.6	26.7
Crabbing	Tactical Dia./L	0.75	0.47	0.61
	Advance/L	0.87	0.52	0.69

In conclusion, the ship has a both superior turning and course keeping ability. The response of the rudder is very smooth as we can see the result of spiral test shown in Fig. 19.The rudder blades have a camber and attack angle even at the position of zero helm angle due to the interaction between the rudder blade and propeller. The interaction model is based on a simplified propeller theory (Yamasaki, 1962, Nakatake 1981) and a vortex lattice method (Lan, 1974) was established as shown in Fig. 22.

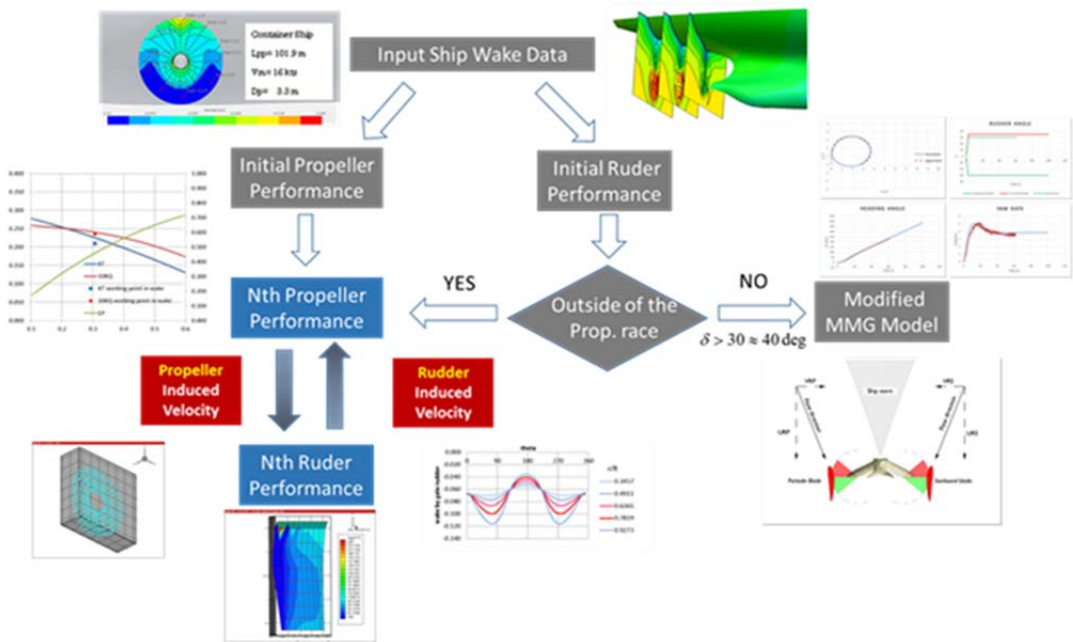

Fig. 22. Systematic design flow of GATE RUDDER based on VLM, SPT and modified MMG

Load distribution on the rudder blades is also important to calculate. The stress due to forces and moment were predicted by using finite element method (FEM). Fig. 23 shows the example of the load distributions for the helm angles at zero degree (left) and 25 degrees (right). The load distributions are viewed from inside. The blue and red colours indicate suction force and pressure force, respectively. The force towards inside (ship center line) can be seen when the rudder angle is zero. This is mainly due to propeller induced velocity calculated by the simplified propeller theory.

$$F_X = \sum_{i=1}^{M}\sum_{j=1}^{N} L_{ij} \sin \propto_g ij \qquad U^* = (Ux^2 + Uz^2)^{0.5}$$
$$F_Z = \sum_{i=1}^{M}\sum_{j=1}^{N} L_{ij} \cos \propto_g ij \qquad \propto_g = \frac{Uz}{Ux} \qquad (11)$$
$$L_{ij} = \rho U^* \cos(\alpha_g - \alpha_g ij)\Gamma_{ij} S_{ij} \qquad \propto_{gij} = \left(\frac{\partial z}{\partial x}\right) ij$$

where F and L are total force acting on the rudder blade and lift force distributed on the surface of the rudder respectively. The lift force L can be calculated by using circulation Γ, velocity U and flow angle α. The suffix x,y and z represents its direction x, y and z respectively.
The suffix ij means the panel number which arranged by m-row and n-column.

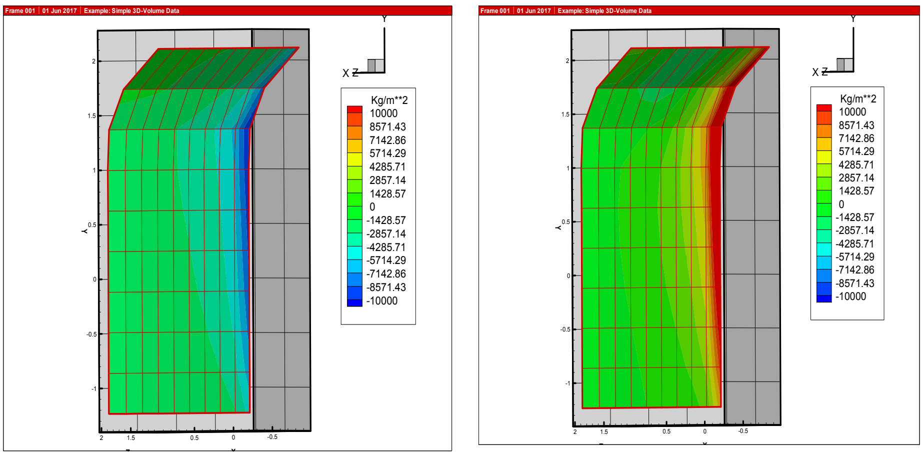

Fig. 23. Load distributions on the ruder surface (camber surface) calculated by VLM

5. Concluding Remarks and Future Work

- The analyzed data for both sea trial and voyage data indicate abt. 14% of fuel saving for the vessel fitted with GATE RUDDER over her sister ship. The predicted energy saving was 8-10% from the study of the model test and numerical study, while the full scale data revealed a remarkable saving 14%. The discrepancy is still very large and this should be investigated with further research which should concentrate not only on the steady state conditions but also on the actual sea conditions where the ship needs small helm to keep the course.

- The above research should be supported by the continuous analysis of the voyage data. The on-board monitoring plan, therefore, has been decided to measure the shaft power by torque meter and the effect of wind waves by using onboard equipment as well as other available data. A dedicated engineer on-board the container vessel will be coordinating this equipment support action.
- During the full-scale trials extremely low wake wash of the vessel with the GATE RUDDER was noted by observations as well as from the video records (see Fig 24). This requires further investigations for the effect of the new rudder system on the stern wave characteristics.
- Finally, the computer simulations and model tests indicated the resistance characteristics of the GATE RUDDER during the maneuvering motion are rather different from those of the conventional rudders and the magnitude of the resistance of GATE RUDDER is less than 1/4 that of a flap rudder. This feature will make a ship safer in the heavy sea conditions such as Beaufort Scale 7 and the GATE RUDDER will be assisting the propeller by producing additional thrust. On this basis it will be very interesting to compare the ship motions of the same vessel with different rudder configurations (conventional rudder vs GATE RUDDER) to take advantage of the motion control by using the GATE RUDDER more effectively.

Fig. 24. Wave generation by conventional rudder (left) and low wake wash of GATE RUDDER (right)

Acknowledgements

The Authors would like to thank their colleagues Dr Serkan Turkmen, Dr Weichao Shi, Mr Alessandro Carchen, Mr Alessandro Marino, Mr Masaki Fukazawa, Mr Hiroyuki Yanaizumi, Mr Masaki Yazawa, Mr Toshifumi Takeda, Mr Tamotsu Kurokawa and Mr Takao Nonaka for their help in the preparation of the manuscripts of this paper as well as their technical contribution into the development of the GATE RUDDER Concept.

This research was supported by Nippon Foundation.

References

Carlton J. (2012). Marine propeller and propulsion. 3rd Edition.

Carchen, A., Shi, W. and Sasaki, N. (2017). Gate Rudder maneuverability simulator. Project Report, Newcastle University

Sasaki, N., Atlar, M. and Kuribayashi, S. (2016). The new hull form with twin rudders utilizing duct effects, J Mar Sci Technol (2016) 21: 297.

Lan, C.E. (1974) A quasi-vortex lattice method in thin wing theory. Journal of Aircraft vol.11, No. 9 (1974), pp. 518-527.

Nakatake, K. (1981). Application method to calculate propulsive performance of ships. Memories of the Faculty of Engineering Kyusyu University vol 41.

Sasaki N., Atlar, M. and Kuribayshi, S. (2015). Advantage of twin rudder system with asymmetric wing section aside a propeller. Journal of Marine Science and Technology.

Sasaki, N. (2011). ZEUS project of NMRI, 1st World NAOE Forum, Osaka, Japan

Suzuki, K., Sasaki, N., Kawamura, T. (2018). Resistance and propulsion to be published by Seizando Shoten Publishing Co.

Turkmen, S., Carchen, A., Sasaki, N. and Atlar M. (2015). Anew energy saving twin ruder system, International Conference on Shipping in Changing Climates, Nov. 2015, Glasgow.

Turkmen, S., Sasaki, N., Atlar, M., Miles, A. and Takeda, T. (2016). The Gate Rudder application to improve poor course keeping ability of ships. A. Yücel Odabaşı Colloquium Series - 2nd International Meeting on Recent Advances in Prediction Techniques for Safe Manoeuvring of Ships and Submarines, 17-18 November, Istanbul, Turkey.

Yamazaki, R. (1962). On the theory of screw propellers. Proc. Symposium Nav. Hydro.

Yasukawa, S., Yoshimura, Y. (2015). Introduction of MMG standard method for ship maneuvering predictions. Journal of Marine Science Technology.