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The Effect of Tip Rake on Propeller Open Water Efficiency and Propulsive Efficiency

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ABSTRACT

This paper discusses the effect of a backward tip rake, BTR on the propeller open water efficiency and the propulsive efficiency based on the results of a model test and RANS analysis at model-scale and at full-scale Reynolds number.

In our previous study, the effect of the BTR on cavitation and pressure fluctuations were investigated by using systematically designed BTR propellers, BTRPs. It was found that the BTRPs are effective to reduce cavitation induced pressure fluctuations.

In the present study, propeller open water tests, self-propulsion tests and RANS calculations were performed on these propellers. The experimental and numerical results on the BTRPs show that there are no serious losses in both efficiencies when the BTR distributions are moderate. In addition, the RANS analysis was performed to investigate the effect of the BTR into the propeller open water efficiency and the propulsive efficiency at full-scale Reynolds number. This calculation on the BTRPs shows that the moderate BTR distributions make no harmful effects on both efficiencies. This effect on the propeller and propulsive efficiencies at the full-scale Reynolds number was recognized the same as those at the model-scale Reynolds number.

Keywords

Tip Rake Propeller, RANS, Model Test, Propeller Efficiency, Self-Propulsion Propulsive Efficiency

1 INTRODUCTION

The geometrical shape of propellers gives crucial effects on propeller performance and cavitation on the propeller blades as well. Recently the tip rake, especially the backward tip rake, BTR in short, that is, the tip bent toward the pressure side of the propeller blades has been paid attention to. This type of propeller is called a backward tip rake propeller, BTRP in short.

For the first time, Gomez et al. (1998) made several researches about tip plate propellers, which is one of the deformed tip propellers. A forward tip rake propeller, FTRP in short, having forward tip rake, that is, the tip bent toward the suction side was developed by Andersen et al. (1986). This propeller is called "KAPPEL Propeller". Dang (2004) suggested that the BTR of a propeller is an effective design parameter to reduce the pressure fluctuations induced by propeller cavitation without any loss in propeller efficiency.

The results of the long-term investigation on a two-bladed FTRP and BTRP were published by Yamasaki et al. (2006). A theoretical calculation and a propeller open water test were performed to investigate the effect of a tip rake into the load distribution of the propeller blades and the propeller open water efficiency. It was found that the FTRPs have higher propeller open water efficiency and higher load on the blade around the tip than those of conventional propellers, while the BTRPs have lower load on the blades around the tip.

The BTRPs were designed for a container vessel and a low speed vessel to decrease pressure fluctuations by Yamasaki et al. (2005a) and Yamasaki et al. (2007), respectively. The investigation to improve the propeller open water efficiency of the BTRPs was conducted by means of a theoretical calculation and model test. The pressure fluctuations decreased without any remarkable loss on the propeller open water efficiency.

In addition, the effect of the BTR on cavitation and pressure fluctuations were investigated by using five kinds of four-bladed propellers systematically. The respective propellers have their own BTR distributions. It was found that the BTRPs are effective to decrease the cavity volume and then to reduce the pressure fluctuations by Yamasaki et al. (2013).

Tip unloaded propellers also have the effects similar to those of the BTRPs on propeller cavitation. When adopting an excessive tip unloaded pitch distribution, the efficiency of the propeller decreases. On the other hand, when adopting the BTR distribution to a propeller, a few papers discuss the effect of BTR on the propeller efficiency and propulsive efficiency as well.

This paper discusses the effect of BTR on the propeller open water efficiency and the propulsive efficiency by means of a model test and RANS analysis not only at model-scale but also at full-scale Reynolds number.

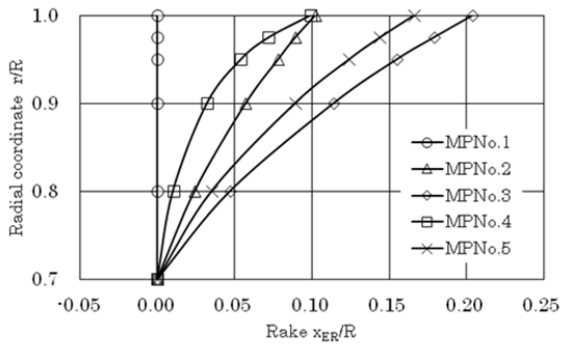


Figure 2: Designed tip rake distributions.

2 SURVEYED BACKWARD TIP RAKE PROPELLERS

A propeller open water test, a self-propulsion test and RANS analysis on five kinds of BTRPs used in the previous systematical cavitation tests were performed to investigate the effect of the backward tip rake distribution into the propeller open water efficiency and the propulsive efficiency. These propellers (MP No.1, 2, 3, 4 and 5) were designed for a medium speed vessel. **Table 1** gives the principal particulars of five propeller models. R is the propeller radius. **Fig. 1** shows one of the propeller models and **Fig. 2** shows five kinds of designed tip rake distributions.

Table 1 Principal particulars of propeller models.

Number of blades		**4**
Diameter	**mm**	**250**
Expanded area ratio		**0.52**
Pitch ratio (0.7R)		**0.71**
Skew angle	**deg.**	**25**

Figure 1: Tested propeller model.

All propeller models basically have the same geometrical dimensions except the respective rake distributions. When changing the skew distribution of a propeller, the position in the shaft direction of the propeller also changes. Therefore an effective rake x_{ER} is used in this paper, as Yamasaki (2005b) defined instead of the geometric rake in drawings. x_{ER} is defined as the distance of the center of a blade measured from the datum line of a propeller. The direction of x_{ER} is defined to be positive towards the stern.

MP No.1: a conventional propeller, whose effective rake angle is zero degrees, designed for the reference propeller.
MP No.2: BTRP, whose effective rake angle gradually varies from 0 to 5 degrees between 0.7R radial position and the tip and is based on the effective rake angle of zero degrees.
MP No.3: BTRP, whose effective rake angle gradually varies from 0 to 10 degrees between 0.7R and the tip and is based on the effective rake angle of zero degrees.
MP No.4: BTRP, whose effective rake angle more radically varies from 0 to 5 degrees between 0.7R and the tip than that of MP No.2 and is based on the effective rake angle of zero degrees.
MP No.5: BTRP, whose effective rake angle gradually varies from 0 to 10 degrees between 0.7R and the tip and is based on the effective rake angle of -7 degrees.
The effective rake distribution x_{ER} from the root to 0.7R of each propeller is slightly modified to connect to that around tip smoothly.

3 PROPELLER OPEN WATER CHARACTERISTICS

3.1 Calculation Method Based on RANS Analysis

The RANS analysis and propeller open water tests on the BTRPs were performed to investigate the effect of the tip rake distribution on the propeller open water characteristics.

The RANS analysis was performed using the SOFTWARE CRADLE "SCRYU/Tetra V10" which is based on the finite volume method with unstructured grids.

The turbulence model, LKE k-kl-ω proposed by Walther et al. (2008) was employed and the turbulence intensity was kept to be 1% for all numerical simulations in this paper. The LKE k-kl-ω was developed to simulate the transitional flow. Kempf's Reynolds number R_{NK} around the flow of a propeller models is 6 x 10^5. **Fig. 3** and **Fig. 4** show a computational domain and the volume mesh on the blade surface of the BTRPs, respectively. **Fig. 5** shows a prism mesh arrangement near the blade to resolve the boundary layer on the propeller blade surface. The minimum thickness of a prism layer was set as a non-dimensional wall distance y^+ for a wall-bounded flow is kept to be 1. The total number of meshes is about 14 million.

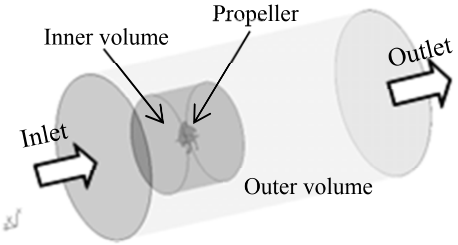


Figure 3: Volume mesh region around propeller.

Figure 4: Grid mesh around blade surface.

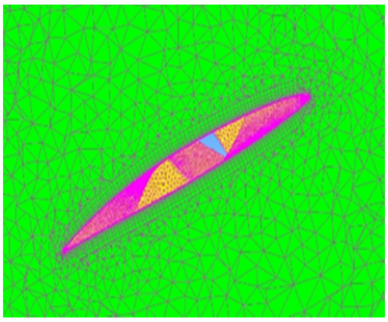


Figure 5: Prism mesh arrangement around blade surface.

3.2 Calculation Results of RANS Analysis

Fig. 6 and **Table 2** show the propeller open water characteristics given by the RANS analysis. **Table 2** shows the comparison of the calculation results on the propeller open water characteristics, POWC among five kinds of the BTRP models at design point, K_T/J^2=0.618.

Comparing the POWC of MP No.2 and 4 whose effective rake angle are 5 degrees near the tip to that of the reference propeller, MP No.1, K_T of MP No.2 and 4 is 0.7% lower, K_Q of MP No.2 and 4 is 1.3% and 1.2% lower, η_O of MP No.2 and 4 is 0.2% higher. Comparing the POWC of MP No.3 and 5 whose effective rake angle are 10 degrees near the tip to that of MP No.1, K_T of MP No.3 and 5 is 1.6% and 1.9% lower, K_Q of MP No.3 and 5 is 2.4% and 2.8% lower, η_O of MP No.3 and 5 is the same as that of MP No.1. These results are classified into two groups based on the tip rake angle. As the effective rake angle becomes larger, K_T and K_Q of the BTRP decrease, and η_O of the BTRP is kept within 0.2% comparing to those of MP No.1.

Table 2: Propeller open water characteristics at design point calculated by RANS.

MP No.	1	2	3	4	5
K_T/J^2	0.618				
K_T	0.143	0.142	0.141	0.142	0.14
$10K_Q$	0.180	0.178	0.175	0.178	0.175
η_O	0.609	0.611	0.609	0.611	0.609
$\Delta\eta_O$ vs MP No.1	-	+0.2%	0.0%	+0.2%	0.0%
$\Delta\eta_O$ vs exp.	-1.1%	-0.9%	-0.5%	-0.7%	-0.9%

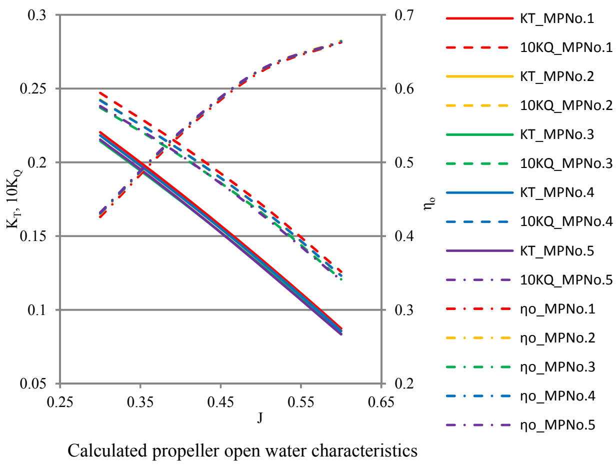


Figure 6: Propeller open water characteristics calculated by RANS analysis.

3.3 Results of propeller open water test

The propeller open water tests at R_{NK} = 6 x 10^5 on MP No.1, 2, 3, 4 and 5 were conducted at a towing tank. **Fig. 7** and **Table 3** show the POWC obtained from the propeller open tests. **Table 3** shows the comparison of the experimental results on the POWC among five kinds of the BTRP models at the design point, K_T/J^2=0.618.

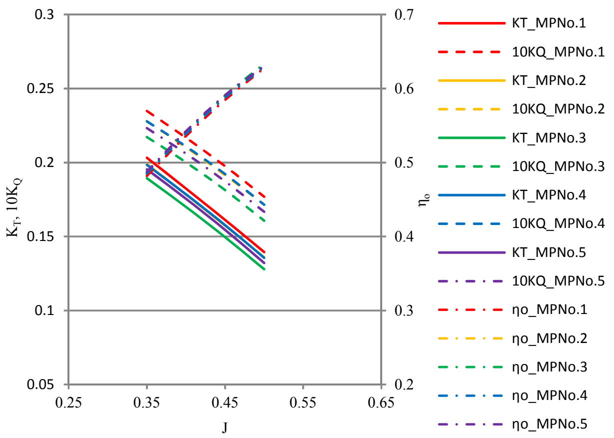


Figure 7: Propeller open water characteristics obtained from the model test.

Table 3: Propeller open water characteristics obtained from the model test at the design point.

MP No.	1	2	3	4	5
K_T/J^2	0.618				
K_T	0.146	0.144	0.139	0.144	0.142
$10K_Q$	0.183	0.179	0.172	0.179	0.176
η_O	0.616	0.617	0.613	0.615	0.615
$\Delta\eta_O$ vs MP No.1	-	+0.1%	-0.5%	-0.1%	-0.1%

Comparing the POWC of MP No.2 and 4 whose effective rake angles are 5 degrees near the tip to that of the reference propeller, MP No.1, K_T of MP No.2 and 4 is 1.4% lower, K_Q of MP No.2 and 4 is 2.3% and 2.1% lower, η_O of MP No.2 and 4 is varied within 0.1%. Comparing the POWC of MP No.3 and 5 whose effective rake angle are 10 degrees near the tip to that of MP No.1, K_T of MP No.3 and 5 is 4.5% and 2.8% lower, K_Q of MP No.3 and 5 is 6.2% and 4.0% lower, η_O of MP No.3 and 5 is 0.5% and 0.1% lower, respectively.

It is found that when the effective rake angles become larger, the POWC, K_T and K_Q of the BTRPs decrease and the efficiency η_O of the BTRPs except that of MP No.3 is kept within 0.1%, comparing to those of MP No.1.

Comparing the RANS analysis results to the model test results, K_T, K_Q and η_O of the RANS analysis results except those of MP No.3 are smaller than those of the model test results. When the effective rake angles become larger, both results show a similar tendency in the variation of the POWC due to the BTR distributions. There is a small variation within -0.5% to -1.1% among both results in propeller open water efficiency. The present RANS analysis is expected to present an adequate tool to evaluate the propeller open water efficiency of BTRPs.

It is also found that the adequate application of the BTR distribution gives no remarkable losses on the propeller open water efficiency from these results of the RANS analysis and model tests on the BTRPs.

4 PROPELLER PERFORMANCE BEHIND HULL

The RANS analysis on MP No. 1, 2, 3, 4 and 5 and the self-propulsion test on MP No.1, 2 and 4 were performed to investigate the effects of the BTR distribution into the propeller performance behind the hull. The resistance test and self-propulsion test were conducted at a towing tank. **Table 4** shows the principal particulars of the hull of a 749GT inlands chemical tanker.

Table 4: Principal particulars of ship hull.

		Ship	Model
Lpp	m	67.0	5.583
Breadth	m	11.3	0.942
Depth	m	5.5	0.458
Draught	m	4.75	0.396

4.1 Description of the Present RANS Analysis

In the present RANS analysis, a full hull body submerged under the design load water line is modeled. In this calculation modeling, a rotational region is introduced, and each propeller is alternately replaced in the rotational region to simulate each propeller performance. **Fig. 8** and **Fig. 9** show the present computational domain and the grid mesh around the hull for resistance calculation. **Fig. 10** shows the grid mesh around the hull with a propeller for the present self-propulsion calculation.

A symmetry condition (double-body model) at a still-water surface is implemented in the present analysis. Then the wave resistance coefficient cannot be calculated and is given by the results of the resistance test.

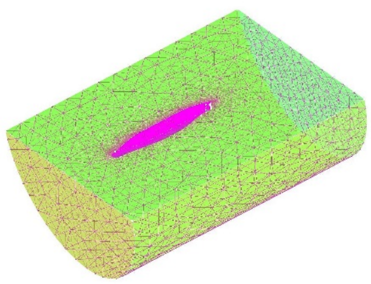


Figure 8: Computational domain.

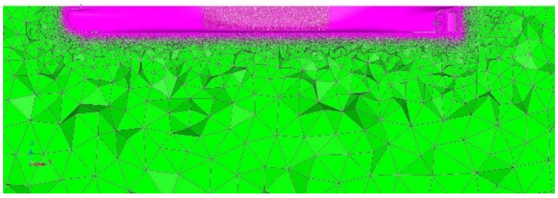


Figure 9: Mesh around hull for resistance calculation.

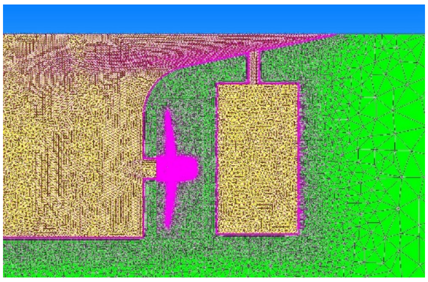


Figure 10: Grid mesh around hull with propeller for self-propulsion calculation.

RANS simulations of the resistance test, self-propulsion test and propeller open water test are performed to analyze the self-propulsive performance at the thrust identity condition as used in the self-propulsion test. At the self-propulsion point, the total resistance of the ship including an additional towing force (ex. skin friction correction) is balanced by the delivered thrust from the propeller. The required propeller thrust is obtained by interpolating the results of three rotational rates of the propeller. The Froude number is 0.271 equivalent to 13.5kt at full scale, $R_{NK} = 4.4 \times 10^5$, $y^+ = 1$ and the total number of the grid meshes is about 21 million.

4.2 Results of Hull Resistance and Wake Pattern

Fig. 11 shows the wake patterns at a propeller plane in the resistance test and the RANS simulation. The wake pattern given by the RANS simulation agrees well with the measured wake pattern, even though the higher velocity region in the wake pattern given by the RANS simulation is a little wider than the measured pattern.

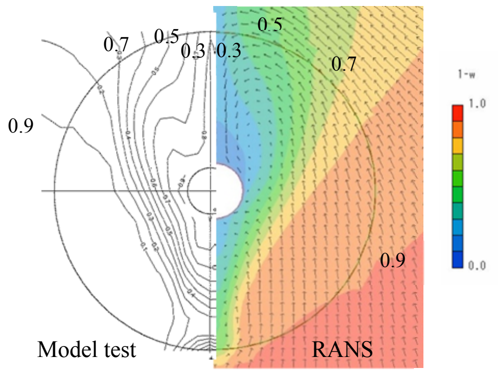


Figure 11: Wake patterns.

Table 5 shows that the form factor calculated by the RANS simulation is 4.9% smaller than that of the measured value. The form factor is calculated from a ratio of the frictional resistance coefficient by the RANS simulation to the Schoenherr's frictional resistance coefficient, C_{F0}. Then present RANS analysis is expected a promising method to evaluate the flow behind hull condition.

Table 5: Form factor (1+K).

Model test	1.312
RANS	1.248

4.3 Results of Propulsive Performance Calculation

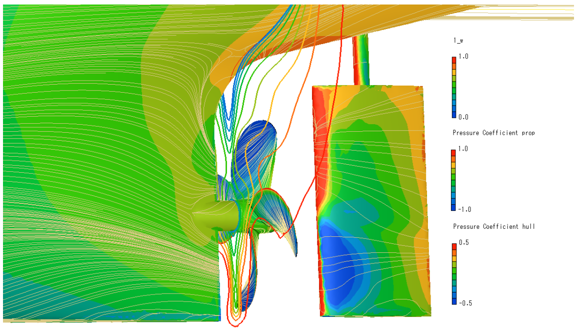
Table 6 shows results of self-propulsive performance by the RANS analysis. **Fig. 12** shows the pressure distributions around the propeller and the wake patterns in front of the propeller models of MP No.1 and 3. The propeller open water characteristics at $R_{NK} = 4.4 \times 10^5$ is used for analyzing self-propulsion factors, while that at $R_{NK} = 6.0 \times 10^5$ is used for the powering. The correction of wake fraction from model test to full scale is given by the Yazaki's method (1966).

Comparing the self-propulsion factors of MP No.2 and 4 whose effective rake angle are 5 degrees near the tip to that of the reference propeller, MP No.1, 1-t of MP No.2 and 4 is the same as that of MP No.1, $1\text{-}w_S$ of MP No.2 and 4 is 0.9% and 1.4% higher, η_R of MP No.2 and 4 is 0.3% and 0.2% higher, η_{OS} of MP No.2 and 4 is 0.6% and 0.8% higher, η_{DS} of MP No.2 and 4 is 0.1% and 0.4% lower. Comparing the self-propulsion factors of MP No.3 and 5 whose effective rake angle are 10 degrees near the tip to that of MP No.1, 1-t of MP No.3 and 5 is 0.2% lower, $1\text{-}w_S$ of MP No.3 and 5 is 2.3% and 1.3% higher, η_R of MP No.3 and 5 is 0.7% and 0.2% higher, η_{OS} of MP No.3 and 5 is 0.8% and 0.5% higher, η_{DS} of MP No.3 and 5 is 1.0% and 0.8% lower, respectively.

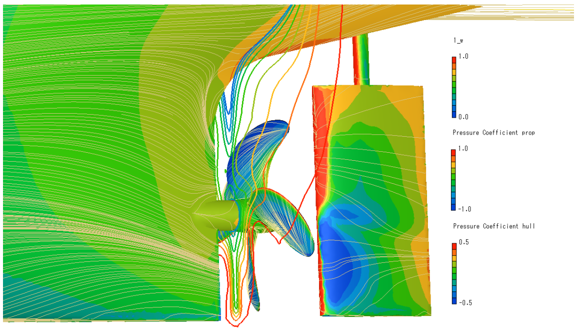
Comparing η_{DS} of MP No.2 and 4 to that of MP No.1, they are lower within 0.4%, while η_{DS} of MP No.3 and 5 is at most 1% lower than that of MP No.1.

Table 6: Self propulsion factor at 13.5kt by RANS analysis

MP No.	1	2	3	4	5
η_{OM}	0.569	0.573	0.575	0.576	0.573
$1\text{-}w_M$	0.609	0.616	0.626	0.620	0.618
$1\text{-}w_S$	0.658	0.664	0.674	0.668	0.667
1-t	0.788	0.788	0.786	0.788	0.786
η_H	1.197	1.186	1.167	1.180	1.179
η_R	1.012	1.014	1.019	1.014	1.014
η_{OS}	0.589	0.592	0.594	0.594	0.592
η_{DS}	0.713	0.712	0.706	0.711	0.708
$\Delta\eta_{DS}$ vs MP No.1	-	-0.1%	-1.0%	-0.4%	-0.8%



MP No.1



MP No.3

Figure 12: Pressure distribution and wake pattern around propellers.

Table 7 shows the results of self-propulsion test by the ship model with five kinds of BTRPs. Comparing the propulsive efficiency η_{DS} of MP No.2 and 4 to MP No.1, they are kept at most 0.3% lower. The test results show no obvious difference in the self-propulsion factors of MP No.2 and No.4 against that of MP No.1. These results of the RANS analysis and the present model tests show that there are not remarkable losses on the propulsive efficiency.

On the other hand, when adopting the larger backward tip rake distributions (The backward tip rake of x_{ER}/R from 0.7R to the tip = 0.17 and 0.20 for MP No.3 and No.5, R is the radius) to a propeller, these rakes gave lower propulsive efficiencies. It is expected that the extreme backward tip rake has a potentially harmful effect on the propulsive efficiency.

Table 7: Self-propulsion factors at 13.5kt by model test.

MP No.	1	2	4
1-ws	0.705	0.712	0.707
1-t	0.829	0.831	0.829
η_H	1.177	1.167	1.172
η_R	1.005	1.005	1.007
η_{OS}	0.616	0.619	0.616
η_{DS}	0.729	0.727	0.727
$\Delta\eta_{DS}$ vs MP No.1	-	-0.3%	-0.3%

5 FULL SCALE PERFORMANCE OF PROPELLERS

5.1 Calculation Method Based on RANS Analysis

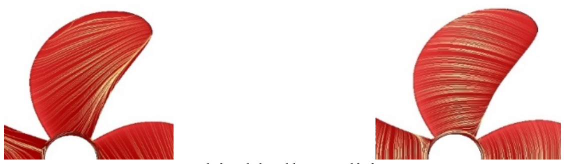
The RANS analysis was performed to investigate the Reynolds effect on the full scale performance of propellers, as Hasuike et al. conducted (2013). The Froude number is 0.271 and is the same as the model scale simulation. Kempf's Reynolds number R_{NK} is 1.9 x 10^7. With keeping the non-dimensional distance y^+ = 1, the number of layers of the prism mesh is increased to keep the total thickness of prism meshes at the higher Reynolds number. The total number of meshes is about 29 million.

5.2 Calculated Results on Propeller Open Water Characteristics by RANS Analysis

Fig. 13 shows the stream lines on the suction side of a blade of MP No.1 at three kinds of Reynolds numbers under the condition of open water and the behind of the ship hull. The propeller angular position behind the hull condition is the 12 o'clock position. The stream lines of both conditions are similar to the stream lines in the flow composed of laminar and turbulent flow at a model scale Reynolds number R_{NK} = 4.4 x 10^5 and 6.0 x 10^5. On the other hand, the stream lines of both conditions were fully turbulent flow at the full scale Reynolds number R_{NK} = 1.9 x 10^7.

Table 8 shows the comparison of the propeller open water characteristics at the advance ratio J of 0.4 among those at the respective Reynolds numbers. As the Reynolds number increases, both the thrust coefficient K_T and the torque coefficient K_Q increase. The propeller open efficiency η_O at R_{NK} = 6.0 x 10^5 is higher than that at R_{NK} = 1.9 x 10^7. The calculated results of the decrease of the propeller open efficiency at R_{NK} = 1.9 x 10^7 is brought by the increase of viscous resistance due to the change to fully turbulent flow.

Open water condition



Behind hull condition

R_{NK} = 4.4x10^5 R_{NK} = 6.0x10^5 R_{NK} = 1.9x10^7

Figure 13: Surface stream lines of MP No.1.

Table 8: Propeller open water characteristics of MP No.1.

R_{NK}	4.4×10^5	6.0×10^5	1.9×10^7
J	0.4		
K_T	0.176	0.179	0.184
$10K_Q$	0.211	0.212	0.220
η_O	0.531	0.538	0.533

5.3 Calculated Results of Hull Resistance and Wake Pattern by RANS Analysis

Fig. 14 shows the comparison of the wake patterns at the propeller plane between model scale and full scale by the RANS simulation. The high wake region at the full scale becomes narrower, where 1-w is lower than 0.8. The wake peak of 1-w at the full scale wake is higher than that at the model scale. **Table 9** shows the form factor of full scale ship is 6.3% larger than that of model scale.

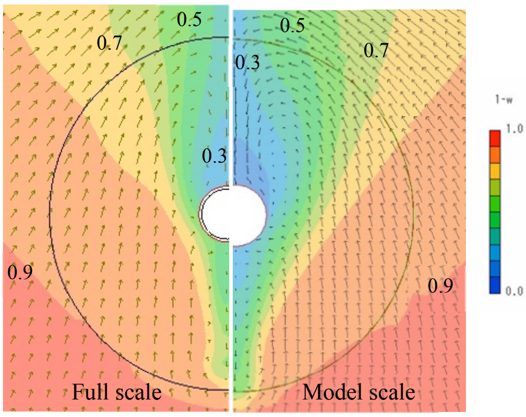


Figure 14: Wake patterns.

Table 9: Form factor, 1+K.

Model scale	1.248
Full scale	1.327

5.4 Calculated Results on Self-Propulsive Performance by RANS

Table 10 shows the calculated results of self-propulsive performance at full scale by the RANS analysis. The propeller open water characteristics at $R_{NK} = 1.9 \times 10^5$ is used for analyzing the self-propulsion factors and powering. Comparing the propulsive efficiencies η_{DS} of MP No.2, 4, and 5 with that of MP No.1, they are kept within 0.3%. On the other hand, η_{DS} of MP No.3 is about 0.7% lower than that of MP No.1 due to the significant loss of wake fraction.

Wake fraction w is significantly affected by the scale effect. Regarding the wake correction factor $1\text{-}w_S/1\text{-}w_M$, the wake correction factor calculated by the RANS analysis is 4.6% larger than that predicted by the Yazaki's method, 7.7% larger than that predicted by the ITTC1957 method.

These results of the RANS analysis show that there are no remarkable losses on the propulsive efficiency in full scale. On the other hand, when adopting the excessive BTR distribution (The amount of change of x_{ER}/R from 0.7R to the tip = 0.20), this amount of the BTR has a potentially harmful effect on the propulsive efficiency.

Table 10: Self-propulsion factors at 13.5kt in full scale.

MP No.	1	2	3	4	5
η_O	0.604	0.609	0.610	0.609	0.609
$1\text{-}w_S$	0.689	0.696	0.703	0.696	0.698
1-t	0.797	0.798	0.797	0.798	0.797
η_H	1.157	1.146	1.133	1.147	1.142
η_R	0.991	0.994	0.996	0.992	0.994
η_{DS}	0.693	0.694	0.688	0.693	0.691
$\Delta\eta_{DS}$ vs MP No.1	-	+0.1%	-0.7%	-0.1%	-0.3%

Table 11: Wake correction factors from wake fraction of the present ship model to that of the full scale ship.

Correction method	Correction factor
Yazaki method	1.08
ITTC1957	1.04 to 1.05
RANS	1.12 to 1.13

6 CONCLUSIONS

This paper discussed the effects of backward tip rake on the propeller open water characteristics and self-propulsive performance. Model tests and RANS analysis were performed by using five kinds of propeller models with the systematically varied backward tip rake distributions.

The following conclusion can be drawn,

(1) Regarding the propeller open water characteristics, the present model tests and RANS analysis show that the propeller open water efficiencies η_O of the backward tip rake propellers except the propeller with the largest backward rake near the tip, MP No.3 vary within 0.2% difference, comparing to that of the reference propeller, MP No.1. There are no serious losses on the propeller open water efficiency of the backward tip rake propellers if the backward tip rake distributions are moderate.

(2) Regarding the self-propulsive performances at model scale, the model tests and the RANS analysis show that the propulsive efficiency η_{DS} of MP No.2 and 4 vary within 0.4% comparing to that of MP No.1. There are no remarkable losses on the propulsive efficiency if the backward tip rake distributions are moderate. When adopting the larger amount of backward tip rake

distributions that the variation of x_{ER}/R from 0.7R to the tip is 0.17 and 0.20, it is expected that they potentially have a harmful effect on the propulsive efficiency judging from the present RANS analysis.

(3) Regarding the propulsive performance at full scale, the propulsive efficiencies η_{DS} of MP No.2, 4 and 5 is kept within 0.3% comparing to that of MP No.1 judging from the present RANS analysis. The moderate backward tip rake distributions might cause no remarkable losses on the propulsive efficiency. When adopting the highest backward tip rake distribution (The amount of effective backward tip rake of x_{ER}/R from 0.7R to the tip is 0.20) of MP No.3, this amount of backward tip rake has a potentially harmful effect on the propulsive efficiency at full scale.

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DISCUSSION

Question from Michael Brown

Have you looked on the effect of changing tip rake on the spanwise circulation distribution? I expect that adding tip rake while keeping all other aspects of the design the same has decreased the circulation in the area near the tip. This means that some of your conclusions may be based on differences in the spanwise circulation distribution rather than differences in the local tip geometry.

Authors' Closure

Thank you for your question and your suggestion. The variation of propeller geometry changes the hydrodynamic parameters of a propeller and finally not only propeller performance but also the related phenomena. **Fig. I** shows the comparison of the radial thrust coefficient distributions $dK_T(r)/dr$ between MP No.1 and MP No.3 instead of the circulation distributions, to demonstrate the effect of the adopting backward tip rake on the radial load distribution. The computational condition of the present RANS analysis corresponds to the hydrodynamic condition of a blade of the propellers operating at the vertical top position in the ship wake. When adding the backward tip rake to the rake of MP No.1, remarkable decrease of the thrust coefficient distribution around the tip of MP No.3 is confirmed, comparing to that of MP No.1. Some of our conclusions are based on differences of the radial load distribution computed by the RANS analysis as you indicated.

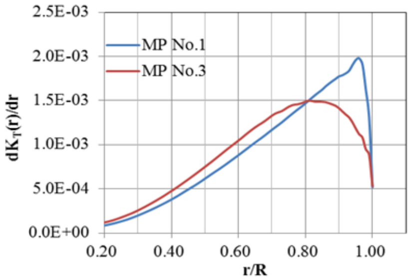

Figure I: Comparison of thrust coefficient distribution between MP No.1 and MP No.3.