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Developing the high efficiency propeller with optimization of skeg profile for twin-screw LNG carrier

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ABSTRACT

Propeller design is generally conducted with only given information after hull form design is fixed. Therefore that is somewhat limited for designing propellers. LNG carriers often adopt the twin-screw system and there is a severe requirement of hull pressure amplitude to reduce hull vibration in spite of a severe wake distribution which is particular to twin-screw. The reason of such distribution is due to skeg equipped obliquely, consequently flow speed changes rapidly in a wake distribution. That tends to cause rapid disappearance of cavitation and cavitation erosion. In order to avoid these cavitation problems, conservative propeller design which sacrifices the propulsive efficiency had to be adopted so far. Therefore the authors considered to optimize whole design to approach improving not only propeller design but also hull form design which considers propeller cavitation performance as a new design concept. Hull from mainly skeg was improved and then a device equipped inside of skeg was developed to improve a wake distribution. Model tests were conducted with before and after improvements of hull form and propellers at SSPA. As a result, wake pattern was improved by the device, and propulsive efficiency increased by 1.8% with improved hull form and propeller compared with base design.

Keywords

Propeller, CFD, Wake, Twin screw LNG, Hull design

1 INTRODUCTION

In order to obtain optimized propulsive efficiency, it is important to design higher efficiency propellers. In general, it is clear that a propeller adopting a large diameter and small blade area has high performance, but in case of adopting small blade area ratio, the cavity volume will increase and lead to an increase of hull pressure amplitude. Due to a rapid change of wake flow particular to twin-screw vessels, not only the increase of hull pressure amplitude but also the rapid disappearance of the cavitation will tend to occur. It can be the risk of erosion. For these reasons, it is difficult to apply small blade area ratio to LNG carriers with twin-screw. In order to solve this problem, hull form was improved with an approach to improve the cavitation performance because the cavitation pattern largely depends on the wake distribution. Figure 1 shows a sample of typical wake distribution of LNG carrier with twin screw. The lines of wake flow in red crowd tightly. That means the flow speed rapidly changes. As targets of improving wake distribution, the following concepts of wake patterns are good for propellers. Figure 2 shows wake patterns of each concept for propellers.

Figure 1. Typical wake dist. of LNG carrier with twin-screw

Concepts of good wake distribution are as follows.

- Horse shoe shaped (round)
- Wide (flow speed slowly changing)
- High velocities and low gradient on the inner side of the skeg (between 0° and 60° in Figure 1)

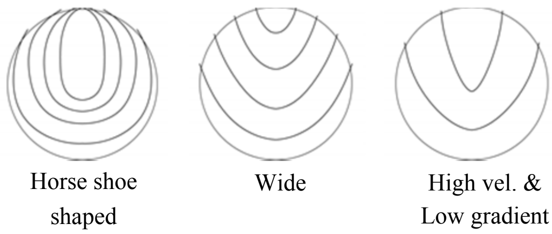

Figure 2. Sample of good wake distribution

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Upon improving the hull and propeller, SSPA was in charge of hull form design, and Nakashima was in charge of propeller design respectively. Firstly, SSPA designed a typical 180km^3 LNG hull form and Nakashima designed a typical propeller based on that hull information. From these typical hull and propeller design as the base design, the hull form was developed according to the concept of improving the wake distribution. In addition, the propeller was developed according to the concept of improving propulsion performance and maintaining cavitation performance. In the design stage, the investigation was conducting by CFD. In order to evaluate the propulsive performance of the different diameter and blade area ratio in model tests, it is necessary to consider the difference of Reynolds number (Kempf's Reynolds number Rn(K)). Since Reynolds number of propeller with small blade area becomes extremely low at self-propulsion test, there is a large difference in Propeller Open Characteristics (POC) values of high Reynolds Propeller Open Water Test (POT) compared with POC at self-propulsion test. If only high Reynolds POT is used for self-propulsion analysis (1POT analysis method), there is a problem that self-propulsion factors (eta-r, ws) can be underestimated. In this study, POT was carried out not only at condition of high Reynolds number but also low Reynolds number close to that of self-propulsion test, and the results were analyzed by 2 POT analysis method (Hasuike 2017). This analysis method is based on ITTC1978 (ITTC 2008). Rn(K) is defined as following formula. The chord length at 0.7R ($C_{0.7R}$) is considered in the formula of Kempf's Reynolds number. V_A denotes propeller advance speed, n denotes propeller rate of revolution, D denotes propeller diameter, and v denotes kinetic viscosity.

$$Rn(K) = \frac{C_{0.7R}\sqrt{V_A^2 + (0.7\pi nD)^2}}{v} \quad (1)$$

2 DESIGN STAGE

SSPA investigated hull form by using CFD software, "CASES" and "SHIPFLOW". "CASES" is the software for parametric modelling, optimization and post processing and SHIPFLOW is the software for CFD gridding and computations using both potential flow method and RANS method. The programs are connected so that CASES creates a command file and geometry which is sent to SHIPFLOW. Then CASES catches the results when they are ready. SSPA designed a typical following hull form as base design. Figure 3 and Figure 4 show the outline of base hull form. The Hull form is improved from this hull form.

- Ship type : 180km^3 LNGC
- Lpp : 287m
- Breadth : 45m
- Draft : 11.5m
- Displacement : 112207m^3
- Cb : 0.7555
- Main engine : 13800kW × 69.0rpm
- Design point : 11750kW × 65.4rpm with 21% sea margin

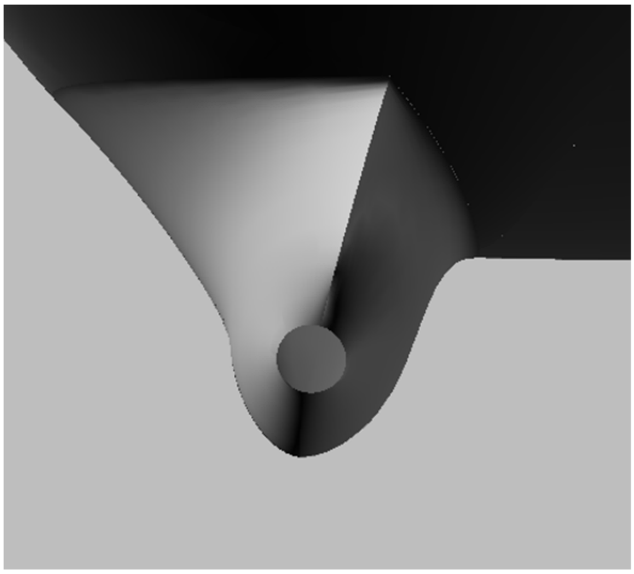


Figure 3. Base hull form of stern part

Figure 4. Base hull form

2.1 Study of skeg design - 1st Phase

Both fore outline of base hull and improved hull were same and the only aft stern part was changed. The dimensions of each skeg are defined as Table 1. The skeg inclination angle means the angle between vertical line and oblique line of skeg as θ in Figure 5. The angle of base hull was 15.0°. The angle of SKEG2 and SKEG4 were 12.5°. That means more acute and close to vertical line. The thickness of stern tube for SKEG3 and SKEG4 was thicker than base hull. Figure 5 shows the comparison of the shapes of each skeg. The blue line in Figure 5 shows outline of base hull.

Table 1. Dimension of each skeg

Hull	Skeg inclination angle θ	Skeg thickness	Displacement
	[°]	-	[m^3]
SKEG1:Base	15.0	Baseline	113311
SKEG2	12.5	Baseline	113305
SKEG3	15.0	Thick	113520
SKEG4	12.5	Thick	113515

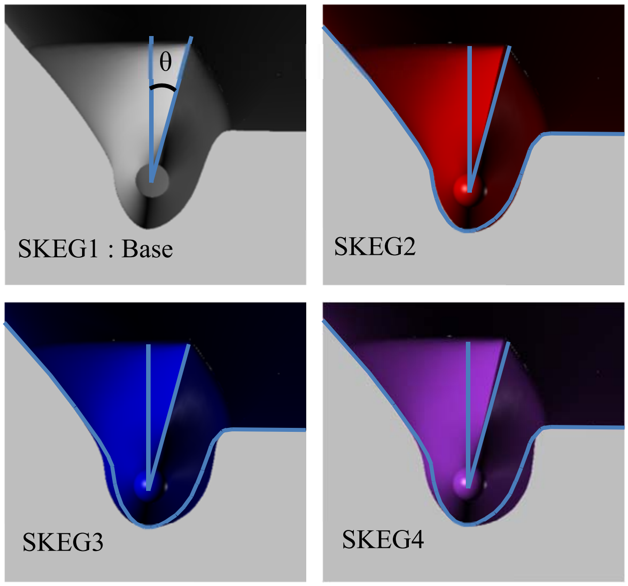


Figure 5. Comparison of each skeg outline

Figure 6 to Figure 9 show each wake distribution by CFD. Any remarkable effective improvement of the wake distribution was not confirmed only by changing the shape of skeg. These wake distributions were almost same in terms of propeller cavitation performance. In order to obtain further improvement of wake distribution, drastic change of the hull form should be necessary.

Table 2 shows the comparison of EHP (Pe) and DHP (Pd) of each skeg by CFD. Pe of SKEG2 was improved by 0.7% and Pd improved by 1.5% in total. However both Pe of SKEG3 and SKEG4 which had thick stern tube were worse than that of base hull. Judging that it is difficult to improve the wake by only changing the shape of the skeg, a device equipped inside of skeg was considered to improve wake distribution. For the study of improvement of the wake distribution by the device, SKEG2 was selected which has the smallest resistance in CFD.

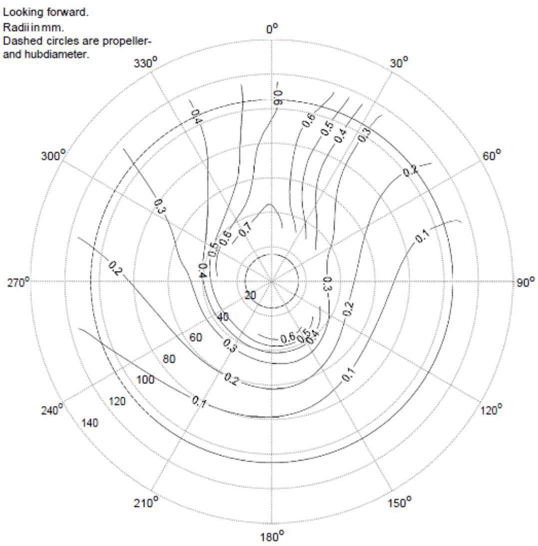


Figure 6. Wake distribution of SKEG1 by CFD

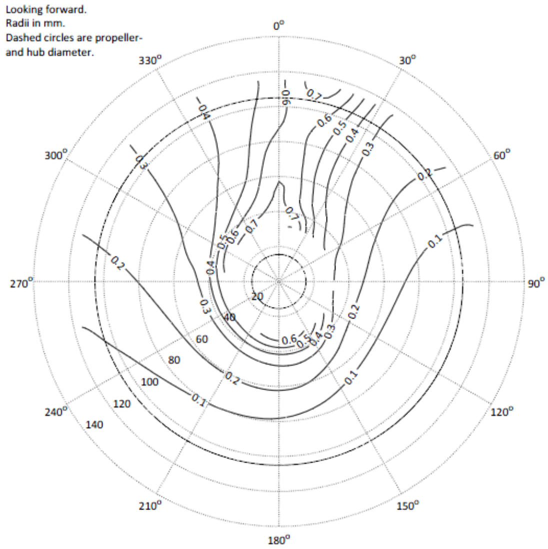


Figure 7. Wake distribution of SKEG2 by CFD

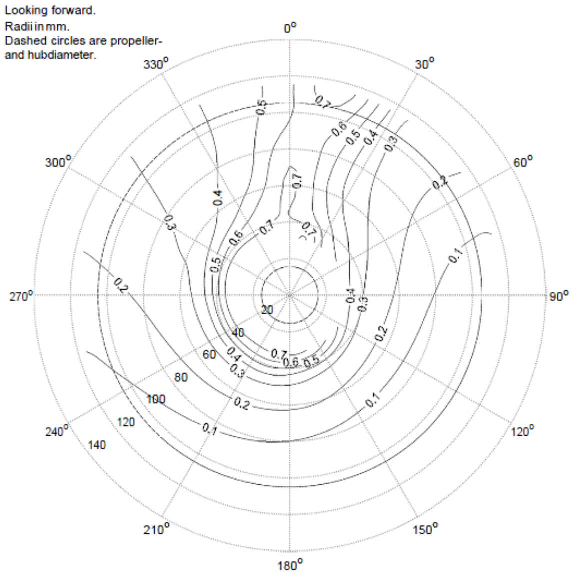


Figure 8. Wake distribution of SKEG3 by CFD

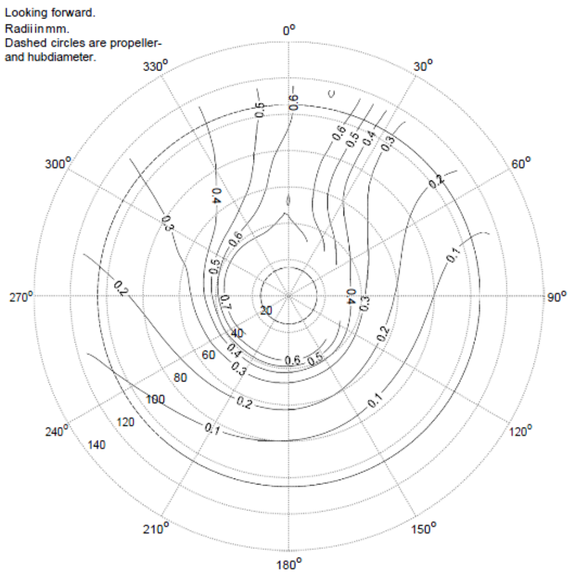


Figure 9. Wake distribution of SKEG4 by CFD

Table 2. **Comparison of Pe & Pd of each skeg**

Hull	⊿Pe	⊿Pd
SKEG1 : Base	-	-
SKEG2	-0.7%	-1.5%
SKEG3	1.4%	0.1%
SKEG4	0.8%	-0.6%

2.2 Study of device - 2nd phase

In view of the improvement effect of wake flow, a device was designed as shown in Figure 10 and the mounting position of the hull was investigated. The device is equipped inside of twin-skeg. Totally 4 positions were studied, Pos.1 to Pos.4. Table 3 shows comparison of Pe and Pd of each position of device. Pe tends to increase by the device.

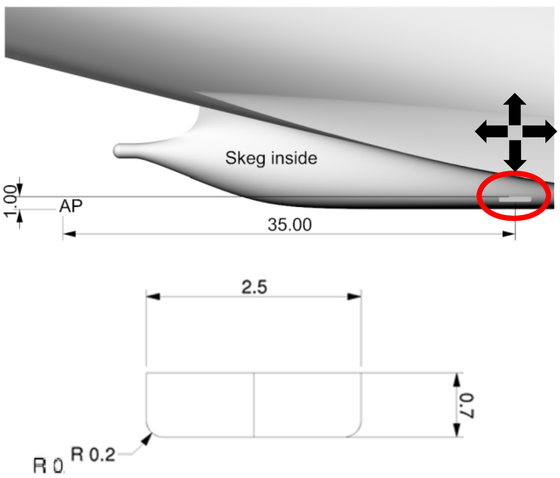


Figure 10. Device and position of device

Table 3. Comparison of Pe & Pd of each device position

Hull	Device	⊿Pe	⊿Pd
SKEG1:Base	-	-	-
SKEG2	-	-0.7%	-1.5%
SKEG2	Pos.1	0.4%	0.7%
SKEG2	Pos.2	0.0%	0.2%
SKEG2	Pos.3	0.1%	0.5%
SKEG2	Pos.4	0.2%	0.6%

Figure 11 to Figure 14 show each wake distribution by CFD. The wake distribution of Pos.1 was changed more largely than the others from that without device, and especially the change of flow speed between 30 ° and 60 ° is moderate in Pos.1.

Judging from CFD calculation, though Pos.2 has the best propulsive performance, Pos.1 was selected for the model tests with emphasis placed on the wake distribution change. Even if device is equipped, it is expected that total efficiency will finally be optimized with recovery of an improved propeller.

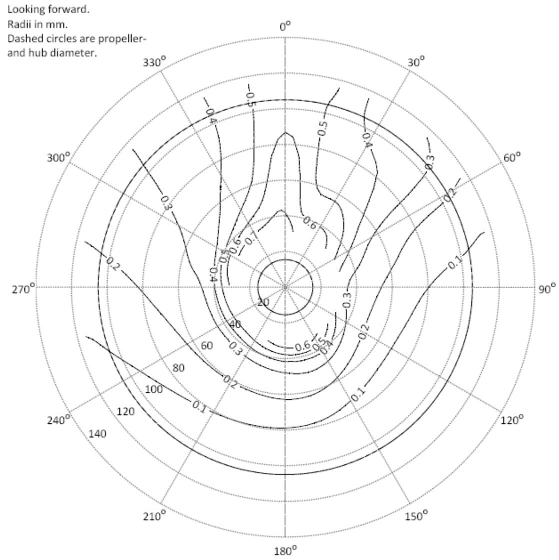


Figure 11. Wake distribution of Pos.1 by CFD

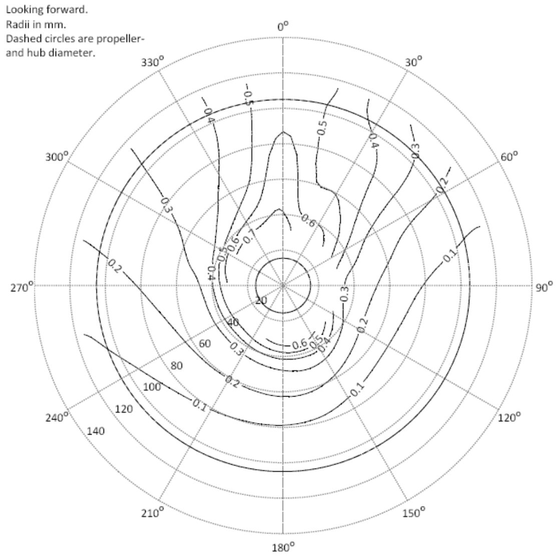


Figure 12. Wake distribution of Pos.2 by CFD

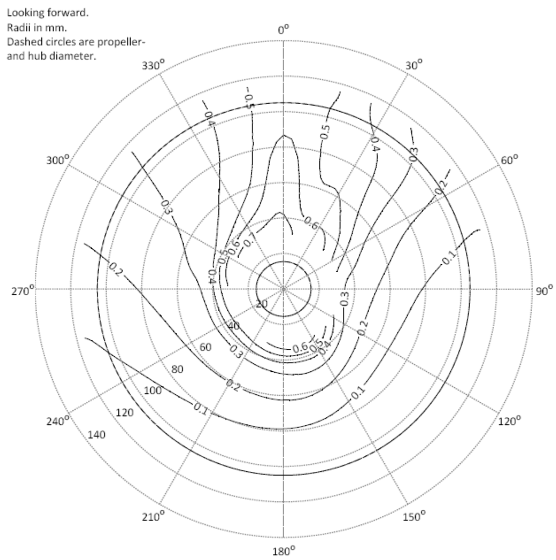


Figure 13. Wake distribution of Pos.3 by CFD

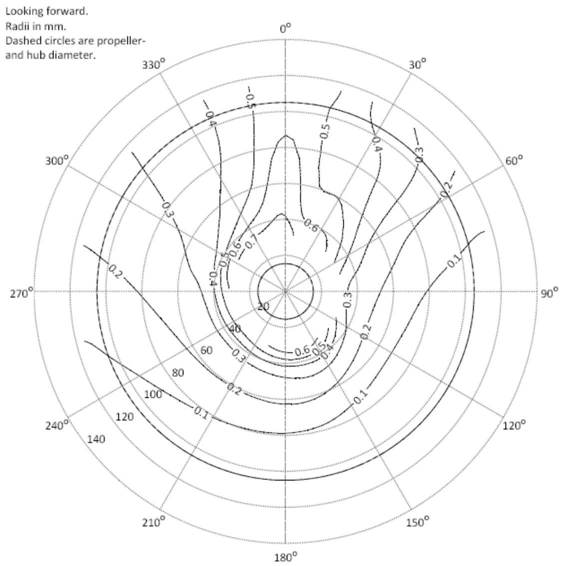
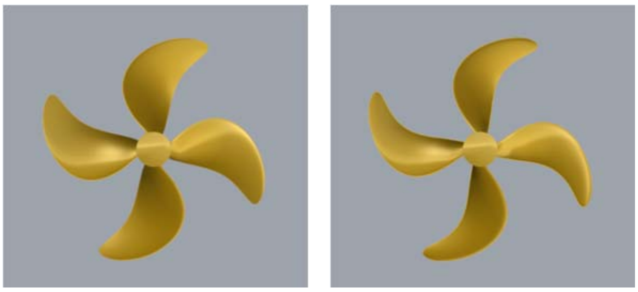


Figure 14. Wake distribution of Pos.4 by CFD

2.3 Design of propeller

In tandem with improvement of hull form, P1 as base design and P2 as high performance propeller with a larger diameter and smaller blade area than P1 were designed. P2 was designed to obtain 2% higher efficiency compared with P1. Figure 15 shows outline of propellers of base design and improved propeller design. Those particulars of propellers are in Table4.



P1 : Base design P2

Figure 15. Outline of propellers

Table 4. Principal particulars of propellers

Propeller No.		P1: Base	P2
Diameter	m	8.3	8.5
N. of Blades	-	4	
Exp. area ratio	-	0.51	0.4
Pitch ratio at 0.75R	-	1.01	0.982

3 MODEL TEST

Following model tests were carried out in SSPA. POT, resistance test, self-propulsion test, and wake measurement were carried out.

3.1 Propeller open water test

Table 5 shows Kempf's Reynolds number of each propeller at POT. Low Reynolds number was determined in consideration of each chord length of propellers. Figure 16 shows the propeller open characteristics of each propeller. Table 6 shows eta-o of each propeller at design point. 1.9% eta-o improvement was confirmed at design point. It was confirmed that the large diameter small blade area was effective.

Table 5. Rn(K) at each POT

	Low Rn(K)	High Rn(K)
P1: Base	2.5*10^5	5.5*10^5
P2	2.0*10^5	5.4*10^5

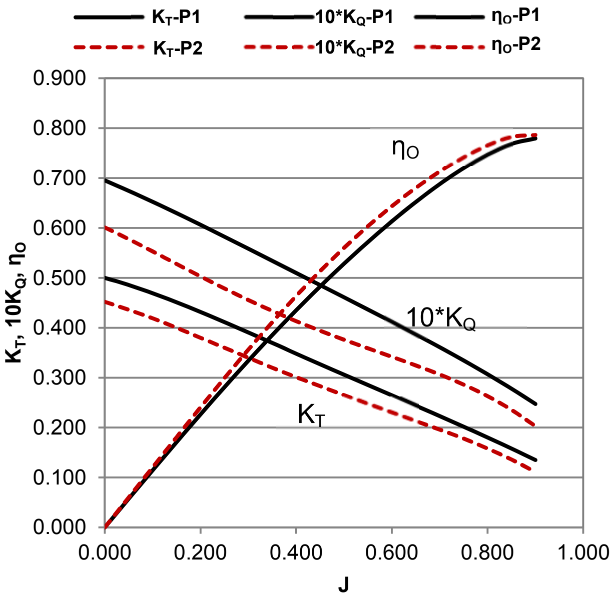


Figure 16. Full scale POC of P1 & P2 at High Rn(K) POT

Table 6. eta-o at design condition of P1 and P2

	P1: Base	P2	⊿eta-o P2/P1
eta-o	0.724	0.738	1.9%

3.2 Self-propulsion test

Table 7 shows the combination of hull, propeller, and device at self-propulsion test. Table 8 shows self-propulsion test results at 19.5knot close to design point. These results were analyzed by 2POT analysis method. Compared with the base design, totally 1.8% efficiency improvement was confirmed by improvement of hull and propeller without a device condition (Case3). It is confirmed that increase of resistance by 2.9% due to hull improvement with the device and 0.7% increase of engine output totally (Case4).

Table 7. Combination of self-propulsion test

	Hull	Propeller	Device
Case1 : Base	SKEG1	P1	-
Case2	SKEG2	P1	Pos.1
Case3	SKEG2	P2	-
Case4	SKEG2	P2	Pos.1

Table 8. Self-propulsion test results w/o Crm correction

	Pe	1-w	1-t	eta-r	eta-o	eta-d	Pd
Case1	8732	0.723	0.806	1.011	0.743	0.837	10427
Case2	8983	0.724	0.813	1.007	0.742	0.839	10706
Case3	8764	0.729	0.809	1.018	0.758	0.856	10234
Case4	8983	0.727	0.812	1.013	0.756	0.855	10502

	⊿ Pe	⊿ 1-w	⊿ 1-t	⊿ eta-r	⊿ eta-o	⊿ eta-d	⊿ Pd
Case1	-	-	-	-	-	-	-
Case2	2.9%	0.1%	0.9%	-0.4%	-0.1%	0.2%	2.7%
Case3	0.4%	0.8%	0.4%	0.7%	2.0%	2.3%	-1.8%
Case4	2.9%	0.6%	0.7%	0.2%	1.7%	2.1%	0.7%

In the model test, the difference of Pe between Case1 and Case2 was 2.9%. The gap was larger than the result of CFD calculation. Therefore some consideration should be necessary for this gap. Hull resistance can separate into wave drag and viscous drag. Table 9 shows total drag coefficient (Ctm) and wave drag coefficient (Crm) of each resistance test. Since the Crm can be considered to be nearly equal before and after the improvement due to the hull change around only the stern part in this time (Ogiwara 2014), Crm is assumed to be same as the base hull. Pe in such case is shown in Table 10. Because in case of same Crm, 1.0% Pd can be reduced, there is a possibility to obtain better performance.

Table 9. Drag coefficient at each condition

	Ctm*1000	Crm*1000
Case1 : Base	3.620	0.147
Case2,4	3.739	0.197
Case3	3.688	0.145

Table 10. Self-propulsion test results with Crm correction

	Pe	1-w	1-t	eta-r	eta-o	eta-d	Pd
Case1	8732	0.723	0.806	1.011	0.743	0.837	10427
Case2	8830	0.724	0.813	1.007	0.742	0.839	10524
Case3	8830	0.729	0.809	1.018	0.758	0.856	10312
Case4	8830	0.727	0.812	1.013	0.756	0.855	10323

	⊿ Pe	⊿ 1-w	⊿ 1-t	⊿ eta-r	⊿ eta-o	⊿ eta-d	⊿ Pd
Case1	-	-	-	-	-	-	-
Case2	1.1%	0.1%	0.9%	-0.4%	-0.1%	0.2%	0.9%
Case3	1.1%	0.8%	0.4%	0.7%	2.0%	2.3%	-1.1%
Case4	1.1%	0.6%	0.7%	0.2%	1.7%	2.1%	-1.0%

3.3 Wake measurement

Table 11 shows the conditions of wake measurement about hull and device. Figure 17 to Figure 19 show wake distributions measured in each condition.

It is confirmed that the change of flow speed of Cond.3 becomes moderate around 30 ° ~ 60 ° because of device at model test as CFD shown.

Table 11. Conditions of wake measurement

	Hull	Device
Cond.1: Base	SKEG1	-
Cond.2	SKEG2	-
Cond.3	SKEG2	Pos.1

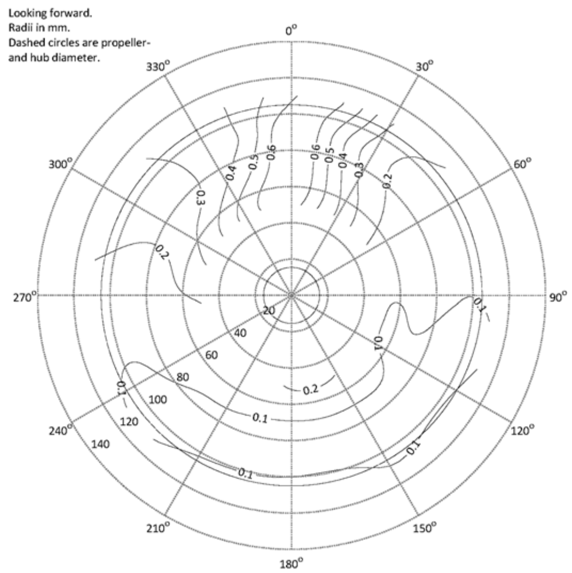


Figure 17. Wake distribution of Cond.1

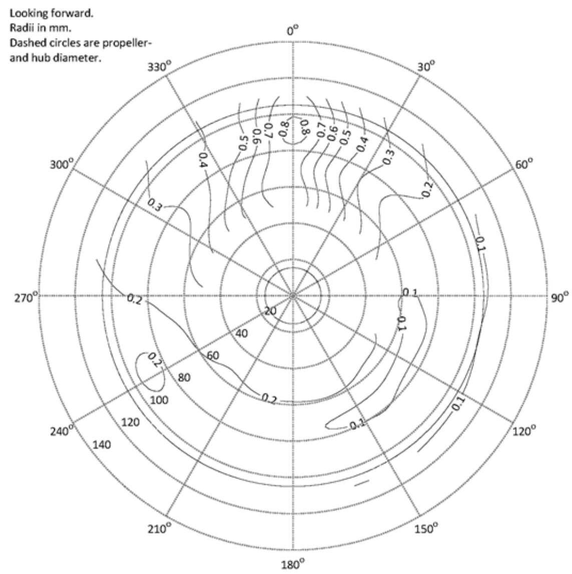


Figure 18. Wake distribution of Cond.2

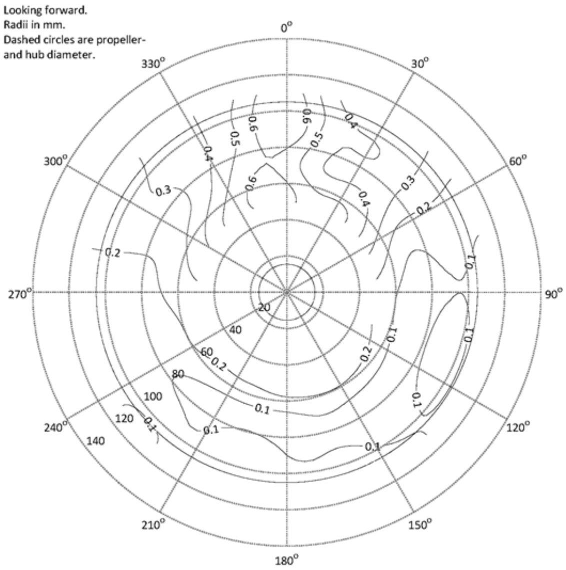


Figure 19. Wake distribution of Cond.2

4 CAVITATION SIMULATION

The cavitation simulation was calculated based on these model test results by CFD. SOFTWARE CRADLE SC/Tetra V14 was used for this CFD calculation. The calculation was done under design condition. The values are the 1st blade frequency. The measurement point was just above the propeller and the distance was about 6.0m from the shaft center height. The hull pressure amplitude is shown in Table 12. The cavitation patterns are shown in Figure 20 respectively. It is expected to reduce the cavity volume and to suppress the hull pressure amplitude at the same level as the base design by improving the wake with improved hull and propeller.

Table 12. Comparison of hull pressure amplitude by CFD

	P1 : Base	P2
	kPa	kPa
Cond.1 : Base	3.08 (-)	3.35 (+8.7%)
Cond.2	4.10 (+33.3%)	4.27 (+38.3%)
Cond.3	2.78 (-9.8%)	2.95 (-4.0%)

5 CONCLUSION

- Compared with the base propeller it was confirmed that the propeller open water efficiency of improved propeller increased by 1.9%, and it was confirmed that the large diameter small blade area is effective as shown in Table 6.
- Compared with the base design by the 2POT analysis, it was confirmed that Pd decreased by1.8% without the device condition as shown in Table 8.
- Compared with the base design by the 2POT analysis, in case of same Crm, it was confirmed that Pd decreased by 1.0% with the device condition as shown in Table 8.

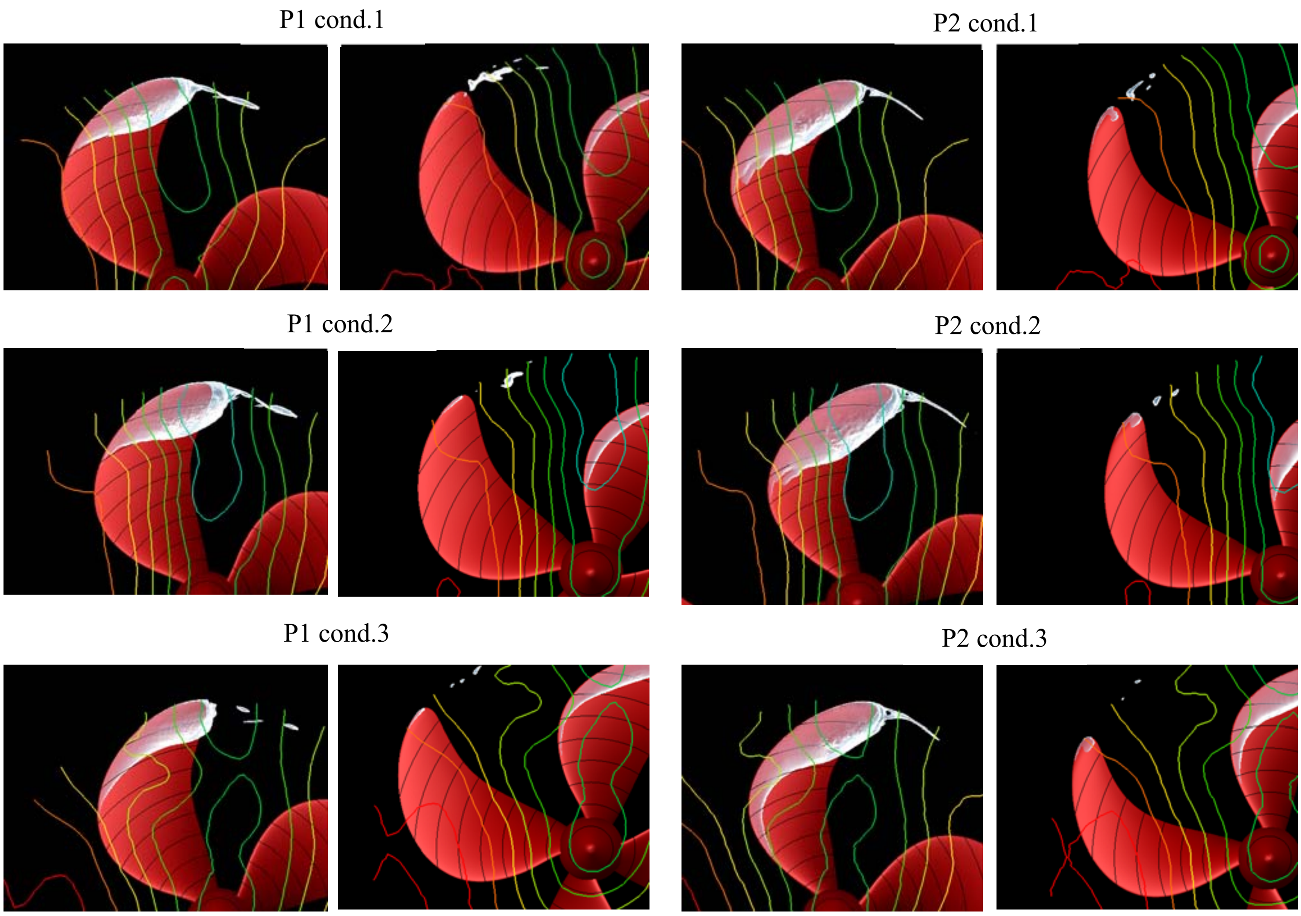


Figure 20. Cavitation pattern of each condition

- By the device, the flow velocity at the top position becomes slower, the flow velocity change around 30 ° ~ 60 ° where the cavitation disappears becomes moderate, and improvement was seen as shown in Figure 19. Because of the effect, in the CFD cavitation simulation, device was able to suppress the amount of cavity volume in both propellers as shown in Figure 20.
- The device will expect to reduce the hull pressure amplitude with improved hull and propeller to the same level as the base design.

6 FUTURE WORKS

- In the design of device, although improvement of wake pattern, there is still room for improvement in terms of performance, it is difficult to compromise improvement of wake distribution and performance, so it is necessary to consider further.
- In this study, the effect of a device is considered in only model scale. In fact it is necessary to consider and investigate the full scale effect by the device for wake distribution and resistance.

ACKNOWLEDGEMENTS

This design of the hull form and the device, CFD calculation of them and model tests are supported by SSPA.

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