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A prediction program of manoeuvrability for a ship with a Gate Rudder system

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Abstract: The Gate Rudder is a special twin rudder system with two rudder blades placed aside of a propeller. Main advantage of this system is the energy saving originated from the rudder thrust which is induced by the two cambered rudder blades comparably efficient to ducted propellers. However, as any rudder's prime task, the performance of manoeuvrability is critical to the Gate Rudder too. With the currently available Manoeuvring Modelling Group (MMG) simulation programs, the simulation is only applicable to the traditional single rudder located behind the propeller. Therefore, how to predict the manoeuvring performance for the gate rudder is the focus of this paper.

On the other hand, a recent study of the Gate Rudder reveals that this innovative system has remarkable flap effect which is well known as a manoeuvring interaction between rudder blades and ship stern. This phenomenon has been observed in the case of conventional rudder and introduced into an MMG-based theoretical model as interaction factor aH. However, the average values of aH for conventional rudder is between 0.1-0.2 in general whilst the aH value for the Gate Rudder is more than twice as much, showing a superior course keeping ability of the Gate Rudder.

The paper presents the manoeuvrability simulation method of a ship with this Gate Rudder system and introduces some examples of comparisons between the model tests and free running tests which was conducted with 2.5 m ship model in the manoeuvring tank at Kyushu University, Japan.

1 INTRODUCTION

1.1 Gate Rudder concept application

The demand for improvements in ship energy efficiency is still a paramount in mitigating CO_2 emissions from shipping in spite of low fuel oil price. Consequently, substantial amount of Energy Saving Devices (ESDs) have been proposed, but so far only cost-effective proposals could survive. In this paper a new ESD, known as "Gate Rudder", will be introduced as applied on a 499 tonnes domestic cargo ship.

The Gate Rudder concept originated from twin rudder systems located aside a propeller. By replacing the conventional rudder by this novel system, many advantages can be gained as shown in Table 1.

Whereas the studies on the propulsive performance of Gate Rudder have been already presented, e.g. Sasaki et al (2015), Turkmen et al (2015), the manoeuvring performance of the gate rudder including a theoretical analysis has not been deeply investigated.

Table 1. Pros and Cons of Gate Rudder

Name	Conventional Rudder	High Lift Rudder	Gate Rudder
Energy saving	base	Equivalent or worse	3-5% better
Turning at Navigation	base	Superior	Better
Course keeping	base	Better	Better
Turning at port	base	Superior	Better
Stopping	base	Better	Better
Berthing	base	Equivalent	Superior
Noise and Vibration	base	Better	Superior
Cost	base	Slightly worse	Depends on design
Impact on Design	base	Equivalent	Superior

Table 2. Steering Modes of Gate Rudder

Name	Functions	Rudder angle
Economy mode	The most efficient operation at calm sea condition	+ 3 ~ + 5 deg.
Rough sea mode	The propeller speed can be increased by accelerated flow	+ 0 ~ + 2 deg.
Steering mode	Normal steering (change the course)	Example -10 & +10dg.
Circle mode	Emergency steering (circle motion)	-30 & +35 deg.
Crash Stop mode	Emergency steering (crash stop)	-30 & -30 deg.
Crabbing mode	Berthing & de-berthing motion	+110 & +60 deg.

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This paper therefore focuses on the manoeuvrability prediction method for the Gate Rudders. The program was established by modifying the hydrodynamic forces of propeller and rudder, considering the interaction as explained in the following sections.

The unique manoeuvring modes of the Gate Rudder described in The Gate Rudder concept originated from twin rudder systems located aside a propeller. By replacing the conventional rudder by this novel system, many advantages can be gained as shown in Table 1.

Whereas the studies on the propulsive performance of Gate Rudder have been already presented, e.g. Sasaki et al (2015), Turkmen et al (2015), the manoeuvring performance of the gate rudder including a theoretical analysis has not been deeply investigated.

Table 2 show superior manoeuvrability with various modes to operate the vessel. Each of the twin rudder blades can be helmed from forward to afterward. The most efficient rudder mode will be crabbing mode which can be seen in Figure 1 (bottom right). This mode promises strong side forces aiding the ship berthing. Table 3 shows an overview of the research programs related to the manoeuvrability investigation of the Gate Rudder.
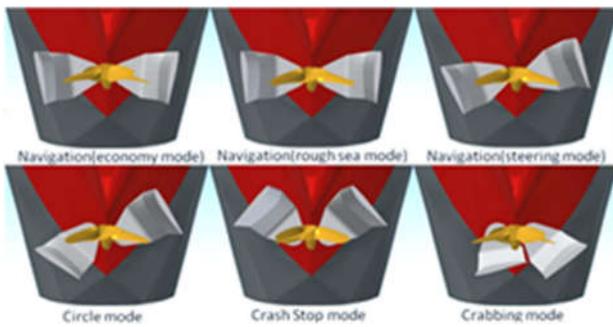
Figure 1. Steering Modes of Gate Rudder

Table 3. Research on manoeuvrability of Gate Rudder

Name	Contents	Facility etc.
Tank Tests	Rudder Force Measurements with 6m Large Ship Model (without yaw angle) Hull Force Measurements with 2 m Ship Model Captive Tests and Free Running Tests with 2.5m Ship Model	NMRI FEL Kyushu Uni.
Simulation	Development of Simulation Program based on MMG model Rudder Control System	Newcastle Uni. & Kamome Propeller Tokyo Keiki
Full Scale Tests	Maneuvering Tests at Sea Trial Monitoring at After Delivery	Yamanaka Ship Yards Newcastle Uni.

1.2 The MMG standard prediction method

The MMG standard prediction method is a nonlinear ship manoeuvring mathematical model based on the concept developed by the Japanese Manoeuvring Modelling Group (Ogawa *et al.*, 1977) and later unified by the Japan Society of Naval Architects and Marine Engineers (*Report of Research committee on standardization of mathematical model for ship maneuvering predictions*, 2013). The standard is composed by four parts, namely:

- Mathematical manoeuvrability model
- Procedure to conduct the required captive model tests
- Procedure to analyse the model tests
- Full-scale manoeuvrability prediction method

Whilst details of the latter three parts can be found in Ogawa *et al.* (1977) and in the *Report of Research committee on standardization of mathematical model for ship maneuvering predictions* (2013), recalling the fundamentals of the first fits within the scope of this work.

The reference coordinate system adopted by the MMG is introduced as reported in (Yasukawa and Yoshimura, 2015):
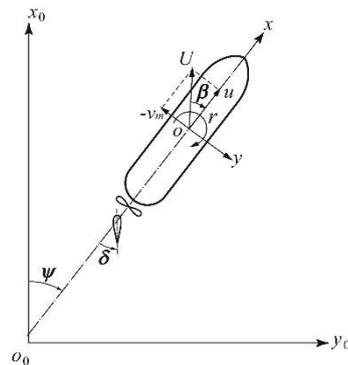
Figure 2. Reference coordinate system (Yasukawa and Yoshimura, 2015)

Where x_0 and y_0 lay on the still water surface, o coincides with the midship point, u and v_m are the components of the ship velocity U along the ship axis, r is the yaw rate and β, δ, ψ the drift, rudder and heading angles respectively. According to the model, the acting forces are subdivided by reason of their source:

$$\begin{cases} X = X_H + X_R + X_P \\ Y = Y_H + Y_R \\ N = N_H + N_R \end{cases}$$

where subscript H, P and R refer to Hull, Propeller and Rudder, respectively.

Hull forces are addressed as functions of the velocity U of the vessel, its drift angle β and yaw rate r with uncoupled and coupled terms up to the third order:

$$\left.\begin{array}{c} X_H \\ Y_H \\ N_H \end{array}\right\} = f\left(U, \beta, \dot{\beta}, \ddot{\beta}, r, \dot{r}, \ddot{r}, \beta r, \beta rr, \dots\right)$$

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The relationships with these variables depend on the geometry of the vessel and it's therefore recommended to carry out captive model tests to obtain the manoeuvrability derivatives. Where this is not possible, statistical regressions may be used for common hull forms such as in (Yamaguchi *et al.*, 2009).

Propeller forces are considered in the longitudinal direction only. The usual representation for the propeller characteristics is used to calculate the propeller thrust K_T keeping into account the change in wake fraction w_P and thrust due to the manoeuvring motion. The function $K_T = f(J_P)$ is represented by a second order polynomial.

The hydrodynamic rudder forces are presented as sum of two fundamental components, namely the lift force acting on the rudder itself and the lift force induced on the hull caused by the so-called flap effect, i.e. the interaction between rudder and hull.

$$\begin{cases} X_R = -(1 - t_R)F_N \sin \delta \\ Y_R = -(1 - a_H)F_N \cos \delta \\ N_R = -(x_R + a_H x_H)F_N \cos \delta \end{cases}$$

where F_N represents the rudder normal force, t_R the change in drag due to rudder-propeller interaction, a_H the magnitude of the flap effect, x_R and x_H respectively the rudder and flap force centroid from mid-ship. The rudder normal is also defined as:

$$F_N = 0.5 \rho A_R U_R^2 f_\alpha \sin \alpha_R$$

With A_R being the rudder projected area, f_α the rudder lift coefficient, $U_R = \sqrt{u_R^2 + v_R^2}$ and α_R respectively the inflow velocity and angle at the rudder, as it can be seen in Figure 3.
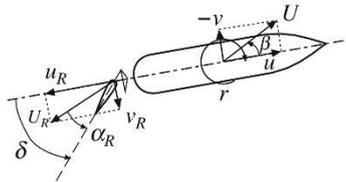
Figure 3. Rudder and ship velocities and angles (Yasukawa and Yoshimura, 2015)

It is worth recalling that in the MMG model the definition of the inflow characteristics comes with consideration of the complex flow straightening phenomena related to the hull/propeller slipstream during any manoeuvre.

Owing to the characteristics described above and the limited number of variables, the MMG standard prediction method thus lends itself to be implemented in a manoeuvrability simulation program.

1.3 Problem definition
Nevertheless, the particular geometry and location of the Gate Rudder, demands additional considerations. A first effect of its uncommon features can be seen in the water flow on the Gate Rudder, due to the closer proximity to the hull and the propeller disc. This also affects the interaction

with the hull during turning manoeuvres, as it will be seen in the following sections. Finally, because of its unique mechanism many steering modes can be explored and the relative helm control thus has to be defined.

2 CFD SIMULATIONS
Commonly, it is acknowledged that the marine rudders are generally positioned behind the propellers at the after end of the marine vessel, whilst the Gate Rudders are set aside the propeller. The Gate Rudder's conceptual design intends to take advantage of the duct effect to produce additional thrust forces. As mentioned earlier, this greatly complicates the flow conditions of the Gate Rudders.

As it has been reviewed in the standard MMG method (Yasukawa and Yoshimura, 2015), the flow velocity for a traditional rudder is basically determined by the effective wake with propeller operating under various heading conditions. However, rare experimental or numerical studies have been conducted to investigate the effective wake aside of the propeller, let alone under various heading conditions.

Therefore, the first task within this study is to understand and predict the flow velocity distribution for the Gate Rudders. In order to perform this task, a simplified full-scale computational fluid dynamics (CFD) model has been established in this chapter.

2.1 Numerical modelling methodology
The numerical model in this paper is built in the commercial CFD software Star-CCM+ to solve the incompressible Reynolds Averaged Navier–Stokes (RANS) equations with Shear Stress Transport (SST) turbulence models. The simulation has been conducted for the target vessel with a full-scale 68m long numerical model. Due to the limitations of computational power and for the purpose to achieve a quick prediction of the velocity distribution aside the propeller, the simulations have been conducted without the free surface to neglect its limited impact on the effective wake.

Table 4. CFD simulation conditions

Ship length	68m
Ship speed	12.81 knots
Propeller diameter	2.5m
Propeller thrust	96.985 kN
Propeller RPS	3.5 to 3.8 RPS (Constant thrust)
Drift angles	0° to 16° (2° intervals) 25° and 35°

However, the flow induced by the propeller cannot be ignored during the effective wake prediction and a virtual disc model at the propeller position has been included to simulate the effect of propellers, where the virtual disc can simulate the propeller flow without an actual propeller modelling. By providing the propeller open water curve, the program can automatically match the correct operating

condition in order to maintain the required thrust to overcome the vessel's resistance. The conditions of the CFD simulation are specified in Table 4 and represent an actual operational profile. The layout of the Gate Rudders arrangement is presented in Figure 4.

2.2 Mesh generation and boundary condition definition

Trimmer mesh generator in Star-CCM+ has been used with prismatic boundary layer mesh control and volumetric mesh control. Mesh overview has been presented in Figure 5. Local mesh refinement has been specified especially in the propeller position and near the bulbous bow as it can be seen Figure 6. In total, 2 million cells have been used in the computational domain.

During the simulation, k-ω Shear Stress Transport (SST) turbulence model has been preferred. Velocity inlet with oblique flow angle and pressure outlet have been applied for the inlet and outlet boundary conditions, while a free-slip wall condition is applied to the bottom boundary.
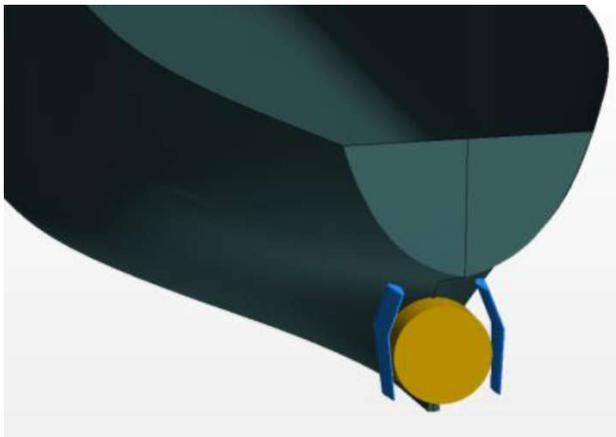
Figure 4. Positions of virtual disc and Gate Rudders
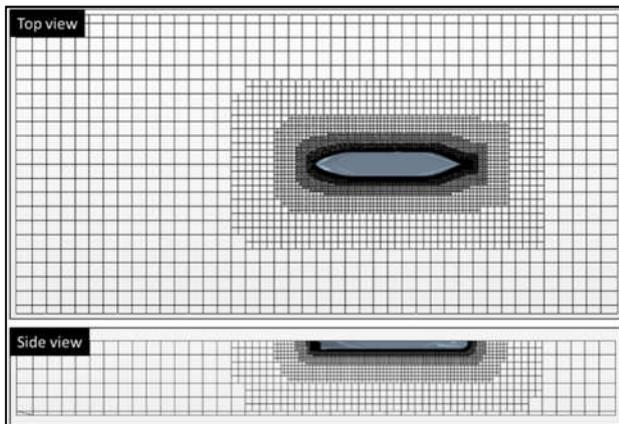
Figure 5. Mesh overview
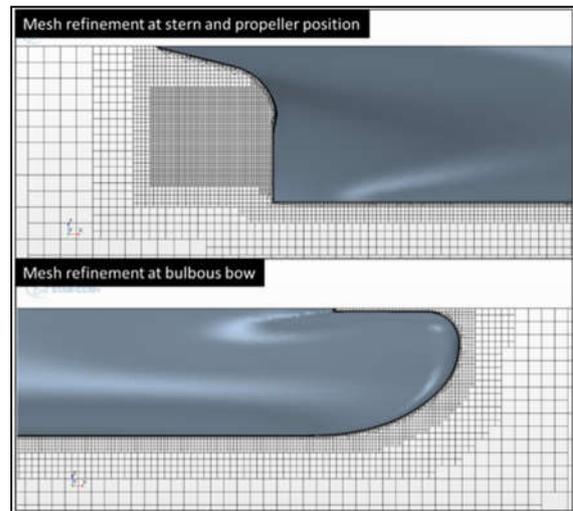
Figure 6. Mesh refinement at stern and bow

2.3 Simulation results and analysis

Based on the above setup, the flow velocity distribution in the Gate Rudder position can be achieved. As shown in Figure 7, the velocity distribution of the section at the propeller position and together with the vector at the Gate Rudder position have been displayed when the oblique (drift) angle is 0°. As it can be seen, the flow is nearly symmetric to the mid-ship but not exactly, due to the rotational effect of this right-handed propeller model. It can also be seen in Figure 8 from the top view of the shaft line section.

Another example of result has been presented is the case of 16° of drift. The same post analysis has been conducted, which has been presented in Figure 9 and Figure 10. Because of the oblique flow angle, the velocity distribution is strongly biased, especially for the starboard side.

Based on the above results, it was possible to parametrise the flow velocity components in the x and y directions for each of the two blades and every rudder angle. Using a powerful statistical software, the velocities were expressed as polynomial functions of the drift and rudder angle in order to be easily calculated inside the simulation program.
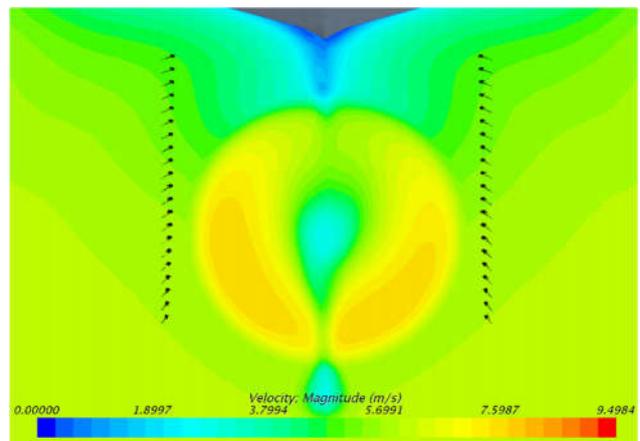
Figure 7. Velocity and vector distribution at 0 degree oblique angle (aft view)

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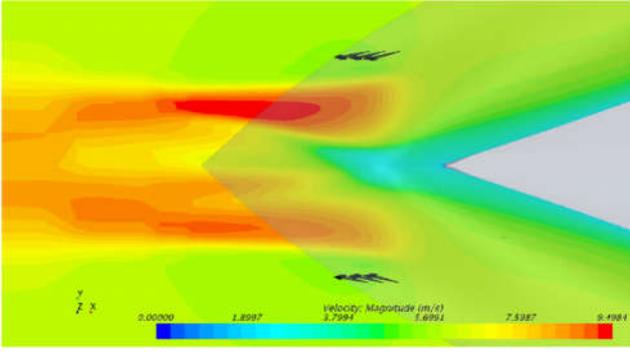
Figure 8. Velocity and vector distribution at 0 degree oblique angle (top view)
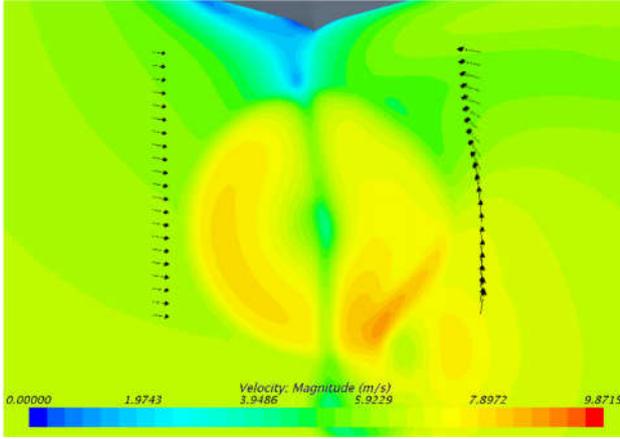
Figure 9. Velocity and vector distribution at 16 degree oblique angle (aft view)
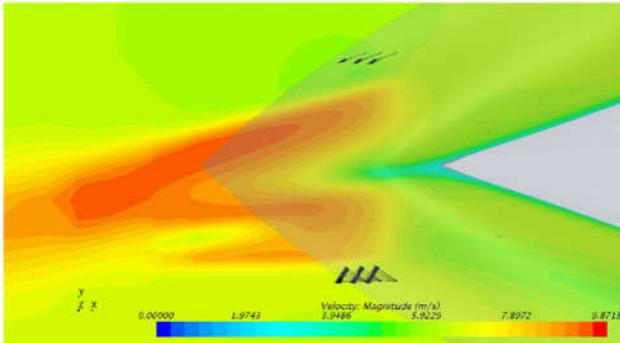
Figure 10. Velocity and vector distribution at 16 degree oblique angle (top view)

3 MANOEUVRABILITY PREDICTION PROGRAM

The manoeuvrability program has been built in Excel environment using VBA to code the MMG prediction model and it aims to simulate the standard ITTC Z-Tests and Circle Test for both conventional and Gate Rudders.

The program comprises an Excel user interface for data input and output analysis and an integrated VBA code handling the iterative solution of the fundamental equations. The first core part of the code is concerned with the determination of the hydrodynamic forces acting on Hull, Propeller and Rudder. The second handles the initialization, a Runge-Kutta discretization method and the controls of simulation and virtual ship.

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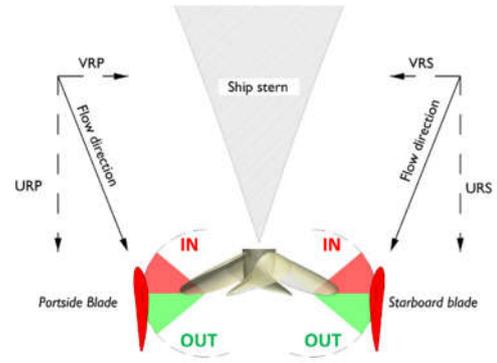
Figure 11. Inflow parameters for the Gate Rudder

3.1 Determination of the hydrodynamic forces

The different hydrodynamic conditions at which the Gate Rudder is subjected had to be initially addressed. Firstly, new parameters were defined to address the inflow components and the peculiar rudder angles assumed by the Gate Rudder as in Figure 11. For convention, rudder angles closer to the hull (*in*) are negative, those farther from the hull (*out*) are positive. In second place, the inflow velocity components need to be determined in order to calculate the inflow angle and, in turn, the rudder force. Whereas for a conventional rudder the velocity components are determined using standard approximation formulas, in this study they could be expressed according to the CFD results as:

$$UR_\sigma = A_0 + A_1\delta_\sigma + A_2\beta_R + A_3\beta_R^2 + \cdots + A_n\beta_R^{n-1}$$
$$VR_\sigma = B_0 + B_1\delta_\sigma + B_2\beta_R + B_3\beta_R^2 + \cdots + B_n\beta_R^{n-1}$$

Where σ identifies either the Port (P) or the Starboard side (S) blade and β_R is the local drift angle at the rudder defined as the algebraic sum of the ship drift angle β and that locally induced by the ship's yaw motion:

$$\beta_R = \beta - \ell'_R r'$$

With ℓ'_R obtained from the captive model tests and r' being the ship's yaw rate (Yasukawa and Yoshimura, 2015). From the above, it is possible to calculate the inflow angle on each blade as:

$$\alpha_{R,\sigma} = \delta_\sigma - \tan^{-1}\left(\frac{VR_\sigma}{UR_\sigma}\right)$$

Therefore, the normal force on each blade can be found:

$$F_{N,\sigma} = 0.5\rho A_R(UR_\sigma^2 + VR_\sigma^2)f_\alpha \sin\alpha_{R,\sigma}$$

Owing to the wide variation of relative position between rudder blades and hull and the significant consequence on the flap effect, it was seen as necessary to specify different flap effect coefficients depending on whether the blades are closer or farther from the hull. Therefore, $a_{H(in)}$ and $a_{H(out)}$ were defined, with each blade assuming at every calculation step the relative value in accordance with its position. The total rudder forces and moments are thus calculated as:

$$\begin{cases} X_R = X_{RP} + X_{RS} \\ Y_R = Y_{RP} + Y_{RS} \\ N_R = N_{RP} + N_{RS} \end{cases}$$

where:

$$X_{RP} = -(1 - t_R)F_{NP} \sin \delta_P$$
$$X_{RS} = -(1 - t_R)F_{NS} \sin \delta_S$$
$$Y_{RP} = -(1 - a_{HP})F_{NP} \cos \delta_P$$
$$Y_{RS} = -(1 - a_{HS})F_{NS} \cos \delta_S$$
$$N_{RP} = -(x_R + a_{HP}x_H)F_{NP} \cos \delta_P$$
$$N_{RS} = -(x_R + a_{HS}x_H)F_{NS} \cos \delta_S$$

3.2 Manoeuvre and simulation controls

The input data are initialised from the user interface depending on whether the rudder mode is set to simulate a conventional or Gate Rudder. As mentioned earlier, the program is built so as to simulate generally 4 zig-zag tests and 2 circle tests; however, in the case of conventional rudder these are set to the standard ITTC cases, i.e. $\pm 10°$, $\pm 20°$ and $\pm 35°$. The required inputs thus pertain:

- Hull dimensions and geometric coefficients
- Hull derivatives and added masses
- Propeller dimensions and performance coefficients
- Rudder dimensions and coefficients
- Gate Rudder initial helm controls for each test and each blade
- Ship speed and propeller rate of revolutions
- Time discretization settings

The hydrodynamic equations are calculated inside a Runge-Kutta loop controlled by the simulation length, time step size and output time set by the user. An integrated autopilot function controls the ship manoeuvre during the zig-zag tests in accordance with the IMO requirements.

Three additional add-ins allow the execution of simple animations, the automatic calculations of propeller speed and to obtain the hull derivatives using Kijima's regression formulas (Yamaguchi *et al.*, 2009).

3.3 Simulation settings

The data used in the simulation of the Gate Rudder manoeuvrability performance are here reported. The principal ship characteristics are listed in Table 5. In addition:

- The Hull derivatives were derived from captive model tests results.
- From the same test $\ell'_R = -1$, $a_{H(in)} = 0.4$, $a_{H(out)} = 0$ and $x_H = -0.45$.
- The Gate Rudder lift coefficient was derived from tests in the Emerson Cavitation Tunnel of Newcastle University, UK as being $f_\alpha = 1.4\pi$.
- The model speed was set $V_S = 0.48 \ m/s$.
- Simulation was run with a time step of $0.05s$ and an output time of $0.5s$ for $200s$.
- The propeller Open Water characteristics were also evaluated in the Emerson Cavitation tunnel and the quadratic equations are:

$$K_T = -0.25J^2 - 0.4J + 0.343$$

$$10K_Q = -0.25J^2 - 0.65J + 0.518$$

To match the experimental validation settings, the Gate Rudder helm angles listed in Table 6 were used.

4 MANOEUVRING TEST VALIDATION

To verify the simulation program, captive tests and free running tests were conducted at the manoeuvring and seakeeping tank of Kyushu University. Pictures of the tank and of the 2.5m wooden model are shown in Figure 12 and Figure 13, respectively. Table 6 shows the test matrix of the manoeuvring tests conducted with the model. Two kind of test were conducted; captive tests and free running tests with the Gate Rudder.

Table 5. Main particulars of the case study ship

Variable	Symbol	Value	
Length	Lpp	2.50	[m]
Breadth	B	0.44	[m]
Draft	d	0.15	[m]
Block Coefficient	Cb	0.714	
Centre of Buoyancy	lcb	−1.81	
Prop. Diameter	Dp	0.09	[m]
Rudder Area (1 bl.)	AR	0.005	[m^2]
Rudder Span (1 bl.)	H_R	0.117	[m]

Table 6. Simulation test matrix

Test	Port blade	Starboard blade
+10 zig-zag	0	−10
-10 zig-zag	0	10
+20 zig-zag	0	−20
-20 zig-zag	0	20
+35 circle	35	−30
-35 circle	−30	35

During the captive tests, the rudder forces of the starboard side rudder were measured simultaneously with the 3 components of the hull forces. During the free running tests, the ship motion was captured by optical means without touching the ship to allow the purest free motion from the carriage.

There were two restrictions for free running tests given by the tank length and the measurement instruments. Due to the length of the tank it was not possible to cover the 2nd overshoot angle. Another restriction was the size of rudder

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steering instruments. As the space was not enough to install two sets of this instrument at the stern (shown in Figure 14), only one side of the Gate Rudder could be controlled. Therefore, some results are predicted by the simulation by superposing the rudder forces which was measured independently.

Figure 12. Model basin of Kyushu University
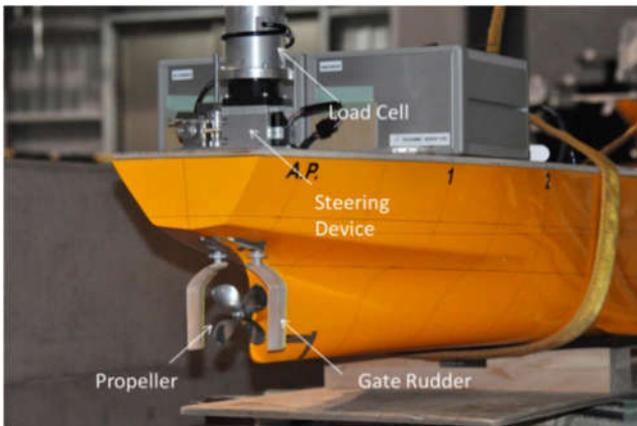
Figure 13. 2.5m wooden model
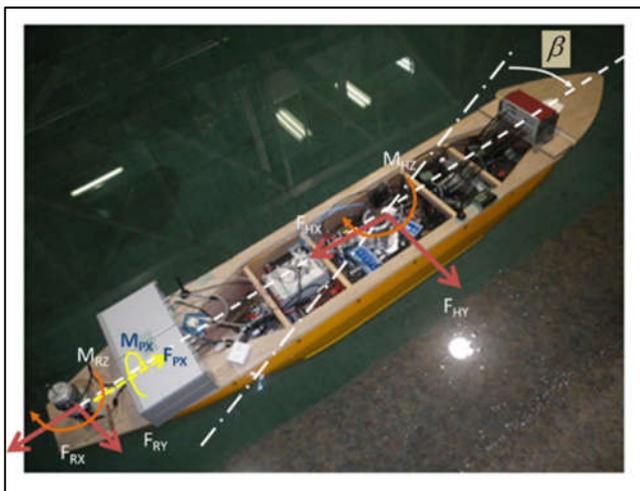
Figure 14. Setup of the manoeuvring test

4.1 Test results and comparison with simulations

The results from the simulation and the free-running test were compared and they are presented in Figure 15 through Figure 18. The blue line represents the simulated results,

the red dashed line the experimental measurements. Due to the facilities limitations, the Portside rudder blade was fixed on 35deg (Starboard turn) and 30deg (Port turn) whilst the only Starboard blade was remotely controlled. The computation closely agrees with the experimental measurements and captures the trajectory of the vessel during the manoeuvre, the differences stemming mainly from particular experimental limitations that could not be reproduced in the simulation.

Figure 15 and Figure 16 show comparisons between the simulated and experimental results for standard 35deg circle tests, with values agreeing particularly for the Portside manoeuvre. This is likely due to the the strong asymmetries in the velocity gradients on the two rudder blades caused by the action of the propeller.

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Figure 15. Starboard 35deg circle test: ship track (a), rudder angle (b) and ship speed (c) time series
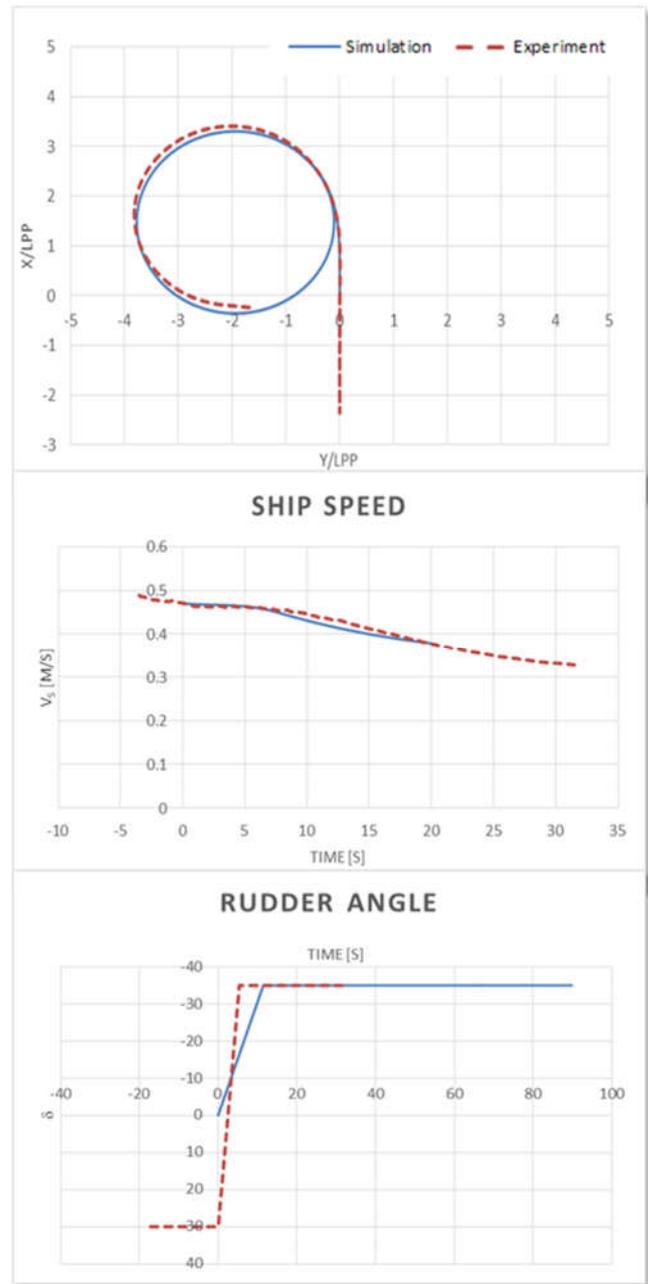
Figure 16. Port 35deg circle test ship track (a), rudder angle (b) and ship speed (c) time series

Figure 17 and Figure 18 plot the time series of the heading angle during two representative zig-zag manoeuvres, -10 and -20. In this case, the Port rudder blade was locked on 0 deg angle with the only Starboard rudder blade changing position. Considering such limitation in the experimental facility, the simulations and experimental measurments agree within reason, despite the evident of slower response of the vessel to the change in helm angle during the model testing.

Figure 19 through to Figure 22 present the heading time series for all the conducted zig-zag tests against the IMO requirements, showing a good perfromance of the Gate Rudder within the standards.

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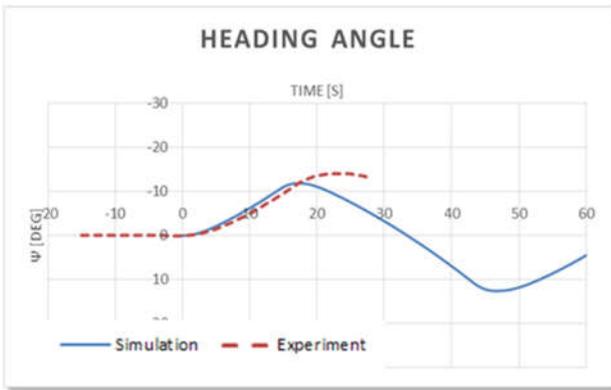
Figure 17. Time series of heading angle during Port 10deg zig-zag test

Figure 18. Time series of heading angle during Port 20deg zig-zag test

Figure 19. Time series of heading angle during Starboard simulated 10deg zig-zag test

Figure 20. Time series of heading angle during Port simulated 10deg zig-zag test

Figure 21. Time series of heading angle during Starboard simulated 20deg zig-zag test
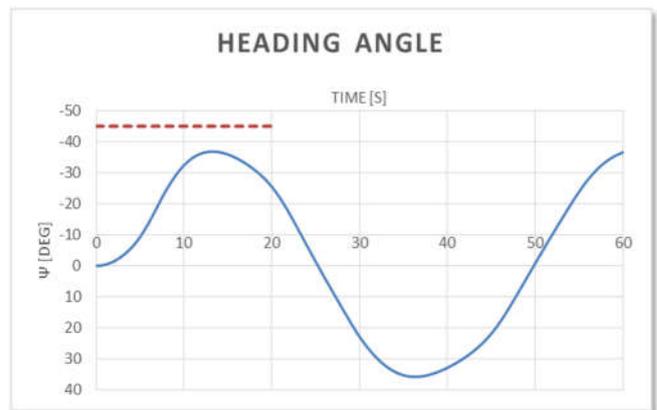
Figure 22. Time series of heading angle during Port simulated 20deg zig-zag test

5 CONCLUSIONS

This paper attempted to address the manoeuvring performance prediction of the conceptual Gate Rudder. The MMG standard prediction method was reviewed and chosen to conduct further development for the Gate Rudders. Considering the interaction between the hull and the propeller, by using the CFD simulations, a detailed analysis were conducted to achieve the flow velocity around the

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Gate Rudders. Based on this analysis, the MMG standard method was tailored in the environment of a simulation program to predict the manoeuvring performance of the Gate Rudder as per the standard ITTC recommended procedures. Finally, Free-running manoeuvring tests were conducted in Kyushu University to validate the program prediction with encouraging results. The project confirmed that the simulation program can simulate fairly well the motions of a vessel equipped with a Gate Rudder and that it can be useful for preliminary manoeuvring performance predictions.

ACKNOWLEDGEMENTS

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