Sasaki, Noriyuki and Atlar, Mehmet (2018) Investigation into the propulsive efficiency characteristics of a ship with the Gate Rudder propulsion. In: A. Yücel Odabaşı Colloquium Series 3rd International Meeting on Progress in Propeller Cavitation And its Consequences: Experimental and Computational Methods for Predictions, 2018-11-15 - 2018-11-16. ,

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A. Yücel Odabaşı Colloquium Series
3rd International Meeting on Progress in Propeller Cavitation
And its Consequences: Experimental and Computational Methods for Predictions
14th – 16th November 2018, Istanbul, Turkey

Investigation into the propulsive efficiency characteristics of a ship with the GATE RUDDER® Propulsion system

N. Sasaki, M. Atlar

Department of Naval Architecture, Ocean and Marine Engineering, University of Strathclyde, Glasgow G4 0LZ, UK

Following the first successful application of the Gate Rudder® propulsion system on a 2500GT container ship (Lpp=102m) in Japan, excellent manoeuvring performance was reported with a significant fuel saving over her sister ship fitted with a conventional rudder propeller arrangement.

Based upon the investigations carried out by using model tests, CFD simulations and the full-scale data of two container vessels, this paper discusses the details of the propulsive efficiency characteristics of a vessel fitted with the GATE RUDDER® propulsion system in comparison those of the same vessel with the conventional rudder-propeller arrangement. In the paper the evolution history of the GATE RUDDER® concept is presented by tracing the development of the state-of-the-art energy saving devices (ESD) involving ducts since the GATE RUDDER® exploits the advantage of the duct effect. The components of the propulsive efficiency parameters, with an emphasis on the thrust deduction and effective wake parameters, are explored and discussed highlighting the differences for the hull with the GATE RUDDER® and the conventional rudder arrangements.

1 INTRODUCTION

In order to improve the energy efficiency of ships, and hence to achieve targeted carbon emission (e.g. EEDI regulations by IMO), various technological and operational solutions have been studied by the maritime industry. These solutions recently include the developments of various novel Energy Saving Devices (ESD) applied on the underwater hull and renewable energy saving devices onboard, using alternative fuel sources and sophisticatedly designed optimal hull forms. Amongst these solutions, e.g. ESD's, still have their challenges to prove their effectiveness regarding performance and cost robustly on full-scale ships. Although many ESDs already exist, and some new types are still being introduced, their effectiveness need to be investigated and proven further by accurate voyage data especially after delivery.

GATE RUDDER ® system is a new and innovative ESD technology for ships to propel and steer them more efficiently compared to conventional rudder propeller as well as other ESDs. As opposed to a conventional single rudder system, which is usually located behind the 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 the vessel with a duct effect and hence produce additional thrust as opposed to the additional drag of the conventional rudder behind the propeller.

This paper presents the principles of the GATE RUDDER® concept by tracing evoluation of the state-of-the-art ESDs involving ducted propulsors. By using model tests, CFD simulations and the full-scale data of two container vessels, the paper explores the details of the propulsive efficiency parameters, with an emphasis on the thrust deduction and effective wake parameters, and discusses the differences for the hull fitted with the GATE RUDDER® and the conventional rudder arrangements.

2 GATE RUDDER CONCEPT

2.1 Evolution of Ducted Propellers

The rudder is one of the significant sources contributing to the ship resistance. The main purpose of the GATE RUDDER® propulsion system is, therefore, to replace this resistance source with the source of a thrust (i.e. similar to an accelerating duct) to improve the propulsor efficiency. With this idea, the replacement of the single

Corresponding author e-mail: Noriyuki.sasaki@strath.ac.uk

rudder blade with a pair of blades and locating each blade aside the propeller can improve the propulsive efficiently significantly, like a ducted propeller, as an effective energy saving device as opposed to the rudder behind the propeller.

The performance of a ducted propeller system is usually evaluated based on their open water performance characteristics which are similar to that of a conventional screw propeller. However, the problems with the cavitation occurring at the inner surface and mainly near the leading edge region of the ducts are a well-known, and unavoidable source of vibration and structural problems, especially for large vessels, such as VLCCs fitted with the ducted propellers. This has been the main reason why we are not able to see this first generation, conventional, accelerating type of ducted propeller on merchant's ships nowadays, while the small workboats, such as tugboats and fishing vessels can still take advantage of this type propulsor.

The second generation ducted propellers are the combination of a propeller, and the duct being placed in front of the propeller. This idea seems to be better than the first generation ducted propeller which suffered from the risks for developing cracks in the connecting part between the duct and the hull plating at the aft end of a ship.

The latter part of the 20th century saw the third generation ducted propellers which appeared as their ducts having much smaller diameter than their propellers and installed slightly away from the propeller at the aft end of a ship. Within this generation, in 2005, NMRI invented their Weather Augmented Duct (WAD) system which was designed to take into account the performance improvement in actual sea conditions in-service. The WAD is to generate more thrust during rough sea conditions, where the ship requires more power to maintain the design speed, compared to the calm sea condition.

Through the above-summarised evolutionary history of the ducted propellers, we may notice the following important issues concerning their designs:

1) Ducted propellers are optimised based on their open water efficiency performance which does not necessarily display the maximum propulsive efficiency

2) The duct of a ducted propeller can be placed at any place if it works well

3) More efficient and critical part of a duct is always the upper half while the lower half of the duct is less efficient or may be considered useless from the propulsive efficiency point of view.

4) The smaller duct in front of the propeller could be one solution for better efficiency

One of the most recent successful ESDs introduced has been the Mewis Duct which was introduced in 2008 in Germany. Mewis described the roots of his novel ESD as shown in Figure 1 by claiming that his concept combines two ideas; one of which is the Sumitomo Integrated Lammern Duct (SILD) while other is the pre-swirl fins. However, the SILD had already integrated the pre-swirl fins in its arrangement.

Therefore, there is no significant difference in these concepts, while it is very obvious that the Mewis duct is a much-improved ESD compared to the SILD which was invented more than ten years before the Mewis Duct. It can be said that Mewis Duct will be the ultimate configuration for the ducted propellers which can be categorized as *Post-propeller* type ducted propulsors.

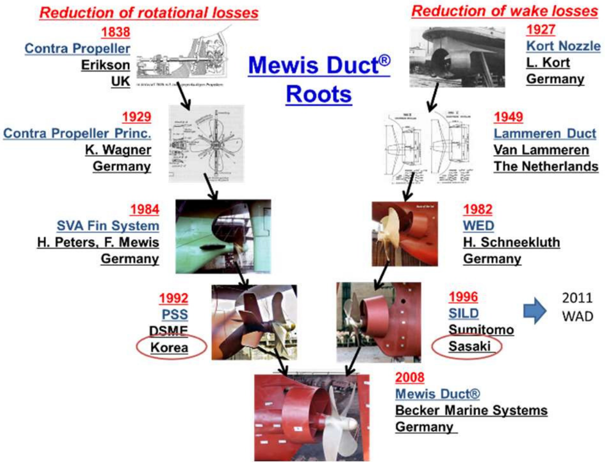


Figure 1 History of Mewis Duct presented by Mewis

2.2 GATE RUDDER® as a Ducted Propeller

As stated earlier, the first generation conventional ducted propellers had minimal scope to be installed on the large commercial vessels due to the problems related cavitation and vibrations which have not been solved even now. However, we have seen through the evolution of the ducted propellers that the duct can be moved to anyplace if it will work well as in the case of many *Post-propeller* type ducted propellers. We are also aware of

Corresponding author e-mail: Noriyuki.sasaki@strath.ac.uk

the fact that the lower part of the conventional duct may not be useful in the ship stern.

Inspired from the above-mentioned evolutionary observations and associated knowledge, the GATE RUDDER® propulsion system has been recently introduced based on the activities in Japan and UK. The major advantages of the GATE RUDDER® propulsion system compared with the *post-propeller* type ducted propellers can be claimed to be as follows Sasaki et al (2015), Sasaki et al (2018). :

1) The accelerating duct-like shape of the GATE RUDDER® with two separated sections (i.e. rudder blades) without their bottom parts, and placed aside the propeller, work as two efficient three-dimensional wings

2) The two separated rudder blades can be rotated independently from the upper parts, as a single rudder blade, to provide more efficient manoeuvring capability to the vessel.

3) The above-described arrangement accelerates the wake flow at the upper part of the propeller plane where the stagnated flow or higher wake shadow exists

4) The rudder blades produce 5-15% of the additional thrust of the propeller, like a duct, and this can reduce the high propeller loading

5) The replacement of a conventional rudder with the GATE RUDDER® system provides more attractive options for the aft end design arrangements.

As we can follow through the evolution of the *Post-propeller* type ducted propeller, the success of this type propulsor relies on the history of the "integration" of the propeller and duct. However, in the case of the GATE RUDDER®, the successful "integration" involves the propeller, hull and the rudder. Hence, more benefit from this integration can be expected as shown in Figure 2.

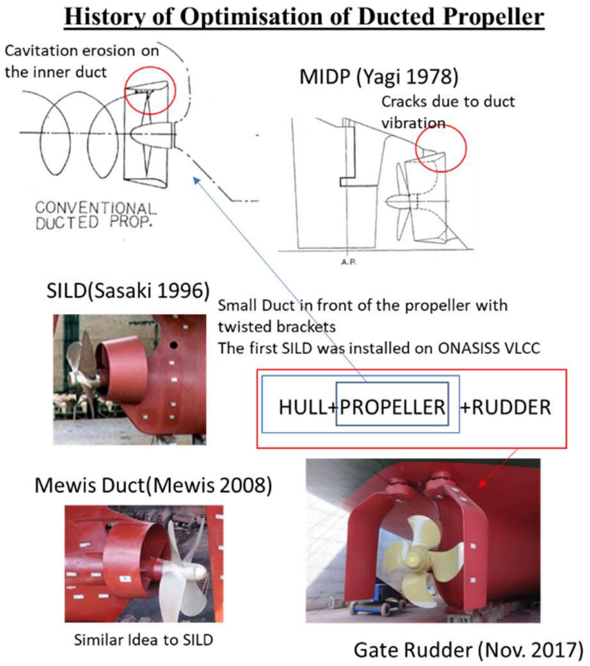


Figure 2 History of Ducted Propellers

2.3 Propulsive Efficiency with GATE RUDDER®

The GATE RUDDER® concept takes advantage of the rather complex integration of the hull, propeller and rudder flow in a unique propulsion system which is difficult to be described, and to be presented by any standard design and power prediction methodology.

If we consider the GATE RUDDER® is a propulsion system which consists of various sub-elements that can generate the required thrust, the propulsive efficiency of the GATE RUDDER® can be represented as the summation of the thrust to delivered power ratio due to the propeller and rudder blade elements as follows:

$$\eta_D = \frac{\sum_{i=1}^{3} T_i V}{\sum_{i=1}^{3} DHP_i} \qquad (1)$$

where, i= 1, 2, and 3 corresponds to the propeller, starboard rudder blade and port rudder blade, respectively. More

Using Equation (1) and assuming that the power is delivered only through the propeller, η_D can be written as follows:

$$\eta_D = \frac{(T_1+T_2+T_3)V}{DHP_1} \qquad (2)$$

Corresponding author e-mail: Noriyuki.sasaki@strath.ac.uk

Because propeller thrust T_1 and delivered power, D_1 can be represented by classical propeller-hull interaction coefficients, it follows:

$$\eta_{D1} = \frac{T_1 V}{DHP_1} = \frac{1-t_1}{1-w_1}\eta_o\eta_R \quad (3)$$

Hence, Equation (1) can be modified as follows:

$$\eta_D = \frac{1-t_1}{1-w_1}\eta_o\eta_R + \frac{(T_2+T_3)V}{DHP_1} \quad (4)$$

By using the simple momentum theory for the propeller efficiency,

$$\eta_D = \frac{1-t_1}{1-w_1}\frac{2\kappa}{[1+(1+C_T)^{0.5}]}\eta_R + \frac{(T_2+T_3)V}{DHP_1} \quad (5)$$

where κthe is a correction factor from the ideal efficiency to actual propeller efficiency, and propeller thrust coefficient, C_T can be calculated by using Equation (6) as a function of water density ρ and propeller disc area S_P:

$$C_T = \frac{T_1}{0.5\rho[V(1-w_1)]^2 S_p} \quad (6)$$

Based on these equations, it is obvious that the following next two characteristics of the GATE RUDDER® are very important for the evaluation of its performance:

1. Interaction between (T_2+T_3) and (1-t_1)
2. Interaction between (T_2+T_3) and (1-w_1)

Although η_R may have a small possibility of change by (T_2+T_3), this change can be neglected if we can avoid any error associated with the design or experimental in nature since the propeller design should be closely related to the change in the flow field. However, any large difference of η_R observed in the model test should be treated with care as the potential source of trouble.

Generally speaking, the above-highlighted interactions strongly depend on the axial distance between the ESD(s) and the aft end (stern post) of the vessel in front of the ESD. If the location of the ESD is far from the aft end, the interaction will be negligibly small. In contrast, if the location of ESD is very close to the aft end, as in the case of *the Post-propeller* type ducted propulsors, a strong interaction should be expected.

Figure 3 shows the efficiency gain in the ideal condition due to the assisting thrust (T_2+T_3) for the GATE RUDDER®. This means the presented values are based on the assumption that there is no interaction between (T_2+T_3) and neither (1-t_1) nor (1-w_1). In the figure, R and P is the hull resistance and required power, respectively.

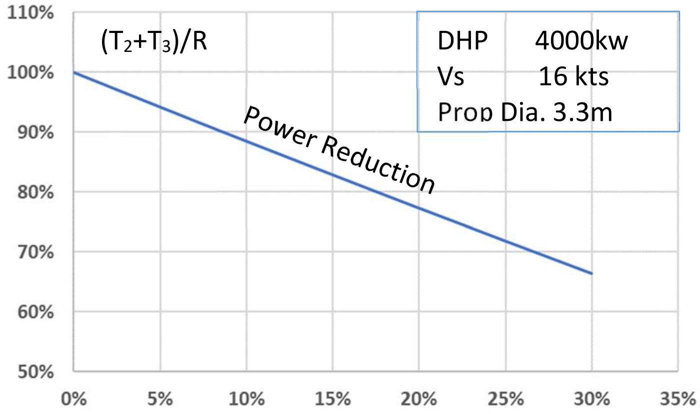


Figure 3 Ideal Power Reduction by Assisted Thrust

Because the calculations in Figure 3 neglect the advantage of the propeller design conditions for lower thrust, the power reduction in this figure is slightly conservative, and further 2-3% can be considered by reflecting this advantage in the propeller design stage.

2.4 Interaction between GATE RUDDER® and Propulsive Coefficients

2.4.1 Thrust Deduction Factor

Thrust deduction factor is the reflection of the resistance increase on the hull due to the action of a propulsor. Because the propulsor creates a suction field at its upstream and hence accelerates the flow in front, this accelerated flow generates larger shear stress on the hull surface of the stern. These effects are the additional resistance source when the ship is propelled by the propulsor(s). To reduce this resistance increase, there are two practical design solutions. First one is to introduce a fine stern shape (with smaller half entry angles) in front of the propeller since the pressure is working on a normal direction to the hull surface. For this purpose, sometimes, cusp shapes are applied to the aft end lines of the ships. The second one is to place the propulsor relatively far from the aft end within the practical limits.

Corresponding author e-mail: Noriyuki.sasaki@strath.ac.uk

In order to investigate the above-mentioned resistance increment on the same vessels (i.e. sister ships) but with two different propulsion arrangements, i.e. one with a conventional rudder-propeller system while the other with the GATE RUDDER® system, the total ship resistances during the towing condition and self - propelled condition were compared for the case of a 2500GT container ships. The results of this comparison is shown in Figure 4

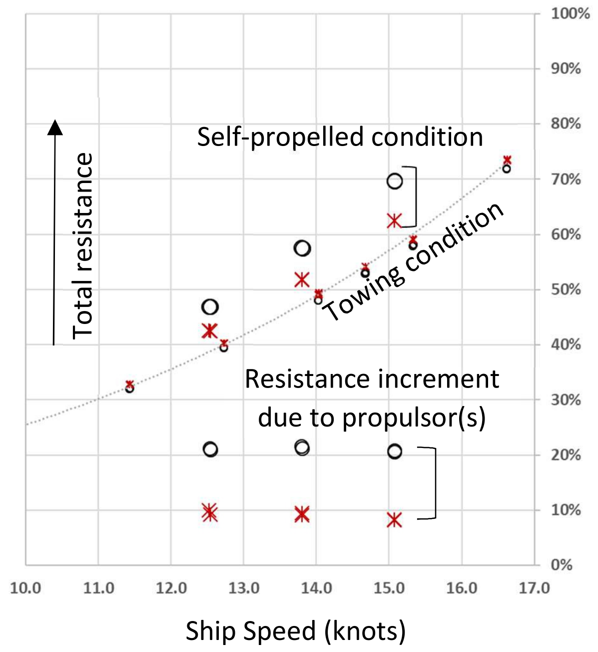


Figure 4. Comparison of total ship resistance between towing and self-propelled conditions for the models of 2500 GT container vessels with conventional and GATE RUDDER® systems.

As can be seen in Figure 4, the resistance increment due to the propeller action for the GATE RUDDER® case is almost half that of the conventional rudder case. This is a general tendency which can be observed with all the model tests conducted with the GATE RUDDER®. These values are directly related to the thrust deduction factor of both rudders case. For example 20% of resistance increment of the conventional rudder case nearly equal to t = 0.2 while for the GATE RUDDER® t = 0.1, respectively.

Figure 5 shows the analysis arrangement of the thrust component from the rudder force measurements with the model of the same ship. This analysis is based the same way of an empirical prediction method for the lift and drag of a three-dimensional wing, and represented by the following formulation.

$$C_L = \varepsilon\kappa\alpha \quad (7)$$

$$C_D = \frac{F_Y' - \kappa\alpha}{\alpha} \quad (8)$$

$$\alpha = \frac{\sqrt{F_X'^2 + F_Y'^2 - C_D{}^2}}{\varepsilon\kappa} \quad (9)$$

$$F_X' = \frac{F_X}{0.5\rho V^2 S_R} \quad (10)$$

$$F_Y' = \frac{F_Y}{0.5\rho V^2 S_R} \quad (11)$$

where, C_L and C_D is the lift coefficient and drag coefficient of the rudder, respectively, while lift L is acting normal to the flow direction. F_X and F_Y are the measured rudder forces at the rudder fixed co-ordinate system as shown in Figure 5.

The measurements of F_X and F_Y allowed to evaluate C_L and C_D easily based on the assumption that that α is small. This measurement data was only available for the starboard side due to the limitation of the model deck space during the self-propulsion tests of the model presented in Figure 4.

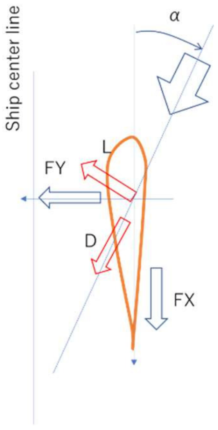


Figure 5. Co-ordinate system for rudder force measurement & analysis

Figure 6 presents the results of the angle of attack analysed from the forces measured on the GATE RUDDER®. As expected the large lift produced on the GATE RUDDER® reflected on the measured angle of attack. This was due to the contraction of the wake flow which was brought about by not only from the hull geometry but also due to the suction effect of the propeller.

Another model test results, which provided further evidence on the interaction amongst the propeller, rudder blades and hull flow, more clearly, conducted at

Corresponding author e-mail: Noriyuki.sasaki@strath.ac.uk

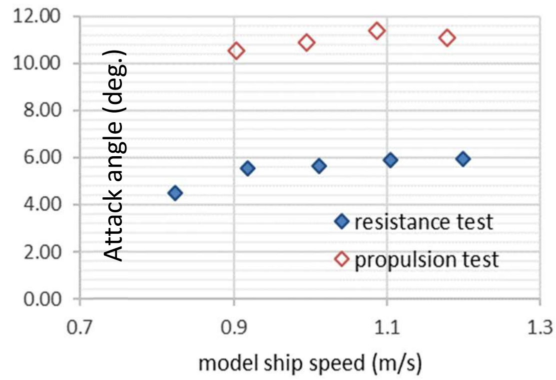


Figure 6. Attack angle α (deg.) analysed from self-propulsion model tests with a GATE RUDDER® model.

the Emerson Cavitation Tunnel using a dummy hull representing a large bulk carrier. As shown in Figure 7, this was a model with a segmented stern section, which is floated to measure the force acting on this section, under the action of the propeller and the model can be fitted with a conventional rudder and GATE RUDDER® for comparison.

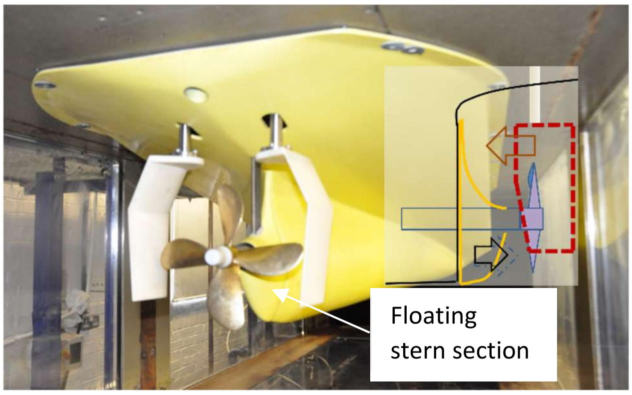


Figure 7. Dummy hull with a segmented and floating stern section with GATE RUDDER® in the Emerson Cavitation Tunnel

Figure 8 shows the results of the measured forces on the GATE RUDDER® and the conventional rudder, in comparison. As it can be seen in this figure, the force acting on the GATE RUDDER® is in the same direction with the propeller thrust and with a magnitude of 4-5% of the propeller thrust. This value is slightly small compared with the figure obtained from the self-propulsion tests in the towing tank because of the exposure of the long and blunt rudder shafts required to measure the rudder blade forces outside the cavitation tunnel at the top. As shown in Figure 8, while the GATE RUDDER® displays increasing forward force (i.e. thrust) with increasing propeller thrust, the conventional rudder presents almost a constant resistance with increasing propeller thrust. increasing propeller loading generates

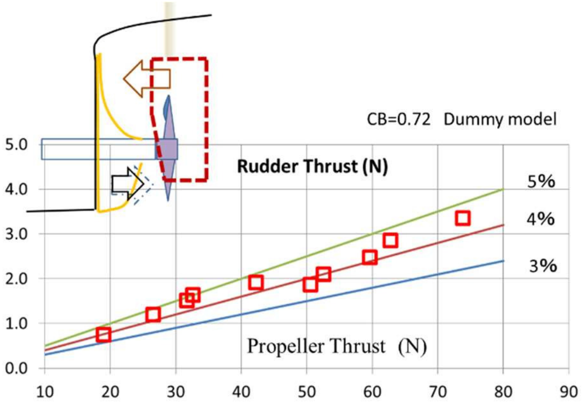


Figure 8. Rrudder thrust generated by GATE RUDDER®

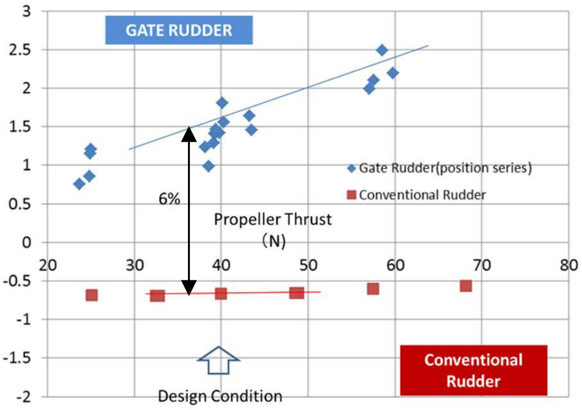


Figure 9. Comparison of rudder force on GATE RUDDER® and Conventional Rudder

Figure 10 shows the measured force acting on the floating stern section of the dummy hull model in the presence of the GATE RUDDER® and that of the conventional rudder in comparison. Apart from some scattered difference in resistance at low thrust (around 30N), both the GATE RUDDER® and conventional rudder arrangements induces similar drag forces on the stern part of the hull. Unfortunately, we could not simulate this case by CFD to provide further insight into

Corresponding author e-mail: Noriyuki.sasaki@strath.ac.uk

the interaction amongst the propeller, rudder and hull flow because of the complexity of test setting in the cavitation tunnel.

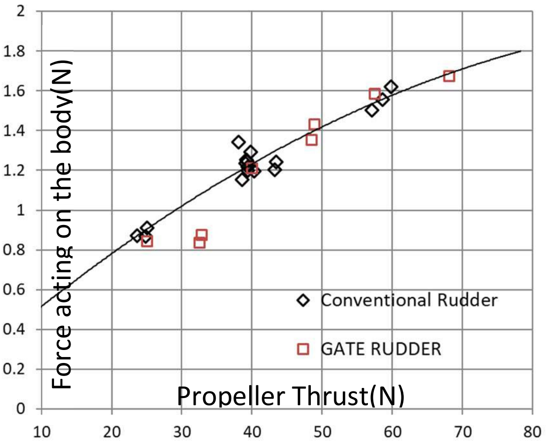


Figure 10 Force acting on the floating stern.

However, the CFD study conducted for the potential application of the GATE RUDDER® propulsion system on a RoRo vessel case provides some useful information on this complex interaction discussed in the following.

Figure 11 shows the comparison of the axial wake velocity ratio distributions at the aft end of a 6.75m RoRo model ship due to a conventional rudder and GATE RUDDER® system including the effect of the propeller's action. In complementing the velocity predictions, the comparative pressure predictions for the same vessel are also conducted for both rudder arrangements and shown in Figure 12.

As shown in Figure 11 for the velocity distributions, it is obvious that the GATE RUDDER® does not affect the flow field around the ship stern so much in front of the propeller except the upper parts, which are indicated by dotted circles Figure 11, where the flow is always stagnating when we applied a conventional amriner stern. This will be favourable from not only the ship resistance point of view but also cavitation and noise aspects. The pressure distribution on both rudder surfaces are shown in Figure 12 and the figure show us that the blades of GATE RUDDER is working as wing of air plane which generates large lift force to one direction.

Based upon the above analysis the thrust deduction parameter appears to be not much affected in the case of GATE RUDDER® arrangement indicating that the resistance increment due to the action of the propeller is proportional to the propeller's thrust. In supporting this observation, the pressure distribution on the hull surface in front of the propeller is almost the same except the upper parts which may improve the thrust deduction factor with the GATE RUDDER®

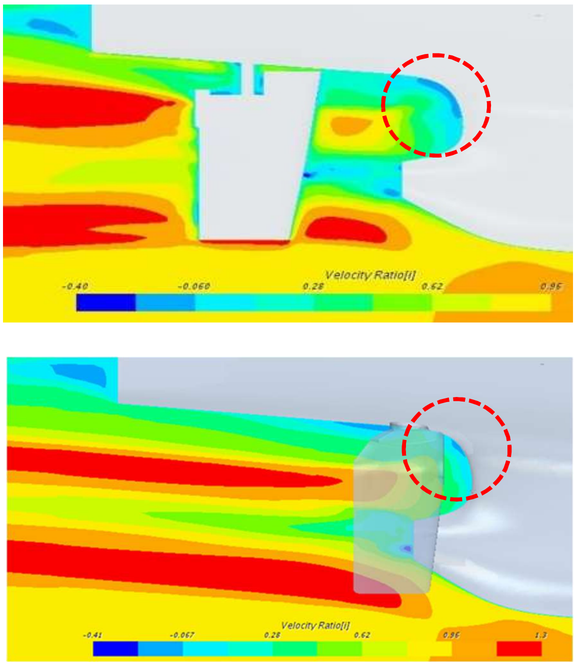
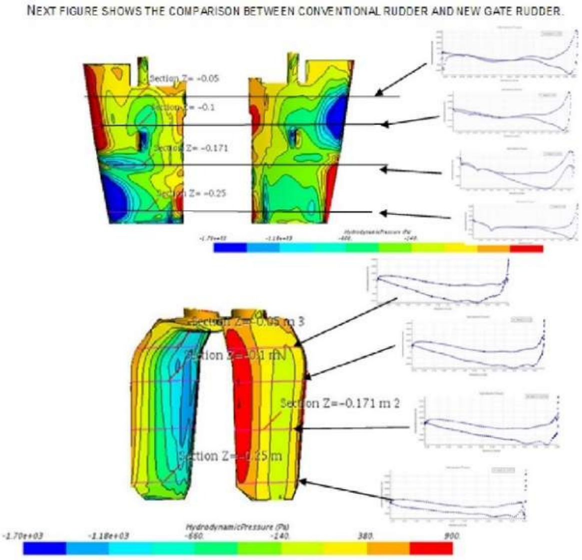


Figure 11 Comparison of axial flow velocity ratios for a RoRo vessel including the action of the propeller:



Conventional rudder (top); GATE RUDDER® (bottom)
Figure 12 Pressure Distributions on the rudder Blade(s): Conventional rudder (top); GATE RUDDER® (bottom)

Therefore, we can conclude that thrust deduction of the ship with GATE RUDDER (t_G) can be represented by using the conventional rudder's thrust deduction (t_C) as follows:

Corresponding author e-mail: Noriyuki.sasaki@strath.ac.uk

$$t_G = t_C \times \frac{T_1}{T_1+T_2+T_3} - \delta t \quad (12)$$

where δt is associated with any contribution from improvement of flow as we saw this in front of the propeller in Figure 11 (dotted red circle)

Regarding to the scale effects of the rudder forces, and hence reflection on the thrust deduction, based on the analysis results of the full-scale data, it appears that the GATE RUDDER® forces experienced in the full-scale can be as high as 30% more compared to the predictions based on the model test measurements due to the low Reynolds number experienced in model scale. This also requires special attention in the power prediction and this is currently being investigated to be reported.

2.4.2 Effective wake

Although the description of the effective wake for a vessel with the GATE RUDDER® can be subjected to further discussion, by following the standard terminologies, it may be helpful if we can idetify 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 will 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 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 is 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 13. 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 the that field with the conventional rudder arrangement will be similar or slightly slower.

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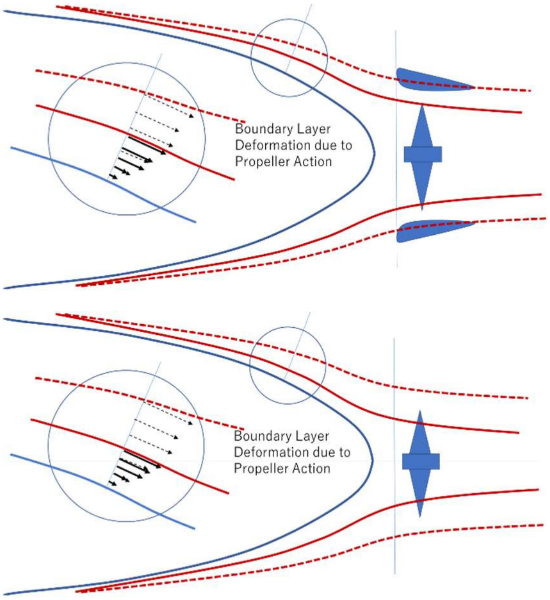

Figure 13. Schematic view of of effective wake resulting from: GATE RUDDER® (top sketch); and Conventional rudder (lower sketch) arrangements.

In order to demonstrate the differences in the effective wake flow of the same hull fitted with the GATE RUDDER® and the Conventional rudder arrangement, CFD computations were conducted for the earlier mentioned RoRo vessel hull with the both rudder configurations and results are compared as shown in Figure 14.

For the evaluation of the effective wake, it will be best to concentrate at the propeller upstream and near the stern region of the hull where the direct interference of the propeller-induced velocities are much reduced or negligible. It is therefore, the CFD simulations of the wake flows for the RoRo vessels are conducted more frequent at the propeller upstream (i.e. at three cross-sections: 0.1D; 0.2D; and 0.3D distances) locations between the propeller and the stern as well as the locations at the propeller plane and 0.1D downtream of the propeller, as shown in Figure 14. Amongst these presentations, perhaps, the first is to concentrate on the wake velocity at foremost location (i.e. 0.3D cross-section) where one may notice the larger region of the high velocity field of the conventional rudder arrangement compared to the GATE RUDDER® arrangement. This means the general tendency of the effective wake with the GATE RUDDER is larger than with the conventional rudder arrangement (i.e. $w_G > w_C$)

Corresponding author e-mail: Noriyuki.sasaki@strath.ac.uk

After this foremost section, if we move further close to the propeller plane and look into the flow velocity it is clear that the GATE RUDDER® induces the velocity change the in rudder blades as such the V-shaped wake pattern (green to blue) is changed to T-shaped wake pattern by the effect of the GATE RUDDER®. This may be more advantageous from the propeller cavitation and noise point of view as we can see the difference of the circumferential velocity distributions for both cases near the propeller plane (-0.1D downstream)as shown in Figure 15.

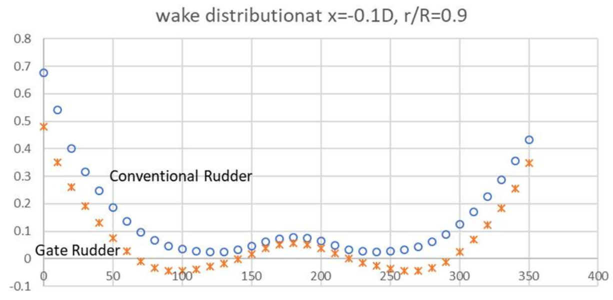

Figure 15. Wake distribution near the propeller plane for different rudder configurations.

5 CONCLUDING REMARKS

Based upon the analysis of the results obtained from the model tests, CFD simulations and the full-scale data of two container vessels, further investigation is conducted on the propulsive efficiency and the associated propeller-hull-rudder interaction parameters of a ship fitted with the GATE RUDDER® propulsion system in comparison with those of the conventional rudder propeller arrangement. The investigation indicated that:

1) Thrust deduction parameter of a hull with the GATE RUDDER® system can be represented by the following simple formula

$$t_G = t_C \times \frac{T_1}{T_1+T_2+T_3} - \delta t$$

where, T_1 is the propeller thrust, T2 and T3 is the thrust generated by each rudder blades of the GATE RUDDER® arrangement while δt is the contribution of regulated flow if exists.

2) Effective wake of a hull with the GATERUDDER® propulsion system is expected to be larger than that of a conventional rudder-propeller arrangement if the GATE RUDDER® is designed properly.

This, in turn, requires that the propeller efficiency should be calculated based on the correct effective wake which is different from that to be obtained by the thrust (K_T) identity method.

3) The wake distribution in the propeller plane can be improved by GATE RUDDER by changing the flow field at upper of stern in front of the propeller.
It seems that a simulated two dimensional wake screen is not enough to evaluate the cavitation and noise of GATE RUDDER system because of different trend of interaction among hull, propeller and rudder as shown in Figure 14 (red square part)

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Corresponding author e-mail: Noriyuki.sasaki@strath.ac.uk

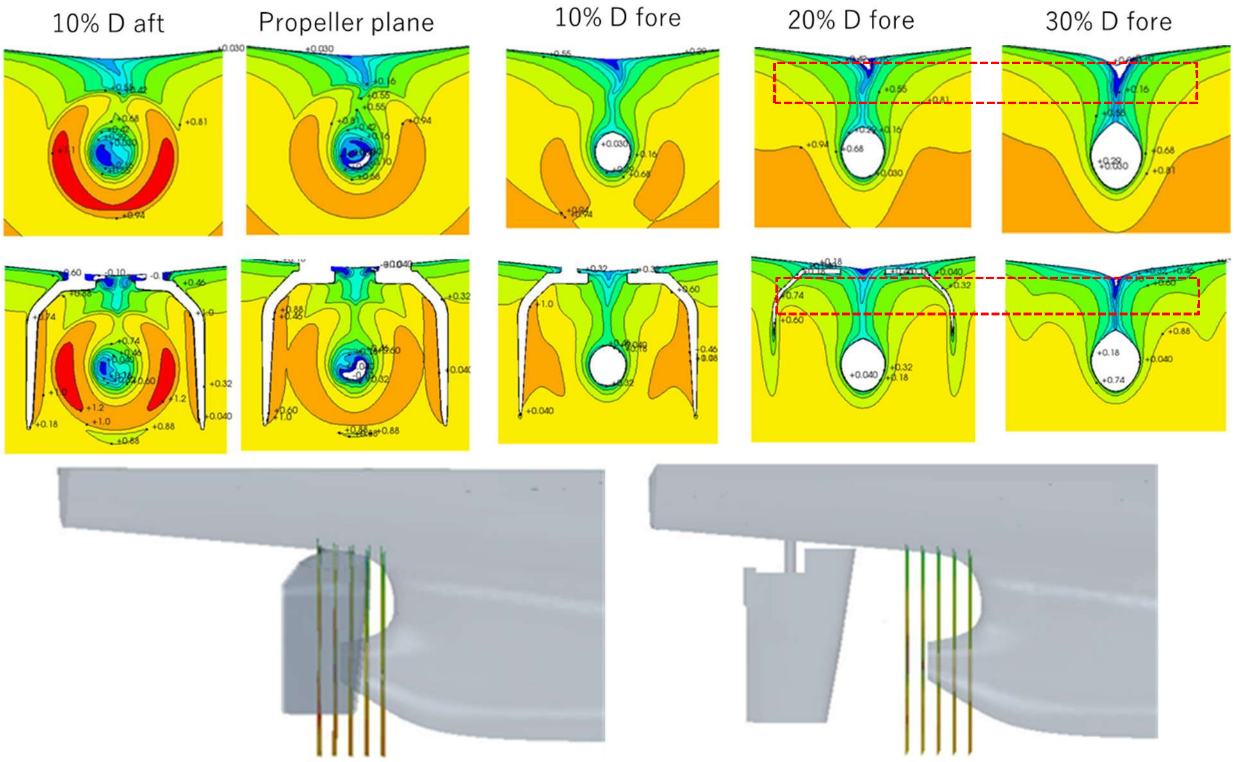

Figure 14. CFD predictions of effective wake and propeller induced velocities at the aft end of a RoRo vessel hull: with Conventional rudder-propeller arrangement (top figure); with GATE RUDDER® arrangement (bottom figure)

Corresponding author e-mail: Noriyuki.sasaki@strath.ac.uk