FULL SCALE PERFORMANCE OF GATE RUDDER

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SUMMARY

This paper introduces full scale performance results obtained from voyage data taken from two 2400 dwt container ships, one equipped with the world's first GATE RUDDER®. This is an innovative design, which is not seen as a conventional energy saving device and which has not been fully explored so far. The recent full-scale trials with this coastal container vessel have confirmed the superior performance of the GATE RUDDER® system which has shown 14% reduction in fuel consumption when compared with it's sister vessel having a conventional rudder system. After 12 months from delivery, the voyage data from both vessels revealed that in some situations the gain could be much larger at abt. 27%. In this paper, the full scale operational performance differences from not only the model test but also the sea trial result are presented.

NOMENCLATURE

C_T Propeller loading factor (-)
DWT Deadweight (ton)
H_W Significant Wave Height (m)
P_0 Power predicted by Tank Test (kW)
P_{ACT} Power measured in service (kW)
R_0 Hull resistance at calm sea (N)
R_A Additional resistance (N)
R_{AA} Additional resistance due to wind (N)
R_{AW} Additional resistance due to waves (N)
R_{AR} Additional resistance due to rudder (N)
R_H Increased hull resistance due to prop. (N)
R_{RC} Resistance of conventional rudder (N)
R_{RG} Resistance of gate rudder (N)
t Thrust deduction factor (-)
T_P Propeller thrust (N)
T_{PC} Propeller thrust of Conv. Rudder case (N)
T_{PG} Propeller thrust of Gate Rudder case (N)
V_W Relative wind velocity (m/sec)
w_E Effective wake factor (-)
w_N Nominal wake factor (-)
w_{NF} Frictional part of nominal wake factor (-)
w_{NP} Potential part of nominal wake factor (-)
w_R Potential rudder wake factor (-)
κ Resistance ratio to hull resistance (-)
κ_P Reduction ratio of main prop. thrust(-)
ψ Relative wind direction (deg.)

1. INTRODUCTION

Rudders are primarily applied on conventional ships for course keeping and manoeuvring. The fundamental studies have been published to investigate the rudder performance mainly from the aspect of manoeuvring.[1)2)] There are a few studies investigating the optimum rudder design for propulsive performance which give us useful information about the rudder positions such as longitudinal position, lateral position and vertical position etc..[3)4)5)]

Photo 1. Conventional Flap Rudder (upper) vs. Gate Rudder(lower)

Table 1 Principal dimensions of Sakura (Flap Rudder) & Shigenobu (Gate Rudder)

	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

However, a ship's rudder is one of the sources in contributing to the ship's resistance when it is located behind the propeller. Within this context, the main purpose of the Gate Rudder® system is to remove this source or rather replace with a thrust source (like a duct) in order to reduce the required main propeller, thrust and hence reduction of required engine power. 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.

The Gate Rudder® has two rudder blades with asymmetric sections, which are located adjacent to 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 ducted propeller and hence produce additional thrust, as opposed to the additional drag of a conventional rudder behind the propeller.[6)7)] Owing to this additional thrust by the Gate Rudder, the required thrust of the propeller as a main propulsor can be reduced more than 10%.

By introducing this ESD based on the simple idea, the interaction among propeller, hull and conventional rudder can be replaced by a completely different interaction scenario. These differences between the conventional rudder and the Gate Rudder systems are analysed theoretically in section 2 and 3.

Photo 1 and Table 1 show a comparison of the conventional rudder and the 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, thus the Gate Rudder® system presents not only more propulsive efficiency but also greater manoeuvrability. In addition to these two major advantages of the Gate Rudder® system, there are other performance superiorities, which are noticed based on further analysis of the voyage data, including reduced resistance during seakeeping performance as well as manoeuvring motion. Such preferred full scale features are explained in section 4 and 5.

2. GATE RUDDER; HOW IT WORKS

2.1 INTERACTION AMONG RUDDER, PROPELLER AND HULL IN CALM SEA

2.1(a) Conventional Rudder System

The propeller produces a much large thrust than the towed hull resistance. This is due to propeller action near the stern.

This scenario can be called vicious circle as shown in Figure 1 because the increase in resistance is proportional to propeller thrust and consequently the propeller thrust is making additional resistance due to this interaction.

The increased resistance ΔR due to propeller action and rudder is defined as follows;

$$\Delta R = \Delta R_H + \Delta R_{RC} \qquad \text{-------- (1)}$$

Where, ΔR_H is increased resistance due to interaction between the propeller and hull, and ΔR_{RC} is resistance of conventional rudder during propelling condition.

Assuming the hull resistance R_0 at towing condition as 100%, ΔR_H and ΔR_{RC} are ranged 15%-25% and 3%-7% respectively depending on stern geometry and rudder type and geometry. Hence, the total increase in resistance will be around 20%-30% in comparison with the hull resistance which was assumed 100%.

This interaction is called thrust deduction and the ratio to the total increase in resistance to the propeller thrust is called thrust deduction factor (t_H).

The thrust deduction factor (t_H) can be measured by the self-propulsion test and ranges from 0.15-0.23 when the resistance test is conducted without the rudder. The thrust deduction factor shows sometimes shows very low values such as 0.12 to 0.08. There are two reasons for this. One possibility is the case when the flow separation at the stern is significant when the propeller is not working. In this case, the resistance of original hull is extremely high due to this separation, however this does not happen during propelling conditions. Therefore, the thrust reduction factor does not indicate accurate values because it contains the effect of flow separation occurring from an unrealistic flow field during the resistance test. Another case is when the propeller is far from the stern boss end and the rudder is not behind the propeller plane. This can be seen in the case of twin screw vessels, and which is not our subject here.

For the typical example, the total increase in resistance due to the propeller action is 25% when t_H =0.20. This means that the required propeller thrust is almost 25% higher than the hull resistance at towing condition. If the rudder resistance ΔR_{RC} can be assumed 5% of the hull resistance, ΔR can be simply calculated at 30% of the hull resistance.

It is well known fact that thrust deduction factor (t_H) is constant with the variation of the propeller thrust. This means ΔR_H will increase (decrease) proportional to the increase (decrease) of the propeller thrust.

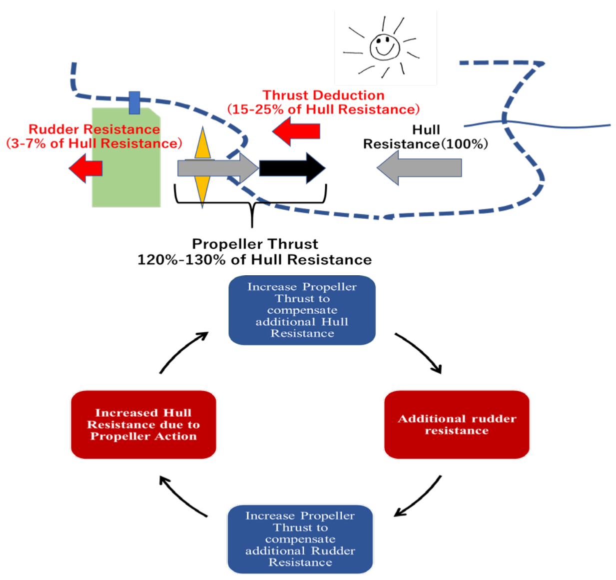

Figure 1 Vicious Circle of Conventional Rudder System (Calm Sea)

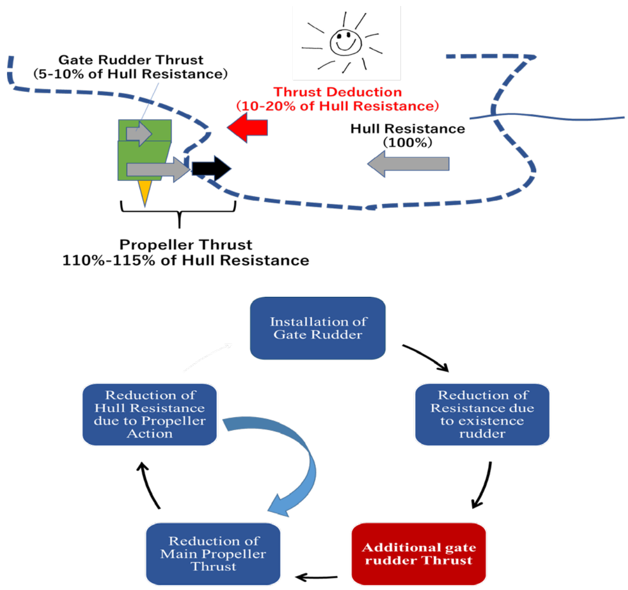

Figure 2 Virtuous Circle of Gate Rudder System (Calm Sea)

The propeller thrust for the conventional propeller system can be calculated from the following equation;

$$T_P = R_0/(1 + \kappa_C - t_H) \text{ -------- } (2)$$

Where, κ_C is rudder resistance ratio to ship hull and given by

$$\kappa_C = -\Delta R_{RC}/R_0 \qquad \text{-------- } (3)$$

2.1(b) Gate Rudder System

By removing the conventional rudder stern and placing the gate rudder adjacent to a propeller as a combined propulsor, we can expect an evolutionary change in the interaction among the rudder, propeller and ship hull.

The main difference is the required thrust of the screw propeller. The propeller thrust can be reduced considerably as shown in Figure 2.

It is noted that the interaction between the hull and Gate Rudder is negligibly small which was reported by Sasaki[7)].

It seems that interaction can occur within the stream tubes which are affected by the propulsor comprising not only a propeller but also rudder blades. The distance between the gate rudder blades is far from the hull within these stream tubes.

The increased resistance ΔR due to propeller action is defined like the conventional rudder case;

$$\Delta R = \Delta R_H + \Delta R_{RG} \qquad \text{-------- } (4)$$

However, there are many differences we should consider.

The first, ΔR_{GR} is negative because the Gate Rudder is producing thrust instead of resistance. The second, ΔR_H is much smaller than the case of equation (1).

We have two reasons for smaller ΔR_H.

One is the fact that the main propeller thrust is smaller than for the conventional rudder case. The main propeller thrust can be calculated by the following equation;

$$T_P = R_0 / (1 + \kappa_G - t_H) \qquad \text{-------- } (5)$$

Where, κ_G is rudder thrust ratio to hull and given by

$$\kappa_G = -\Delta R_{RG}/R_0 \qquad \text{-------- } (6)$$

Comparing equation (2) to equation (5), the reduction ratio (κ_P) of the propeller thrust can be obtained easily as shown in Figure 3 for the typical case of $t_H = 0.18$.

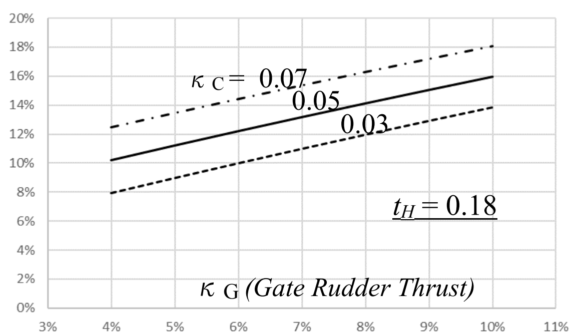

Figure 3. Thrust Reduction Ratio κ_P

Figure 3 shows the fact clearly that the Gate Rudder system can reduce the required main propeller thrust considerably.

The second reason for smaller ΔR_H is the fact that the interaction between the Gate Rudder blades and the hull is negligibly small.

This fact was found at Newcastle University when the force measurement for the floating stern model was conducted. Photo 2 shows the model ship with floating stern section. It was revealed that the increased resistance on the stern part is only dependent on the main propeller and the effect of the Gate Rudder thrust was negligibly small [7].

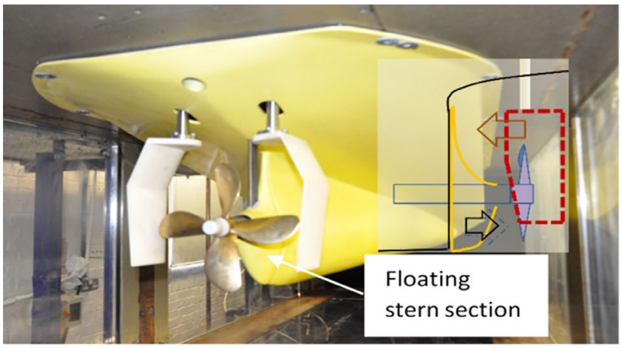

Photo 2 Floating Stern Model to investigate the Interaction among Propeller, Rudder and Stern

It is noted that the average values for κ_C and κ_G is 4% and 6% respectively for the model scale. This implies that the reduction ratio of the main propeller thrust (κ_P) by the Gate Rudder system at calm sea will be expected to be more than 10% according to the Figure 3.

Here, κ_P is the reduction ratio of the main propeller thrust for the conventional rudder case (T_{PC}) and the gate rudder case (T_{PG}) respectively, and represented by

$$\kappa_P = (T_{PC} - T_{PG}) / T_{PC} \quad \text{-------- (6)}$$

It seems that κ_P is the most important parameter for prediction power savings with the Gate Rudder.

2.2 INTERACTION AMONG RUDDER, PROPELLER AND HULL AT ROUGH SEA

The increased resistance ΔR due to propeller action at rough sea condition is defined as follows;

$$\Delta R = \Delta R_H + \Delta R_R + \Delta R_A \quad \text{-------- (7)}$$

Where, ΔR_A is the increased resistance due to wind, waves and rudder steering to keep the ship heading constant. Hence, ΔR_A can be represented by

$$\Delta R_A = \Delta R_{AW} + \Delta R_{AA} + \Delta R_{AR} \quad \text{-------- (8)}$$

Where, ΔR_{AW} and ΔR_{AA} are the added wave and added wind resistance respectively. ΔR_{AR} is the increased rudder resistance which originated from following reasons;

1) Increased propeller loading (higher slip stream)
2) Rudder helm to keep the course constant

The second contribution has an extremely large impact on the resistance compared with the first one. The increased rudder drag due to increased propeller loading is not so large because the drag can be compensated by higher leading edge suction so called.

On the contrary, the increased rudder resistance due to higher helm activity shows almost the same level to added resistance as from waves and wind, which are unavoidable.

This will bring us further detrimental effects in the "vicious circle" as shown in the Figure 4.

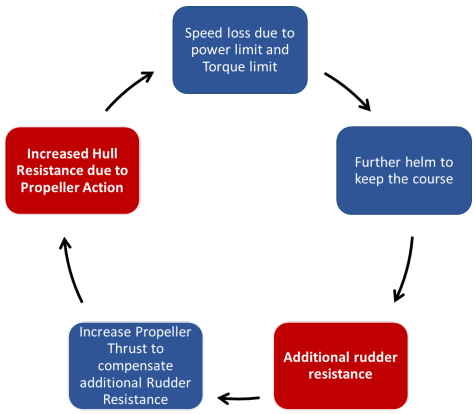

Figure 4 Vicious Circle of Conventional Rudder System due to Rough Weather

On the other hand, the Gate Rudder system shows the remarkable reduction in the rudder resistance during helm action.

Figure 5 shows this advantage and the model test revealed that the Gate Rudder system has a strong possibility to reduce the sea margin owing to such favourable characteristics. The measurement may not be so accurate because of the low Reynold number of the test conditions, however the difference is very clear.

This remarkable change in rudder drag was also confirmed from the manoeuvring test results during her sea trial. It appeared on her higher ship speed during the manoeuvring motion.

Photo 3 Test Set up for Rudder Force and Hull Force Measurements

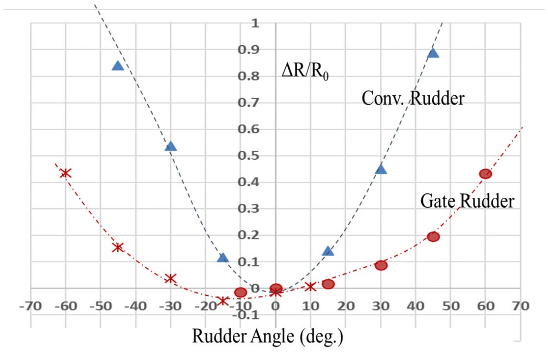

Figure 5 Hull Resistance Increment Ratio introduced by the Rudder Helm

Figure 5 shows the measured rudder resistance during the helmed condition with propeller rotation using the 2.5 m model shown in Photo 3

Taking the difference of this rudder resistance into account, the required main propeller thrust in rough sea condition can be represented as follows:

$$T_{PC} = (R_0 + \Delta R_{AW} + \Delta R_{AA})/(1 + \kappa_{CA}(\delta) - t_H) \text{ for Conv. Rudder} \quad \text{-------- (9)}$$

$$T_{PG} = (R_0 + \Delta R_{AW} + \Delta R_{AA})/(1 + \kappa_{GA}(\delta) - t_H) \text{ for Gate Rudder} \quad \text{-------- (10)}$$

Here, the difference of ΔR_{AW} and ΔR_{AA} between the rudder systems is neglected,

From the characteristics of wing, $\kappa_{CA}(\delta)$ and $\kappa_{GA}(\delta)$ can be represented by following formula respectively:

$$\kappa_{CA}(\delta) = C_1 \ \delta^2 + \kappa_C \quad \text{-------- (11)}$$

$$\kappa_{GA}(\delta) = C_2 \ \delta^2 + \kappa_G \quad \text{-------- (12)}$$

Where, C_1 and C_2 can be obtained from Figure 5 as 1.559 and 0.267 respectively, however these values will vary depending on the rudder configuration.

3. WAKE SCALING

The conventional full scale wake prediction is based on following two ideas;

(1) The inflow at the propeller plane will be increased by a thinner boundary layer than that of model scale due to higher Reynolds number.
(2) The propeller inflow will be increased further due to the effect of propeller action

The wake flow representing effect (1), only is called nominal wake and the wake including effect (2) is called the effective wake.

Therefore, the difference between nominal and the effective wake originates from the deformation of the boundary layer which is caused by propeller suction. It is obvious that this deformation strongly depends on the propeller suction which is almost proportional to propeller thrust.

This phenomenon can be seen frequently during the propeller loading variation in the propulsion test. Therefore, the full scale effective wake can be represented as follows;

$$w_{EM} = w_{NM} - \delta w(C_{TM}) \quad \text{-------- (13)}$$

$$w_{ES} = w_{NS} - \delta w(C_{TS}) \quad \text{-------- (14)}$$

Where $\delta w(C_T)$ is a linearized deformed wake function for a propeller loading factor given by

$$\delta w(C_T) = C^* * C_T \quad \text{-------- (15)}$$

C^* can be obtained from the result of a propeller loading variation test during the propulsion test.

Because w_N contains a potential wake originating from the ship stern and rudder, w_N can be replaced by

$$w_N = w_{NF} + w_H + w_R \quad \text{-------- (16)}$$

Neglecting the difference of relative boundary thickness between the model and ship, w_H and w_R can be regarded as the same value for the model scale and full scale.

Based on this idea, the ITTC wake scaling procedure is introduced as follows;

$$w_{NS} = ((1+K)C_{FS} + \Delta C_F)/(1+K)C_{FM} * w_{NF} + w_H + w_R \quad \text{-------- (17)}$$

$$w_{ES} = w_{NS} - \delta w(C_{TS}) \quad \text{-------- (18)}$$

Assuming

$$\delta w(C_{TS}) = ((1+K)C_{FS} + \Delta C_F)/C_{FM} * \delta w(C_{TM}) \quad \text{---- (19)}$$

w_{ES} *can be represented by*

$w_{ES} = ((1+K)C_{FS}+\Delta C_F)/C_{FM} *w_{EM} +w_H+w_R$---- (20)

Assuming the sheer stress part of the thrust deduction factor is negligibly small,

$w_H = tp = t$ -------- (21)

Finally,

$w_{ES} =((1+K)C_{FS}+\Delta C_F)/C_{FM} *w_{EM} + t + w_R$----- (22)

Through the above procedure, there are two parts where we should take the difference into account as follows for the Gate Rudder case;

$w_R = 0$ -------- (23)

$\delta w(C_T)= C^* * C_{TG}$ -------- (24)

Where,

$C_{TG} < C_{TS} < C_{TM}$ -------- (25)

4. PREDICTION AND SEA TRIAL RESULTS

4.1 PREDICTION OF FULL-SCALE GATE RUDDER PERFORMANCE

Delivered power (P) at ship speed (V_S) can be obtained from following equations;

$P = T_P * V_S*(1-w_{ES}) / \eta_P$ -------- (26)

η_P can be estimated based on propeller-rudder open water characteristics of the designed propeller with a gate rudder.

If the propeller-rudder open water test is not available, the following empirical formula can be used for the first stage estimation.

$\eta_P = \alpha *2 /(1+ (1+C_T)^{0.5})$ -------- (27)

α is coefficient and around 0.78-0.82 for a conventional propellers.

For the case of the container ship shown in Table 1, the power curve will be obtained by the following equations using the model test data.

$P = T_P * V_S*(1-w_{ES}) / \alpha *2 /(1+ (1+C_T)^{0.5})$ ---- (28)

$T_P = R_0/(1 + \kappa_G - t_H)$ -------- (29)

$w_{ES} = ((1+k)C_{FS}+\Delta C_F)/(1+k)C_{FM} *w_{EM} +t_H$ --- (30)

For fully loaded conditions;

$t_H = 0.113$
$w_{EM} = 0.369$

$w_{ES} = 0.340$

$\kappa_G = 0.023$ (model scale)

For sea trial conditions;

$t_H = 0.140$

$w_{EM} = 0.373$

$w_{ES} = 0.364$

$\kappa_G = 0.023$ (estimated)

Using these data obtained from the model test, estimated power curves are compared with full scale data in next section.

4.2 SPEED TRIAL DATA

The speed trial was conducted according to the normal procedure for a shipbuilder which is three sets of double runs. The ground speeds by DGPS were recorded and power and fuel consumptions were calculated by engine parameters such as LI and Pmax, and flow meter respectively.

The obtained power (Figure 6) was examined from several aspects, however the most important aspect was considered to be fuel consumption and it was concluded that the fuel oil consumption ratio of the engine (g/kw,hrs) of both vessel was almost the same.

Table 2 and Table 3 show the raw data for the speed trials for two vessels.

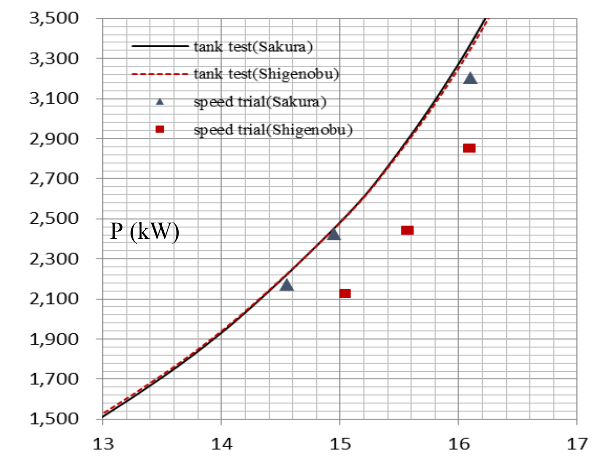

Figure 6 Tank Test and Speed Trial Results of two Ships

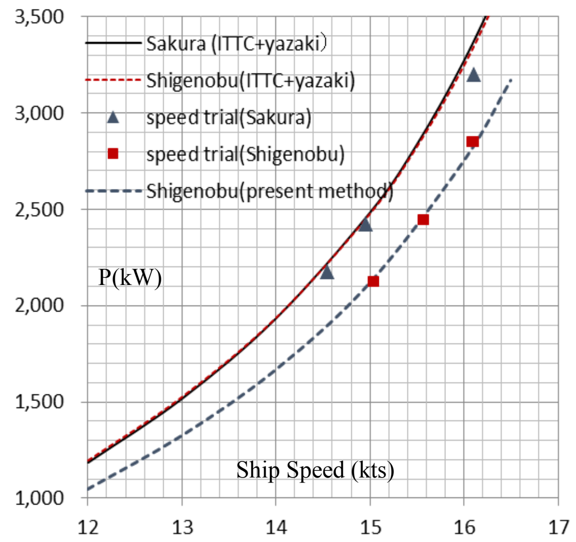

Figure 7 New Power Prediction Method

Table 2 Speed Trial Result (Conventional Rudder)

	Speed(kt)	Power(kw)	Vw(m/s)	φ(deg)	Hw(m)
1st run	13.433	2230	5.0	0.0	0.2
2nd run	15.636	2230	8.0	10.0	0.2
3rd run	14.107	2535	5.0	9.0	0.3
4th run	15.745	2535	10.0	10.0	0.3
5th run	15.455	3275	7.0	0.0	0.1
6th run	16.634	3275	10.0	10.0	0.1

Table 3 Speed Trial Result (Gate Rudder)

	Speed(kt)	Power(kw)	Vw(m/s)	φ(deg)	Hw(m)
1st run	16.174	2430	8.0	-20	0.75
2nd run	14.679	2490	11.0	20	0.75
3rd run	16.2	2705	6.0	-30	0.75
4th run	15.435	2749	13.5	10	0.75
5th run	16.426	3256	3.5	-10	0.75
6th run	16.416	3362	13.0	10	0.75

Figure 6 shows the analysed data of the two ships and the difference in power at the same speed is 14%. This is enormous because we have never seen such an evolutionary energy saving device since the event of the competition between HMS Alecto and HMS Rattler.(say which is prop & which a Paddle)

As explained in the sections 2 to 3, the powering procedure and wake scaling of the gate rudder case is different from a conventional rudder case. Using the conclusions derived from section 4.1, power obtained from the sea trial is compared to the prediction as shown in Figure 7.

In addition to the power, the effective wake was investigated. Because the difficulty in measuring the gate rudder thrust, the present analysis was made based on the K_Q identity which is derived from propeller torque. This value is affected by the flow acceleration due to the gate rudder blades and corresponds to conventional powering procedures.

Therefore, we have only possibility for the validation of the accuracy of conventional powering procedures for wake scaling. The result is very interesting. In the Figure 8, it is very obvious that the prediction of the effective wake based on the conventional way is not working properly.

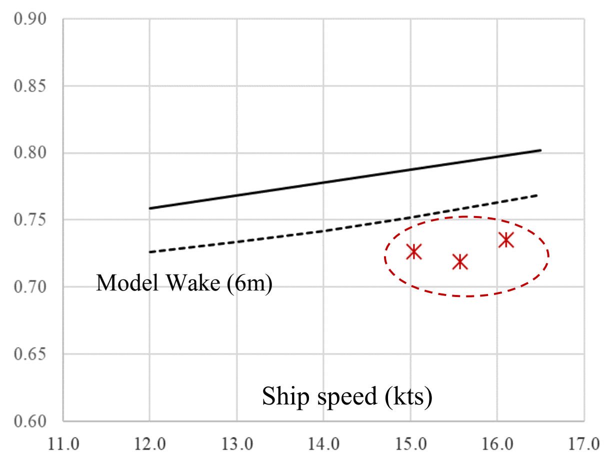

Figure 8 Conventional Wake Scaling Method and Sea Trial Result(GR)

The reason of this discrepancy is very clear. The existing wake scaling is not able to distinguish the actual effective wake and rudder induced velocities. If we want to use the conventional powering procedure, we need to separate the obtained propeller advance speed into these two components, i.e., actual effective wake and rudder induced wake. If the ship stern and the propeller diameter are similar for two rudder configurations, the gate rudder induced wake can be roughly estimated by the difference of two obtained propeller advance speeds.

4.3 MONITORING DATA AFTER DELIVERLY

As explained in the section 2.2, the better performance of the gate rudder was expected for actual sea conditions because of higher loading of the propeller due to waves, wind and hull fouling. According to the sea margin data of the similar vessel (L*B*D*d =110.7*17.4*8.2*5.4), the sea margin of the ship with conventional rudder was expected to be around 25%. The sea margin data for the two vessels were provided by the ship owner[8].

Here, the sea margin (power margin) was calculated by the following simple formulae.

$SM = (P_{ACT} - P_0) / P_0$ -------- (31)

$PACT = PMES * (DWT/6000)2/3$ ------- (32)

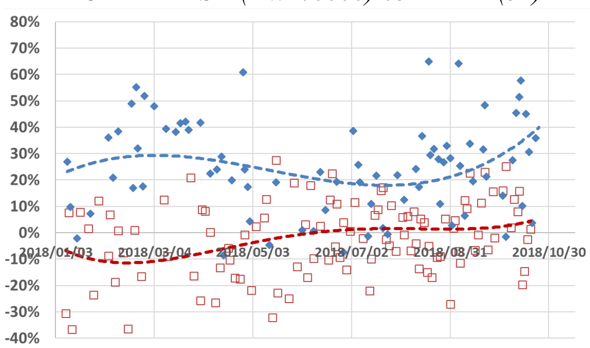

Figure 9 Sea Margin of two Ships
(Sakura: upper, Shigenobu(GR): lower)

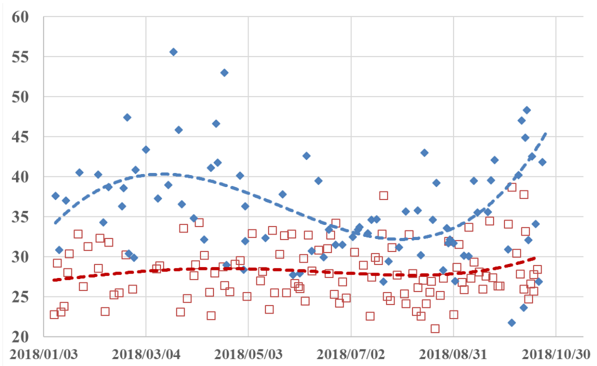

Figure 10 Litre/mile of two Ships

(Sakura: upper, Shigenobu(GR): lower)

Figure 9 and Figure 10 shows the difference of sea margin (power margin) and litre/mile data of the two vessels respectively.

This is a quite an interesting result. On the grounds that the two vessels are running on the same day and the same route (Tokyo-Hachinohe-Tomakomai), it is apparent that the difference of the two vessels has originated from only the rudder systems.

The obtained sea margin from the vessel with the conventional flap rudder is around 26% while the vessel with gate ruder is -1%. The largeat difference between the two vessels occurs during winter, In contrast, in summer when the weather is calm, the difference is very close to the sea trial results of 14%.

And so, the difference of actual sea margin from the calm sea conditions can be regarded as 13% instead of 27%.

Table 4 Summary of Voyage Data

	Vs(kts)	*P(kw)*	*Cadm*	*sea margin*	*litre/mile*
Shigenobu	*13.37*	*2217*	*254*	*-1%*	*28.3*
Sakura	*11.86*	*2044*	*186*	*26%*	*37.6*

Notes: The data does not include a short voyage of less than 10hrs, Sakura(Flap Rudder), Shigenobu(Gate Rudder)

Table 4 shows the averaged voyage data collected from Jan. 2018 to Oct.2018.

5. CONCLUSION

The recent full-scale speed trials with this domestic container vessel have confirmed the superior performance of the Gate Rudder system which has shown 14% reduction during speed trials. In addition to this excellent result, the voyage data revealed that in some situations the gain is much larger at 27% in terms of power margin and 33% for the litre/mile ratio.

The propulsive performance of two rudder systems was theoretically investigated. As a conclusion, the gate rudder can be regarded as a ducted propeller system and the conventional powering procedure, which has been used for the conventional rudder system, will not work properly for this new rudder system especially in the prediction of effective wake. The new powering procedure presented in this paper appears to be working well, however further investigation will be required to establish the accurate powering procedure for the gate rudder system as a new propulsor system.

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