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Optimization of the Propeller with ECO-Cap by CFD

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ABSTRACT

It is considered that the propeller efficiency is improved by weakening propeller hub vortex. On that account, the behavior of the hub vortex which was generated behind general propeller caps was investigated by computational fluid dynamics analysis and a special cap, named ECO-Cap, was developed and optimized which has small 7 fins to prevent the hub vortex generation. Furthermore, the effect of ECO-Cap was verified by model test and by monitoring the fuel oil consumption at a vessel in service.

Keywords

CFD, Propeller, Hub vortex, Energy saving device, ECO-Cap, Rudder erosion.

1 INTRODUCTION

In recent years, the ship speed and propeller loading increase more and more. Especially, the tendency is remarkable in container ship. When the horsepower per unit area is 700-800 kW/m^2 or more and the ship speed is 22-23 knots or more, Mikael Grekula et al.[1)] pointed out the problem of rudder erosion. Juergen Friesch[2)] described the causes of rudder erosion were propeller tip-vortex cavitation and propeller hub-vortex cavitation and he introduced new twisted rudder TW05 to reduce the risk of cavitation erosion in his paper.

Yamasaki et al.[3)] developed Non-Hub Vortex (NHV) propeller, features of this NHV propeller has confirmed an increase in efficiency by reducing the hub vortex. It is known that PBCF (Propeller Boss Cap Fins) which was developed by Ouchi et al.[4)] has similar effect. Kawamura et al.[5)] investigated the characteristics of PBCF at the model and full scale Reynolds number by CFD (Computational Fluid Dynamics) analysis. Recently, several special caps in order to increase the propeller efficiency have been developed by some manufacturers or shipyards. Those special caps were expected to avoid rudder erosion as well as improve propeller efficiency.

22nd ITTC (The International Towing Tank Conference) appointed the Specialist Committee on Unconventional Propulsors[6)] described that the power saving or efficiency gain of PBCF expected at the full scale will be 2 to 3 times greater than the model scale predictions in their final report.

The authors developed a new special cap which was named ECO-Cap in order to increase efficiency and to avoid rudder erosion by reducing hub vortex. The purpose of this paper is to predict ECO-Cap performance by CFD and to verify the prediction by model test and monitoring FOC (fuel oil consumption) at a vessel in service.

2 ANALYSIS BY CFD

2.1 Propeller particulars and analysis model

CFD analyses of two propellers were carried out. Propeller-A was 6 bladed highly skewed with large blade area propeller for large container vessel and Propeller-B was 5 bladed semi skewed with small blade area propeller for bulk carrier.

Table 1 and Figure 1 show the propeller particulars and profiles. These propellers were designed to confirm the performance of the propeller with cap.

Table 1: Propeller particulars

		Propeller A	Propeller B
Number of blades	-	6	5
Dia. (Model/Actual)	mm	240 / 9500	265 / 6700
Pitch ratio at 0.7R	-	1.043	0.833
Exp. area ratio	-	0.81	0.44

(a) Propeller-A (b) Propeller-B

Figure 1: Profile of Propellers

RANS calculations were performed by SOFTWARE CRADLE SCRYU/Tetra Ver.10 which is a commercial CFD code and is based on a finite volume method with an unstructured grid. The Shear Stress Transport k-ω model was applied to the turbulence model. The authors simulated the flow field around a propeller in non-uniform wake flow. Figure 2 shows the computational domain. The computational domain was composed of the inner rotational part including the propeller ("Inner volume" in Figure 2) and the outer stationary part ("Outer volume" in Figure 2). The stationary part and the rotational part were connected discontinuously. Steady velocity and zero pressure were prescribed at the inlet and the outlet boundary, respectively. The numerical mesh was an unstructured grid, and basic cells were tetrahedral and prismatic cells were applied to near the surface of propeller and cup for resolving the boundary layer. The first layer thickness of the prism layer was set to a non-dimensional wall distance for a wall-bounded flow (y+ in short) =1. The total number of elements was about 32 million.

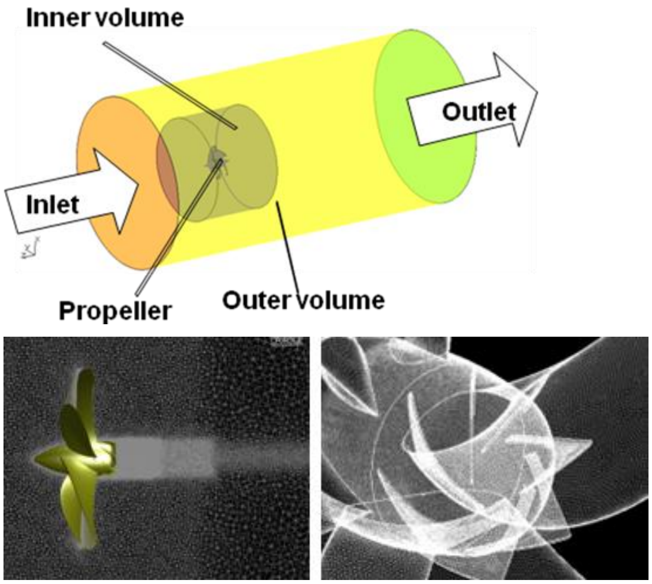
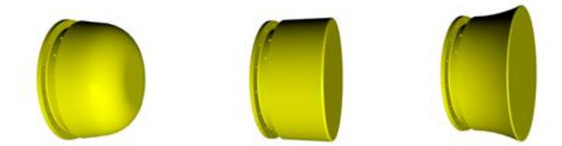


Figure 2: Numerical grids for CFD

2.2 Analysis of general propeller caps.

Firstly, the CFD analyses for general propeller caps were carried out. Figure 3 shows the typical profile of general propeller caps.

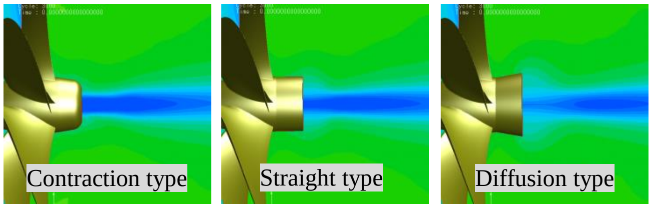


(a) Contraction type (b) Straight (c) Diffusion

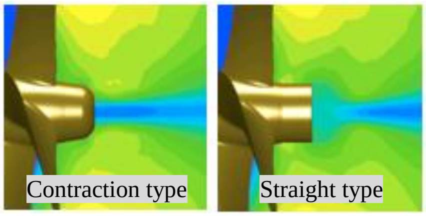
Figure 3: Profile of general propeller caps

Figure 4 shows the pressure distribution behind the propeller caps in the result of CFD analyses. Reynolds number was abt.2 x10^6 in this analyses. Blue part indicates negative pressure by hub vortex.

In Propeller-A, blue area behind straight type was slightly smaller than the area behind contraction type and the area behind diffusion type was the most smallest of three caps. In Propeller-B, the negative pressure behind cap was smaller than it in Propeller-A. Therefore, hub vortex behind 5 blades propeller is expected to be weaker than it behind 6 blades propeller. The effect to reduce the negative pressure by straight type was seen as with Propeller-A. From above, the straight cap or diffusion cap can reduce the hub vortex.



(a) Propeller-A



(b) Propeller-B

Figure 4: Pressure distributions behind each propeller caps

Secondly, the hub vortex at Propeller-B was visualized which was based on CFD analysis result. In this paper, the absolute value of rotational flow against propeller axial direction was used for vortex visualization. Figure 5 shows the isosurface of the absolute value of rotational flow. The rotational flows were generated from each blade's trailing edge and gathered at the backward center of propeller cap. Then hub vortex was generated.

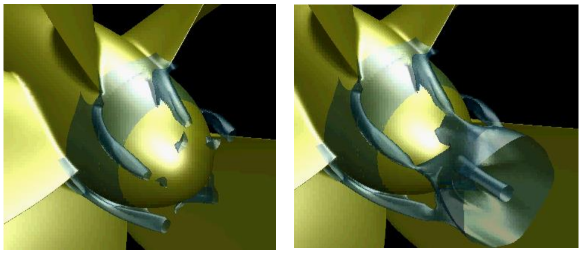


Figure 5: Phases of hub vortex generation behind Propeller-B

2.3 Design of ECO-Cap

The authors developed a new cap to reduce hub vortex which was named ECO-Cap. It has small fins to prevent the concentration of the rotational flow. The base of the cap is contraction type and the number of fins is 7 to avoid corresponding with the number of propeller blades. The reason why is to reduce the interference between propeller blade and fin by shifting the phase each blade and fin.

Three ECO-Caps were designed to optimize the effect of reduction hub vortex with propeller. Figure 6 shows the shapes of ECO-Caps. The features of them are as follows:

Case-1	Revolve projection of fins was cylinder and the end of fins were converged at the backward center of propeller cap
Case-2	Revolve projection of fins was same as case-1 and the end of fins were not converged at the backward of propeller cap
Case-3	Revolve projection of fins was thickened toward the end and the end of fins were not converged at the backward of propeller cap


(a) Case-1 (b) Case-2 (c) Case-3

Figure 6: Shape of ECO-Cap

Figure 7 shows the rotational flow behind ECO-Cap with Propeller-B by CFD analysis. In Case-1, hub vortex was generated at the center of converged fins (red circle). The fins of Case-2 and Case-3 were not converged and the hub vortices behind them became weaker than Case-1.

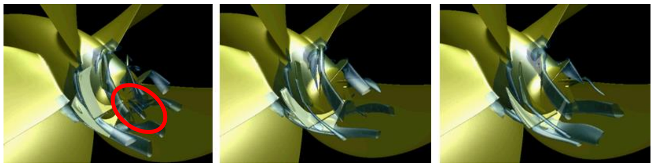

(a) Case-1 (b) Case-2 (c) Case-3

Figure 7: Rotational flow behind ECO-Cap with Propeller-B

Figure 8 shows the pressure distribution of each ECO-Cap with Propeller-B by CFD analysis. The negative pressure areas (blue area) of each ECO-Cap were obviously fewer than those of the general caps shown in Figure 4. Especially, the effect of the negative pressure reduction of Case-3 was the most effective of the three.

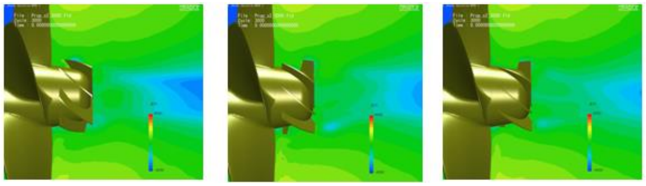

(a) Case-1 (b) Case-2 (c) Case-3

Figure 8: Pressure distribution behind ECO-Cap with Propeller-B

Two propellers (Propeller-A and Propeller-B) with ECO-Cap Case-3 and with contraction type cap were analyzed by CFD.

Figures 9 and 10 show the propeller characteristics comparison of ECO-Cap with the contraction type cap by CFD at Propeller-A, Propeller-B, respectively. Both charts indicate that K_T with ECO-Cap was higher and K_Q with ECO-Cap was lower than those with the construction type cap. As the results, the propeller efficiency with ECO-Cap was more effective than it with the contraction type cap. The improvement of propeller efficiency was 1.23% at maximum in Propeller-A with ECO-Cap and was 0.61% at maximum in Propeller-B with ECO-Cap

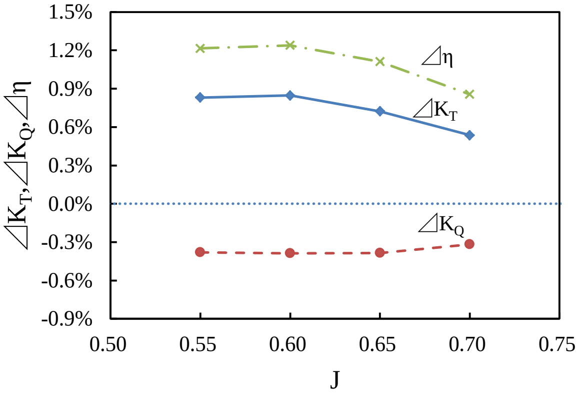


Figure 9: Comparison of the Propeller characteristics at Propeller-A (ECO-Cap/contraction)

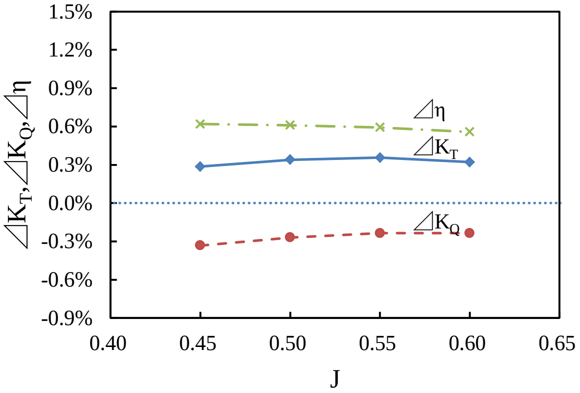


Figure 10: Comparison of the Propeller characteristics at Propeller-B (ECO-Cap/contraction)

Figures 11 and 12 show $\delta K_T / K_T$ and $\delta K_Q / K_Q$ on each component (propeller blade, propeller boss and cap) at Propeller-A, Propeller-B, respectively. It was found that the improvement of the propeller efficiency was due to mainly influence of cap instead of propeller blades.

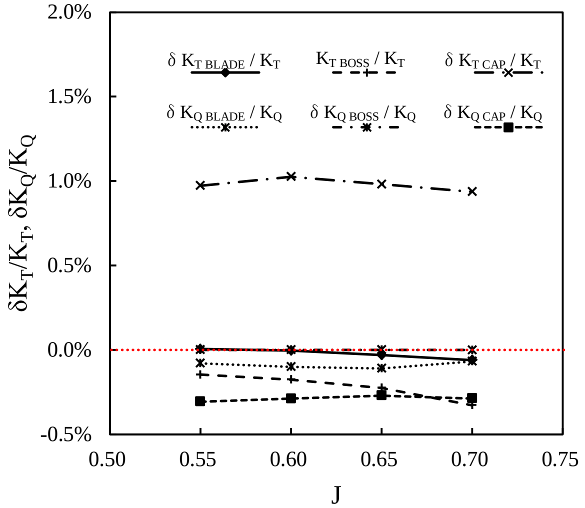


Figure 11: Comparison of $\delta K_T / K_T$ and $\delta K_Q / K_Q$ on each component at Propeller-A (ECO-Cap/contraction type)

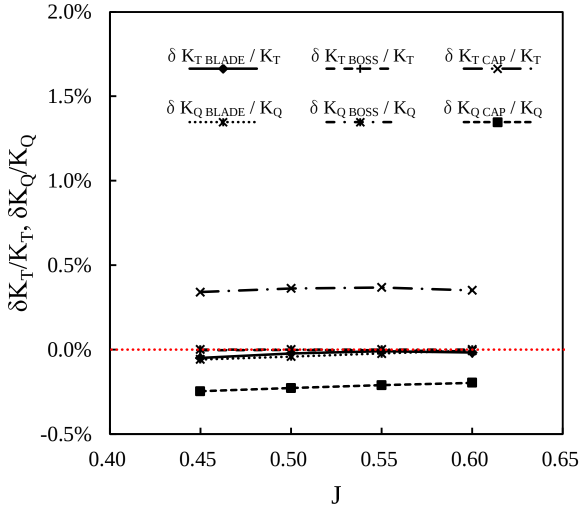
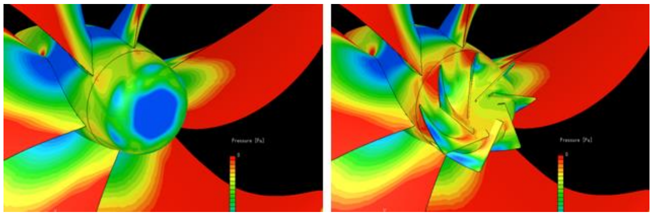


Figure 12: Comparison of $\delta K_T / K_T$ and $\delta K_Q / K_Q$ on each component at Propeller-B (ECO-Cap/contraction type)

Figure 13 shows the pressure distribution on propeller and cap surface. Contraction type had strong negative pressure (blue area) on the backward of propeller cap. On the other hand, the negative pressure on the backward of ECO-Cap dissipated. It is considered that such dissipation of negative pressure is the cause of improvement of propeller efficiency.



(a) Contraction type (b) ECO-Cap

Figure 13: Comparison of pressure distribution on surface of contraction type and ECO-Cap for Propeller-A

3 CONFIMATION BY MODEL TEST

3.1 Procedure of model test

Figure 14 shows the model test facility. Model test was carried out by circulating water channel in West Japan Fluid Engineering Laboratory Co., Ltd. These model tests were carried out at Reynolds number of abt.4 x 10^5, and were adopted reverse propeller open test (POT) to measure the propeller characteristics to confirm the effect of cap difference.

Figure 14: Facility to measure the propeller characteristics by reverse POT

3.2 Model test results

Figures 15 and 16 show the model test result of the propeller characteristics comparison of ECO-Cap with contraction type cap at Propeller-A, Propeller-B, respective. In Propeller-A, K_T of ECO-Cap was increased and K_Q was almost decreased. Therefore the propeller efficiency was increased 1.28% at maximum. In Propeller-B, K_T was increased and K_Q was slightly increased. Therefore the propeller efficiency was increased 0.69% at maximum.

The tendency of increasing propeller efficiency by ECO-CAP at model test was almost similar the result CFD analysis. However, the tendency of K_Q at Propeller-B was remarkably different. As yet, the reason why is unclear.

Figure 17 shows the result of hub vortex visualization test. To confirm the strength of hub vortex, the test was carried out by air injection method. Propeller-A with contraction type generated hub vortex which was stronger than Propeller-B with contraction type did. And it was confirmed that the hub vortices in both propellers ware reduced by ECO-Cap.

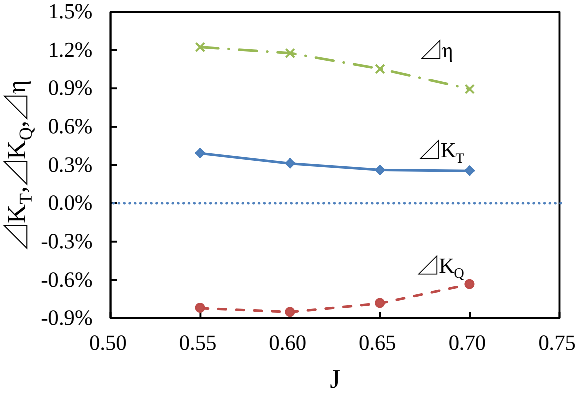


Figure 15: Comparison of propeller characteristics by model test at Propeller-A (ECO-Cap/contraction)

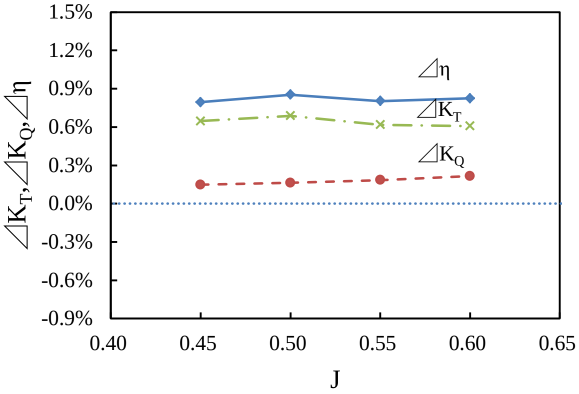
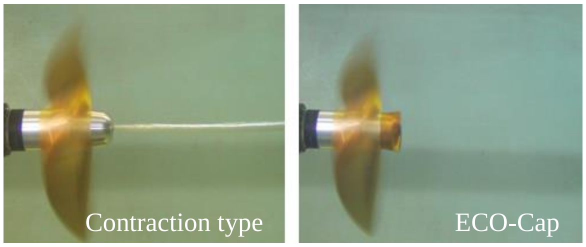
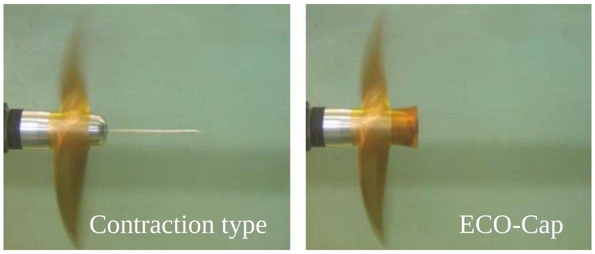


Figure 16: Comparison of propeller characteristics by model test at Propeller-B (ECO-Cap/contraction)



(a) Propeller-A



(b) Propeller=B

Figure 17: Flow visualisation test for hub vortex

4 VERIFICATION WITH VESSEL IN SERVICE

To verify the effect of ECO-Cap, ECO-Cap installed to a vessel in service and the FOC was monitored. The detail information is described in Table 2.

Table 2: Particulars of this ship

Kind of ship	Car ferry
Engine	2 Sets
BHP	956 kW
RPM (Engine/Propeller)	356.0 rpm / 211.0 rpm
Propeller (left & right handed)	
Number of blades	4
Propeller Diameter	2650 mm

This vessel's propeller caps were exchanged for ECO-Cap. Figure 18 shows the picture of ECO-Cap installed to this vessel.

The FOC was monitored before and after ECO-Cap installation. Figure 19 shows comparison of FOC before and after ECO-Cap installation at same month. Figure16 indicates the FOC was 2.8% decrease in average.

This result was more improve than the model test result and the tendency of the result corresponds to ITTC's opinion.

Figure 18: ECO-Cap for car ferry

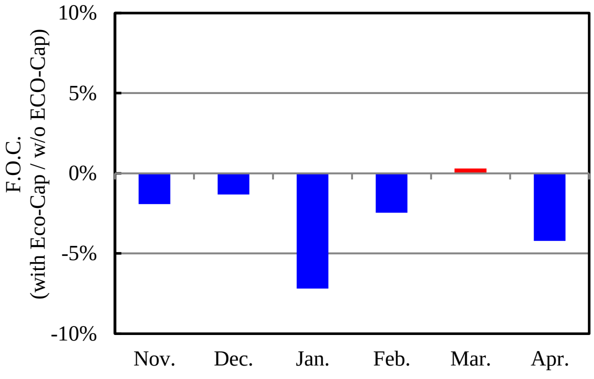


Figure 19: Comparison of FOC

CONCLUSION

1) Increase of total efficiency by ECO-Cap was predicted by CFD and confirmed by the model test. Furthermore, the effect to make the hub vortex weak was confirmed by flow visualisation test.
2) It was predicted by CFD that ECO-Cap prevents the generation of the hub vortex. It is expectid that this phenomenon make the hub vortex weak. Therefore it is expected to avoid rudder erosion as well as to improve the efficiency by reducing the hub vortex.
3) About the increase of efficiency by ECO-Cap in model test, MPNo.1 was max.1.28% and MPNo.2 was max.0.69%.
4) As the result of monitoring FOC by a car ferry, ECO-Cap reduced FOC by 2.8% in average.
5) On a vessel in service, the effect of FOC reduction was more improvement than model scale. That tendency corresponded to ITTC's opinion.

After this, the authors will try the numerical analysis of ECO-Cap include hull by CFD, and confirmation the efficiency in actual operating.

NOMENCLATURE

D	$Propeller\ diameter$
V	$Velocity\ of\ the\ flow$
n	$Rate\ of\ revolution\ per\ second$
ρ	$Mass\ density$
ν	$Coefficient\ of\ kinematic\ viscosity (m^2/sec)$
J	$Advance\ coefficient\ of\ propeller\quad J = \frac{V}{n \cdot D}$
T	$Thrust\ of\ propeller\ and\ propeller\ cap$
K_T	$Thrust\ coefficient\quad K_T = \frac{T}{\rho n^2 D^4}$
Q	$Torque\ of\ propeller\ and\ propeller\ cap$
K_Q	$Torque\ coefficient\quad K_Q = \frac{Q}{\rho n^2 D^5}$
η	$Propeller\ efficiency\quad \eta = \frac{J \cdot K_T}{2\pi K_Q}$
R_{nD}	$Reynolds\ number\quad R_{nD} = \frac{n \cdot D^2}{\nu}$
ΔK_T	$K_{T\ ECO-Cap}/K_{T\ contraction\ type\ cap}$
ΔK_Q	$K_{Q\ ECO-Cap}/K_{Q\ contraction\ type\ cap}$
$\Delta\eta$	$\eta_{\ ECO-Cap}/\eta_{\ contraction\ type\ cap}$
δK_T	$K_{T\ ECO-Cap} - K_{T\ contraction\ type\ cap}$
δK_Q	$K_{Q\ ECO-Cap} - K_{Q\ contraction\ type\ cap}$
$\delta\eta$	$\eta_{\ ECO-Cap} - \eta_{\ contraction\ type\ cap}$

REFERENCES

1. Mikael Grekula and Per Lindell, "Cavitation EROSION Damage on Semi-Spade Rudders", The Swedish Club Letter 1-2007
2. Juergen Friesch, "RUDDER EROSION DAMAGES CAUSED BY CAVITATION", CAV2006, Aug.,2006.
3. Shosaburo Yamasaki, "High Efficiency Propellers - NHV Propeller with Smallest Blade Area", IPS'10, Apr.,2010.
4. Kazuyuki Ouchi, "Effect and Application of PBCF(Propeller Boss Cap Fins)", Journal of M.E.S.J., Vol.27, No.9, 1992.
5. Takafumi Kawamura, "Model and full scale CFD analysis of propeller boss cap fins (PBCF)", Journal of Marine Science and Technology, Vol.17, Dec.,2012.
6. Neil Bose et al, "Final Report and Recommendations to the 22nd ITTC", The Specialist Committee on Unconventional Propulsors, 1999

DISCUSSION

Question from Rickard Bensow

Have you made optimization of the cap for different propellers and do you then get different optimal designs?

Authors' Closure

Thank you for your question. We have made optimization of the cap for several propellers by CFD and the results of them were almost same designs. Therefore we think that we don't have to change design of ECO-Cap except for special propeller such as CPP.

Question from Dmitriy Ponkratov

1. Slide 26 also shows the reduction of tip vortex cavitation. Any comments on that?

2. Were the hull roughness conditions the same for "before / after" sea trials?

Authors' Closure

Thank you for your question.

1. Unfortunately, we can't publish the image of slide 26. Slide 26 showed the movie of the results of cavitation test with and without ECO-Cap. Those tip vortex strength were appeared like to different by different condition of light. Actually, both tip vortex strength is same. Of course both cavitation tests were carried out at same condition.

2. Although we didn't measure the roughness, we think it was almost same because that hull is docked every year.

Question from Yan Xing-Kaeding

1. Have you performed the CFD analysis in Full scale?

2. Which parameters have been investigated in terms of the fins?

Authors’ Closure

Thank you for your question.

1. Now we get the result of CFD analysis in full scale. In full scale, the efficiency gain by ECO-Cap is 1.5 to 3.2 times greater than model scale. It is nearly the same as ITTC’s guidance. We presented at Nutts 2015 titled “Propeller Particulars and Scale Effect Analysis of ECO-Cap by CFD”

2. We investigated about number, position, pitch, size and shape. Unfortunately, we can’t publish each effect.

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