Cavitation tunnel tests and full-scale review of the first Gate Rudder system installed on the 400TEU container ship

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Abstract:

Following the successful installation of the world's first GATE RUDDER® system on a 400TEU container ship (see Figure 1), superior fuel saving and manoeuvring performances have been recorded with this vessel over her sister ship fitted with a conventional rudder. Also, noticeable reductions in the aft end vibrations and noise have been reported by the captains and crew of these vessels in service. This paper describes and discusses the results on the recent cavitation tunnel tests conducted in the Emerson Cavitation Tunnel with the same geometry of the full-scale rudders and propellers for the above-mentioned vessels except for the same wake distribution due to the current limitation of the test facility used. The results presented in the paper may help to shed a light on the full-scale cavitation and noise performances of the two sister ships currently operating between the North and South of Japan by following the same route.

Keywords: Gate Rudder, Cavitation, Noise

1. INTRODUCTION

"GATE RUDDER®" is a novel twin rudder arrangement which has blades with the asymmetric cross-sections enveloping the propeller at the upper part and aside the propeller as shown in Figure 1. This concept was originated in Japan (Sasaki, 2013) and has been further developing with joint activities in the UK and Japan, Sasaki et al (2018). Advanced energy saving and steering capability of the GATE RUDDER® have been demonstrated through both experimental and numerical studies (Sasaki et al. 2015, Turkmen et al. 2015) and recently this propulsion system was installed on a 400TEU domestic container ship in Japan for the first time.

Advanced energy-saving feature originates in the rudder thrust induced by the cambered twin rudder blades and the propeller, acting as an efficient accelerating ducted propulsor. The remarkable flap effect of the GATE RUDDER® increases the lateral forces and the yaw moment leading to improved steering and course keeping capabilities as reported in (Carchen et al, 2016, Turkmen et al. 2016). Moreover, the recent sea trials confirmed that the GATE RUDDER® system has provided more than expected based on the previous studies, Sasaki et al (2018).

Recently, a pioneering experimental study on the cavitation and noise characteritics of the GATE RUDDER® has been completed in the Emerson cavitation tunnel for the first time invloving a GATE RUDDER® system. These tests were conducted in comparative manner, and involved with a GATE RUDDER® and its counterpart conventional single rudder combined with the same propeller.

Figure 1. First full-scale GATE RUDDER® system

This paper presents the details of these tests and results of the cavitation and noise performance of the both rudder arrangements and discusses the results. Following this introductory part, the remaining sections

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of the paper describe the test set-up & conditions in Section 2, the results and discussion in Section 3 and concluding remarks drawn from the study in Section 4.

2. TEST SET-UP & CONDITIONS

The experiments were carried out in the Emerson Cavitation Tunnel (ECT) of Newcastle University, which has a measuring section of 3.1m x 1.21m x 0.8m (LxBxH), as shown in Figure 2 and described in details in (Atlar, 2011).

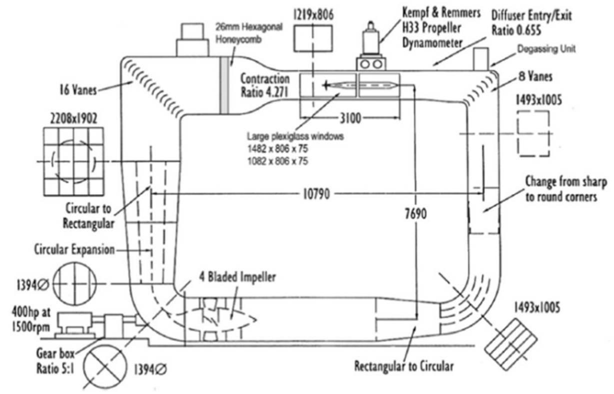

Figure 2. Emerson Cavitation Tunnel

The aft end and propeller arrangements of the conventional rudder (without the flap) and GATE RUDDER® systems were represented with the model rudders and propellers of the two vessels with a scale ratio of 21 and fitted in the downstream of the K&R H33 dynamometer of the ECT as shown in Figure 3.

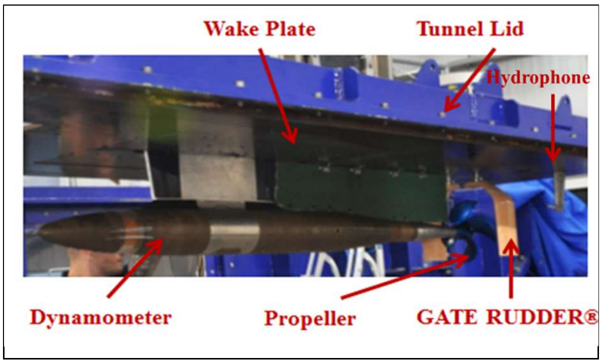

Figure 3. Test set-up with GATE RUDDER® at ECT

The model propeller and rudder geometries for the conventional rudder and GATE RUDDER® systems were provided by KAMOME Propeller Co, LTD. The same Controllable Pitch Propeller (CPP) model of a 250mm diameter with four-blades and high skew was used behind the conventional rudder and GATE RUDDER® systems as shown in Figure 4. The model propeller designed for the conventional propeller was used for both rudder systems in order to investigate the cavitation and noise characteristics in comparative manner,

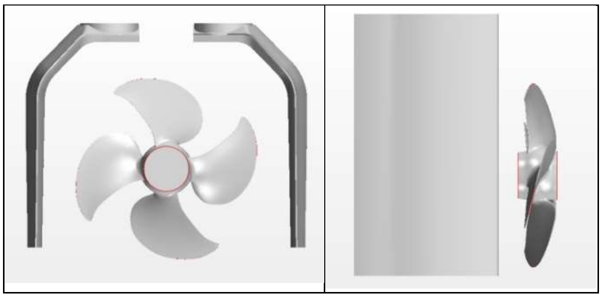

Figure 4. GATE RUDDER® system (Left) and Conventional Rudder system (Right)

While the measuring section of the ECT usually allows a reasonable size dummy hull with a properly scaled aft end arrangements, in this investigation, a very crude wake simulation arrangement was used due to the time limitation for the facility. In this arrangement, the wake of the H33 dynamometer was combined with the wake of a vertical plate of 0.85m length and 0.02m thickness which was placed between the trailing edge of the dynamometer strut and the model propellers with a diameter of 250mm, as shown in Figure 3. The wake plate was also covered with a sand paper of grit P36 to trip the wake flow in turbulent regime.

During the experiments following performance characteristics and associated parameters were monitored and recorded:

- *Propeller performance* (tunnel and shaft speed by encoder, torque and thrust by K&R H33 dynamometer)
- *Cavitation dynamics* (Extend and severity of cavitation recorded by high speed cameras)
- *Underwater noise levels* (Frequency and Sound Pressure Levels by B&K Type 8103 miniature Hydrophone)

During the tests, the propeller thrust and torque as well as the shaft rpm were recorded by a data collection rate of 100Hz. The URN characteristics were recorded by using a B&K 8103 Hydrophone located inside the tunnel in a streamlined strut aligned with the tunnel main flow. The distance between the hydrophone and propeller plane centre was longitudinally 170mm, transversally 235mm and vertically 80mm. The cavitation observations were recorded by using moving and still cameras from the side and bottom windows of the ECT for each test condition. As well as the oxygen and

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temperature of the tunnel water. Also, during the tests the background noise level, water temperature and dissolved air content were checked and kept similar for each test.

Test were conducted at 5 different operational conditions of these ships that varied from a bollard condition e.g. experienced in harbour manoeuvring (Test 1) to service (MCR) condition at 16.1 knots (Test 5). Table 1 presents these test conditions.

Table 1 Test conditions

Parameters	Test1	Test2	Test3	Test4	Test5
V_a (m/s)	0	0.925	1.56	3.00	3.97
n (rpm)	1200	1438	1438	1438	1925
P_v (mmHg)	-200	-200	-200	-200	-400

where V_a is advance speed; n is propeller shaft speed, P_v is the vacuum level applied during the tests.

3. RESULTS AND DISCUSSIONS

In the following the propeller performances and cavitation observations are given in separate sections i.e. for the GATE RUDDER® (in Section 3.1) and Conventional Rudder arrangements (in Section 3.2) while the noise measurement results are presented in a common section (Section 3.3).

3.1. GATE RUDDER® test results

The initial conditions for the tests are given in Table 2 while the corresponding performance data for the propeller of the GATE RUDDER® set-up corresponding to the test conditions of Table 1 are presented in Table 3

Table 2 Initial conditions for the GATE RUDDER® system tests

GATE RUDDER® test conditions	*Value*
Tunnel water density (kg/m^3)	1006
Vacuum applied (mmHg)	849
Atmospheric pressure (mmHg)	758
Tunnel Temperature (deg)	20.2

Table 3 Propeller performance data with the GATE RUDDER® system

	V	N	J	K_t	σ_n
Test1	0	20.0	0	0.37	4.31
Test2	0.925	24.1	0.15	0.33	4.31
Test3	1.56	24.0	0.26	0.29	4.31
Test4	3	24.1	0.50	0.18	4.31
Test5	3.97	32.1	0.50	0.18	1.66

Figure 5 shows the cavitation patterns experienced with the GATE RUDDER® system corresponding to Test1 (i.e. bollard condition). All propeller blades displayed moderate strength of tip vortex cavitation emanating from the leading edge of the blades, and not exactly from the tip but from a smaller radius due to the high skew of this propeller. The cavitating vortices appeared to be larger in thickness and stronger in strength at the upper part of the propeller plane than those at the lower part. The cavitating tip vortices twisted like ribbons leaving at the blade edges and continued in the downstream. While the traces of the tip vortices could not be detected by eye beyond the rudder trailing edges a well-develop hub vortex cavitation was observed in downstream as perturbed by transient distortions.

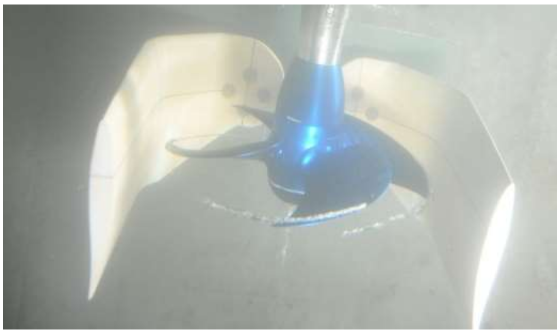

Figure 5. Cavitation pattern observed in Test 1 condition

Sample views of the cavitation patterns observed in the Test 2 condition is shown in Figure 6. A well-developed steady leading-edge sheet cavitation combined with the earlier mentioned tip vortex cavitation was covering about 10% of the suction side of the blade surfaces. This was accompanied by the dominant hub vortex cavitation extending to the downstream. Similar to the previous test condition, the cavitating tip vortices were leaving the blade leading edges almost half-way in a twisted ribbon form and extending in the downstream of each blade. These vortices were visible up to two full revolutions of the propeller's slipstream and after which becoming unsteady and desinent.

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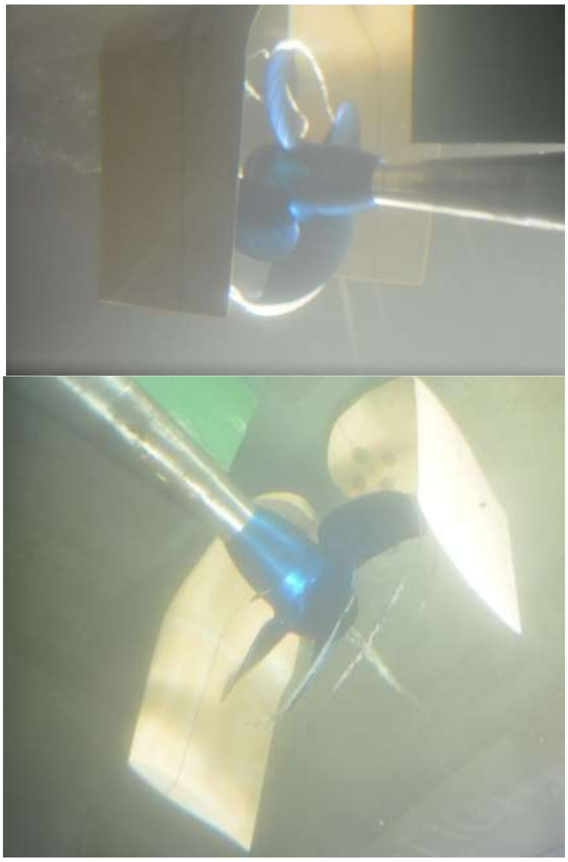

Figure 6. Cavitation pattern observed in Test 2 condition

Figure 7 shows the cavitation patterns observed in Test 3 condition. The pattern and cavitation dynamics observed in this condition were similar to Test 2 with reduced strength due to less loading on the propeller. However, the twisted cavitating vortex was still visible with the unsteady appearance after the rudder blades as well as the persistent cavitating hub vortex in the downstream.

The sample views of the cavitation pattern observed in Test 4 condition are shown in Figure 8. The tip vortex cavitation still occurred but much weaker and intermittent. The strength of the cavitation reduced greatly and after one full revolution. The tip vortex cavitation became almost invisible as well as the hub vortex cavitation. This condition is corresponding to 10kts in full scale.

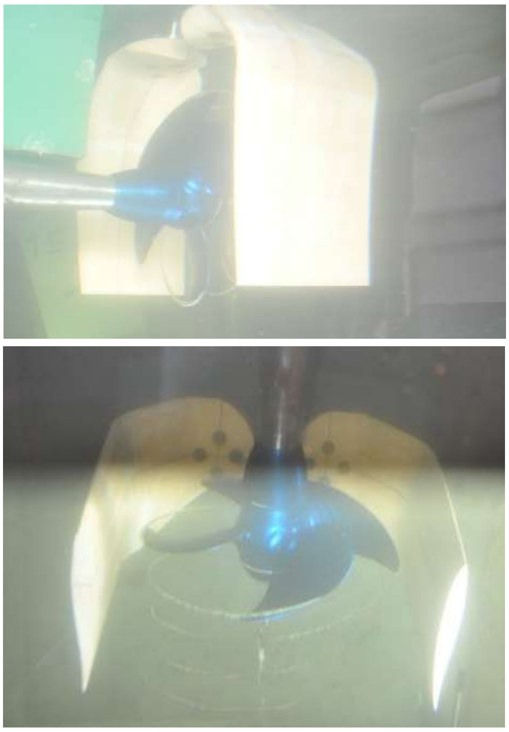

Figure 7. Cavitation pattern observed in Test 3 condition.

Figure 8. Cavitation pattern observed in Test 4 condition

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Figure 9 displays the cavitation pattern observed during the Test 5 condition which corresponds to the MCR condition of the full-scale vessel at 16.1 knots. In spite of the relatively low propeller loading, the reduced cavitation number corresponding to this operating condition imposed the strongest tip vortex combined with the largest extent of sheet cavitation at the leading edge which covered about 15% of each blade. The cavitating tip vortex extended well beyond the GATE RUDDER® blades and this was also accompanied by the strong hub vortex cavitation in the downstream of the hub.

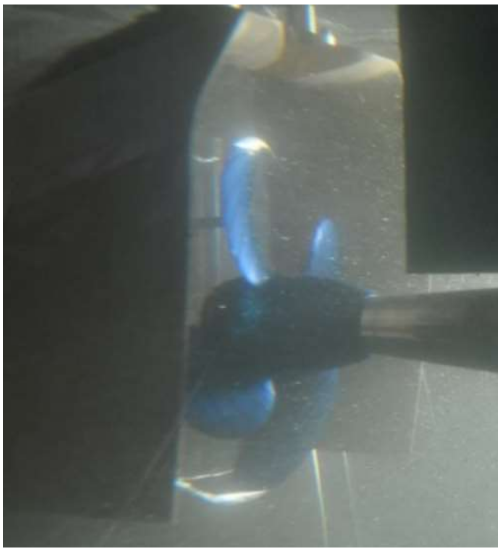

Figure 9. Cavitation pattern observed in Test 5 condition

3.2. Conventional rudder test results

The initial conditions are given in Table 4 Initial conditions for the Conventional Rudder system tests

. The torque and thrust coefficients are presented in Table 5 Propeller performance data with the Conventional Rudder system.

Table 4 Initial conditions for the Conventional Rudder system tests

Conventional rudder test condition	*Value*
Tunnel water density (kg/m3)	1006
Vacuum applied (mmHg)	846
Atmospheric pressure (mmHg)	765
Tunnel Temperature (deg)	17.8-18.0

Table 5 Propeller performance data with the Conventional Rudder system

	V	N	J	K_t	σ_n
Test1	0	20.1	0	0.42	4.31
Test2	0.925	23.9	0.15	0.38	4.31
Test3	1.56	23.9	0.26	0.33	4.31
Test4	3	23.9	0.50	0.22	4.31
Test5	3.97	32.19	0.49	0.22	1.66

Figure 10 shows the cavitation pattern experienced with the conventional rudder system corresponding to Test 1. All propeller blades displayed strong tip vortex cavitation emanating from the leading edge of the blades and combined with a narrow leading edge sheet cavitation. Because of the relatively high skew of the propeller blades, the cavitating vortices were leaving the blade leading-edges before the tips twisted like ribbons extending in the downstream.

Due to the effect of the wake plate, there were deformations of the tip vortices at the TDC and these deformations were combined with the effect of the rudder in downstream resulting in the bifurcation of the tip vortex at the rudder leading edge. In spite of the accentuated sheet cavity dynamics at the wake shadow and deformation of the tip vortex at the rudder leading edge, the tip vortex cavitation was transported in downstream through the propeller slipstream by interacting with the rudder and visible by eye for 3 to 4 revolutions of the propeller slipstream and disappearing afterward. No hub cavitation could be observed in this condition.

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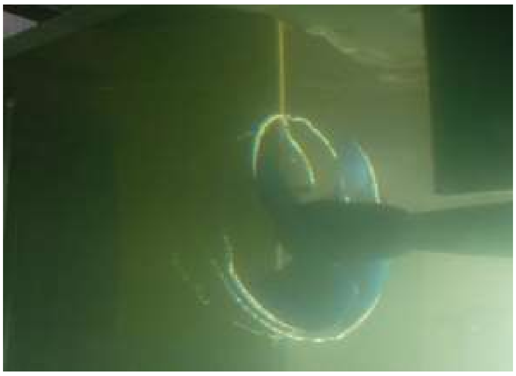

Figure 10. Cavitation pattern observed in Test 1 condition

Typical cavitation patterns observed in the Test 2 condition are shown in Figure 11. A strong tip vortex cavitation combined with the well-developed leading-edge sheet cavitation, which covered almost 15% of each blade surface, was observed. The extent and strength of the cavitation observed were increased around the TDC due to the effect of the wake plate as well as the dynamometer's strut.

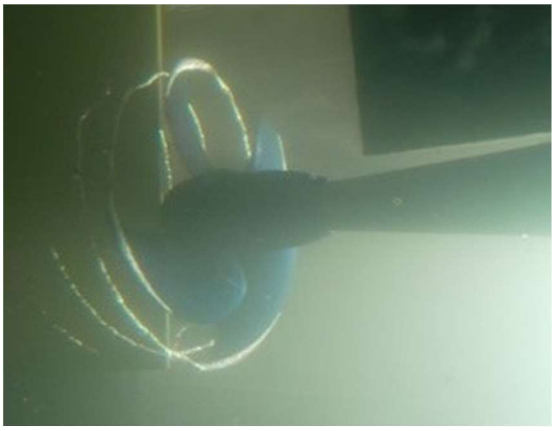

Figure 11. Cavitation pattern observed at Test 2 condition

The cavitating vortices emanating from all blades extended to the rudder and were deformed by the presence of the rudder before reaching at the leading edge of the rudder especially at the TDC and its vicinity. This deformation was combined with the effect of the rudder in downstream resulting in the bifurcation of the tip vortex at the leading edge. In spite of the accentuated sheet cavity dynamics at the wake shadow, first deformation of the tip vortex at the rudder leading edge, and then interacting with the rudder, the persistent tip vortex cavitation was transported in downstream through the propeller slipstream and the rudder without losing its strength. No hub vortex was visible for this test condition.

Figure 12 shows the cavitation patterns observed in Test 3 condition. The pattern and cavitation dynamics observed in this condition were similar to Test 2 with reduced extent and strength of the cavitation patterns due to less loading on the propeller.

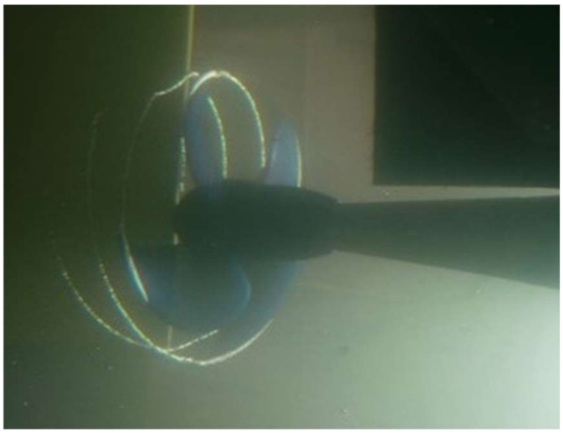

Figure 12. Cavitation pattern observed at Test 3 condition

However, the twisted cavitating tip vortex was still visible while the well-develop leading edge cavitation covered about 10% of the propeller tip. The cavitating tip vortex was steady and less perturbed by the wake effect and still interacting persistently with the rudder. No hub vortex was observed.

The cavitation patterns observed in Test 4 condition are shown in Figure 13. Intermittently flushing tip vortex cavitation could be observed only at the TDC and its vicinity due low propeller loading for this condition. Also no hub vortex was observed.

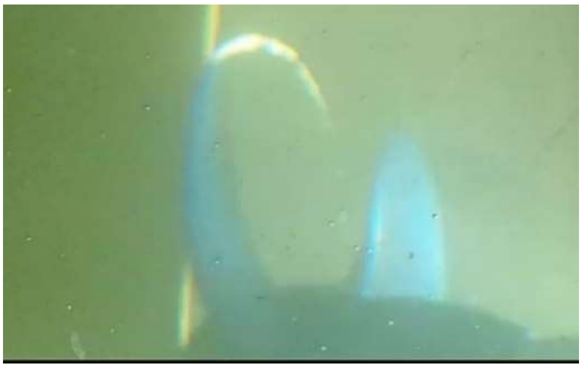

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Figure 13. Cavitation pattern observed at Test 4 condition

As shown in Figure 14, much reduced cavitation number corresponding to the Test 5 condition displayed strongest tip vortex cavitation combined with the largest extent of the sheet cavitation at the leading-edge of the blades covering almost 20% of their suction sides. The deformation and bifurcation of the tip vortices at the leading edge of the rudder around the TDC were accentuated while the the strong cavitating vortices were still interacting with the rudder without losing their strength and extending along the chord of the rudder and its downstream. However, no hub vortex cavitation was observed.

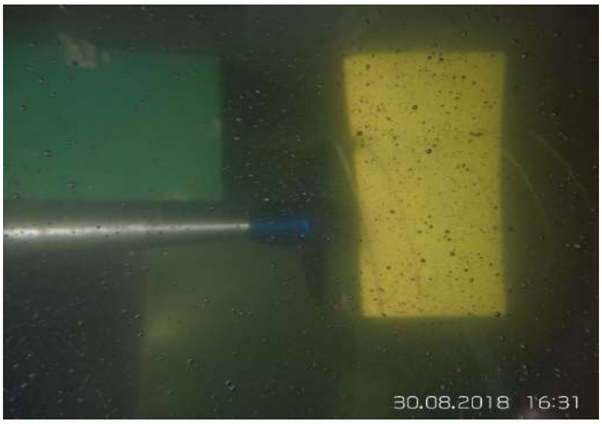

Figure 14. Cavitation pattern observed at Test 5 condition

3.3. Comparison of cavitation patterns

Based upon the observations of the cavitation patterns with the two rudder systems it can be concluded that both rudder arrangements presented similar cavitation patterns on their blades, which mainly involved the tip vortex cavitation combined with the leading edge sheet cavitation at the suction side of the blades. However, it was noticed that the strength and extent of the tip vortex and leading edge cavitation were reduced for the GATE RUDDER® system compared to those observed with the conventional rudder arrangement.

It was also noticed that the cavity dynamics at the TDC and BDC of the conventional rudder were rather different due to the presence of the rudder and its direct interaction with the propeller's slipstream. The deformation of the cavitating tip vortices at approach to the conventional rudder and their bifurcation at the leading edge displayed rather complex cavity dynamics as opposed to almost regular and steady appearance of the cavitating vortex trajectories of the propeller inside the GATE RUDDER® blades. It was also noticed that there was a slight difference in the thickness of the cavitating vortices at the upper and lower part of the propeller plane with the GATE RUDDER®.

However, the GATE RUDDER® system displayed continuous hub vortex cavitation for almost all the test conditions while the conventional rudder system did not due to the weakening effect of the rudder behind the propeller.

3.3. Comparison of noise measurement results

The comparative SPL (dB) measurements are presented for both rudder systems in the same graphs at narrow frequency band as shown from Figure 15 to 19 corresponding to earlier stated five test conditions.

Since the differences between measured sound pressure level and background noise level was greater than 10dB, no adjustments were necessary (ITTC 2014). The first five blade passing frequencies (BPF) are shown in these graphs by the dashed vertical lines. Half BPFs are also appearing in these graphs. This might be caused by different noise sources e.g. it may be associated with the grub screw at propeller hub. Apart from that, it can be clearly seen that the noise level mostly contributed by the cavitating vortex from the leading-edge in the frequency range between the first and third blade passing frequency (BPF) where the tonal noise is appearing. The cavitating hub vortex contributes the noise level at the middle-frequency range.

By investigating the comparative noise levels and patterns for all the test cases, the noise generated by the propeller appeared to be developing in the same way for both rudder systems. Overall, there is an indication that

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the GATE RUDDER® seemed to be quieter than the conventional rudder arrangement apart from the results in the Test 1 condition (Figure 16). In the rest of the test conditions, the GATE RUDDER® system presented reduced noise levels at the first few BPFs while the differences between the two rudder systems can be hardly seen in the middle and high-frequency ranges. The reason can be attributed to both the strong hub vortex cavitation and the tip vortex cavitation contributing to the noise level at this frequency ranges.

One evidence of the strong hub vortex contribution in the noise level can be confirmed at the test 4 condition where the GATE RUDDER did not generate hub vortex cavitation, and hence only at this condition a noticeable reduction of the noise level can be seen at the frequency range from 600 to 1100Hz. Perhaps another reason for not being able to have a clear evidence with the reduction in the noise levels with the GATE RUDDER® system in these tests is the absence of the proper hull wake simulation due to the time restrictions. According to the vibration measurements and captains' comments on both vessels, the noise and vibration were considerably lower on board the vessel with the GATE RUDDER® system. The wake distribution, which was not simulated in this test campaign, seems to be important and needs to be investigated further to take into account the interaction between the GATE RUDDER® and the ship stern.

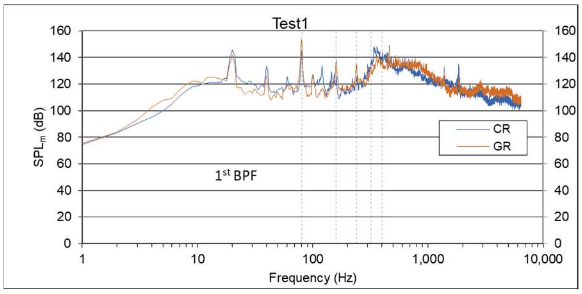

Figure 15. Comparison of the noise levels in the narrow band measured with the GATE RUDDER® and Conventional Rudder systems for Test 1 condition

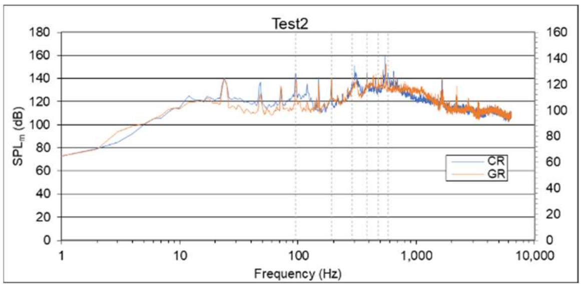

Figure 16 Comparison of the noise levels in the narrow band measured with the GATE RUDDER® and Conventional Rudder systems for Test2 condition

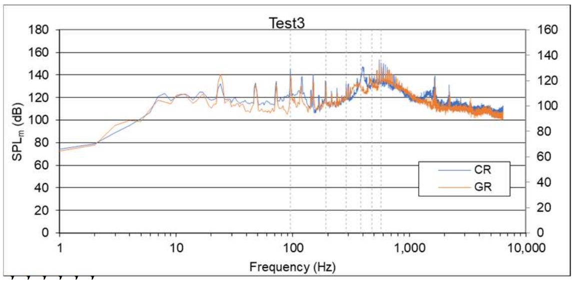

Figure 17. Comparison of the noise levels in the narrow band measured with the GATE RUDDER® and Conventional Rudder systems for Test3 condition

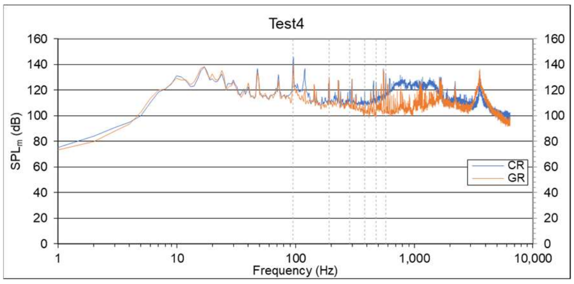

Figure 18. Comparison of the noise levels in the narrow band measured with the GATE RUDDER® and Conventional Rudder systems for Test 4 condition

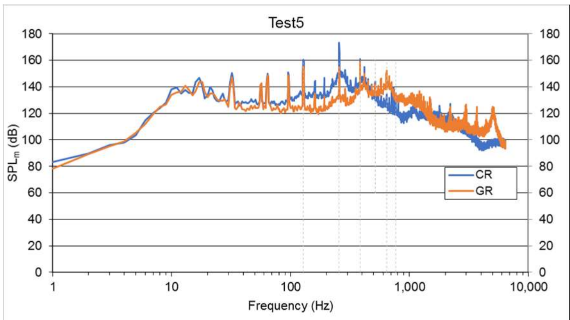

Figure 19. Comparison of the noise levels in the narrow band measured with the GATE RUDDER® and Conventional Rudder systems for Test 5 condition

3.4 Full Scale reporting

After the delivery of these vessels, the Authors were onboard the GATE RUDDER® driven ship to witness her performance monitoring, and at the same time, collecting invaluable information regarding the performance of the two vessels from the captain who had experience with the two vessels continuously. The information obtained from the captain is summarized in Table 5.

Table 5 Full Scale Ship Monitoring and on-board experience

(Data in the table are authorized by the ship owner)

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	Sakura	Shigenobu
Rudder system	Flap Rudder	GATE RUDDER®
On board meas.	-	11-12 April 2018
Captain's experience	Aug.2016-Nov.2017	Dec.2017-Oct.2018
Fuel Saving	base	15-20% saving
Berthing	base	easier
Turning	base	better
Vibration	many trouble with navigation lights	No trouble
Noise	base	Quiter

Test 5 is the service condition that the ITTC recommended scaling procedure (ITTC, 2014) was applied. Although there might be uncertainty caused by factors (i.e. tunnel wall, viscous flow, dissolved gas content, reverberant environment, et.) the procedure provides good prediction (Atlar et.al, 2001). Results of one-third octave analyses for the model propeller was utilized. In Figure 20, measured noise level for the rudders in one-third band was used to predict full scale noise level.

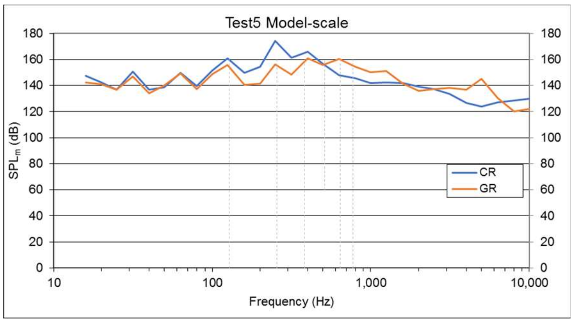

Figure 20. Comparison of the noise levels in the one-third octave band measured with the GATE RUDDER® and Conventional Rudder systems for Test 5 condition in model-scale

Noise result measurements were converted from one-third octave band to equivalent 1 Hz bandwidth (SPL_1) using the given equation:

$$SPL_1 = SPL_m - 10Log_{10}\,(0.23f_0) \tag{1}$$

where f_0 is the centre frequency. The noise level was corrected for the 1m reference distance by given equation below:

$$SPL = SPL_1 + 20Log_{10}\left[\frac{d}{d_{ref}}\right] \tag{2}$$

where d is the distance between hydrophone and $0.7R$ above the shaft line. R is the radius of the propeller. The formulas are given below to calculate the noise level differences (ΔL) and the frequency shift between model-scale and full-scale:

$$\Delta L_{(P)} = 20\,log_{10}\left[\left(\frac{D_s}{D_m}\right)^z\left(\frac{r_m}{r_s}\right)^x\left(\frac{\sigma_s}{\sigma_m}\right)^{y/2}\right] + 20\,log_{10}\left[\left(\frac{n_s D_s}{n_m D_m}\right)^y\left(\frac{\rho_s}{\rho_m}\right)^{y/2}\right] \tag{3}$$

$$\frac{f_s}{f_m} = \frac{n_s}{n_m}\sqrt[2]{\frac{\sigma_s}{\sigma_m}} \tag{4}$$

where the subscripts s and m refer to full-scale and model scale, respectively. D is the diameter, r is the reference distance, σ is the cavitation number, ρ is the density (1025kg/m3 for the sea water and 1006kg/m3 for the tunnel water), n is the rotation speed (rps) and f is the frequency. z, x y are the constants defined by the test facility, Reynolds number, theoretical assumptions and the model test method. In the study, the values are chosen as y=2 and z=1 (Atlar et.al, 2001). It is not necessary to use the value of x as both full-scale and model-scale reference distances are 1m.

The frequencies are shifted with the ratio 0.11 and the noise levels are increased 31dB for the conventional rudder and 29dB for the GATE RUDDER® system. Predicted full-scale noise levels of both vessels are compared in Figure 21. Noise level change can be clearly observed around the first three BPF the noise spectra. The smaller propeller diameter and less load on the blades of the propeller with the GATE RUDDER® lead to a noise reduction.

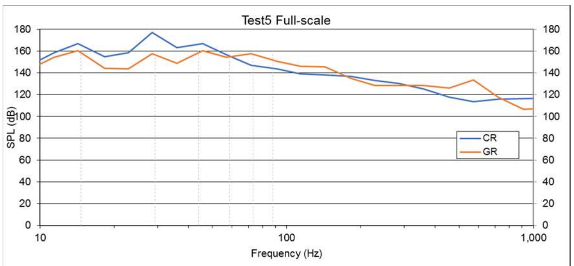

Figure 21. Comparison of the noise levels in the narrow band measured with the GATE RUDDER® and Conventional Rudder systems for Test 5 condition in full-scale prediction.

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4. CONCLUDING REMARKS

This paper presented the recently completed cavitation tunnel tests for the first time on a GATE RUDDER® system in comparison with a conventional rudder system based on the two full-scale sister ships fitted with these rudder systems. The crew of the two vessels experienced the noticeable differences in the vibration and noise characteristics at the aft end of these ships in service for the favour of the GATE RUDDER® fitted vessel. The tunnel tests, therefore, aimed to shed a light on this and to provide preliminary evidence for the crew's experience. The tests involved mainly the cavitation observations and noise measurements in the absence of a properly scaled hull wake due to the time restrictions. The tests results indicated that:

- Both rudder systems displayed similar cavitation patterns involving the tip vortex cavitation and leading-edge suction side cavitation. The GATE RUDDER® system also displayed additional hub vortex cavitation while the conventional rudder system did not. The extent and strength of the two former type cavitations with the GATE RUDDER® system were reduced compared to those of the cavitation observed with the conventional rudder system.

- The cavitation dynamics of the conventional rudder were different and complex especially at the TDC and BDC regions due to the interaction of the slipstream with the rudder while the GATE RUDDER® had much less activity with an almost regular slipstream trailing downstream in the envelop of the GATE RUDDER® blades.

- The measured noise levels were generally similar for both vessels although the GATE RUDDER® system appeared to be slightly quieter in spite of the strong hub vortex development with the GATE RUDDER® system when the conventional propeller design was used as in this test case. It is believed that the conduct of the tests with the proper wake simulation reflecting the interaction between the GATE RUDDER and ship stern, which is shown in Appendix A at Figure A.1, would help for much accurate assessment of the noise characteristics of the GATE RUDDER® as well as cavitation and vibrations that are due to be conducted in very near future.

- According to the ITTC recommended procedure, it is expected that the increased noise level (ΔL) of GATE RUDDER® fitted vessel is lower than the conventional rudder fitted vessel when the results were extrapolated to full-scale. Moreover, less power demand caused by the extra thrust originated from the GATE RUDDER® system should also lower the engine load which leads to the reduction of the structure-borne noise.

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Appendix A – Comparative wake data

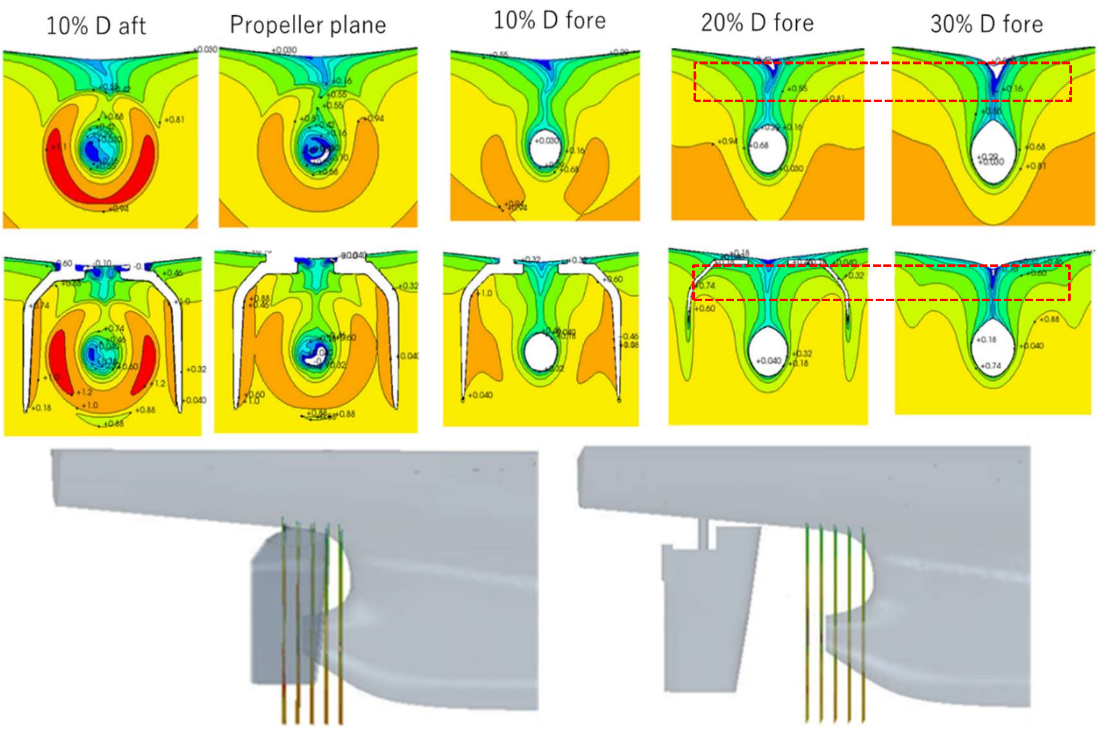

Figure A.1 CFD predictions of effective wake and propeller induced velocities at the aft end: Conventional rudder-propeller system (top figure); GATE RUDDER® system (bottom figure)

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