**Investigation on Full Scale Performance of the Propeller Boss Cap Fins (PBCF)**

K Kimura and S Ando, Akishima Laboratiries(Mitsui Zosen) Inc., Japan
S Ono, Y Tanaka and S Takeuchi, MOL Techno-Trade, Ltd. (MOL Tech), Japan
N Asanuma, Mitsui O.S.K. Lines, Ltd. (MOL), Japan

**SUMMARY**

The propeller boss cap fins (PBCF) is well known to be one of the most successful energy-saving devices for ships. More than 3,300 sets have been sold since its first introduction in 1987. In this paper, SPIV measurements and CFD computations were carried out in order to investigate the reasons for the difference in the energy saving effects of PBCF in model test and in full scale data. It was confirmed to evaluate the full scale energy saving effect of PBCF by taking into account the propeller inflow in the real ship. As these results, it was suggested that EFD and CFD analysis using simulated full scale ship wake is effective to estimate the energy saving effect of PBCF in full scale. And the effect of energy saving was confirmed to increase in combination with PBCF and other ESD. Also, it was confirmed that the effectiveness of the combination of PBCF and other ESD for EEDI improvement. Furthermore, it was confirmed that PBCF is an effective device to reduce the underwater radiation noise from the cavitation test.

**NOMENCLATURE**

- $D$: Propeller diameter (m)
- $J$: Advance coefficient
- $n$: Rotation speed (rps)
- $K_T$: Thrust coefficient $K_T = \frac{\text{Thrust}}{\rho n^2 D^4}$
- $K_Q$: Torque coefficient $K_Q = \frac{\text{Torque}}{\rho n^2 D^5}$
- $\eta$: Propeller efficiency $\eta = \frac{J}{2 \pi K_T}$
- $R_{nd}$: Propeller Reynolds number $R_{nd} = \frac{n D^2}{\nu}$
- $R_n$: Ship Reynolds number $R_n = \frac{V_S \rho}{\nu}$
- $V_S$: Ship Speed (m s$^{-1}$)
- $\nu$: Kinematic viscosity (N s m$^{-2}$)
- $\rho$: Density of water (kg m$^{-3}$)
- $P$: Pressure (N m$^{-2}$)

**1. INTRODUCTION**

The propeller boss cap fins (PBCF) is well known to be one of the most successful energy-saving devices for ships. More than 3,300 sets have been sold since its first introduction in 1987. However, the reasons for the difference in a gain in propeller efficiency between full scale and model scale by installing PBCF have not been clarified. The investigation and development of PBCF were originally performed by Ouchi et al [1,2,3]. They confirmed that thrust increases and torque decreases, thus the efficiency increases with the introduction of PBCF. The measured increase of the efficiency in their model experiments was from 1 to 2%. Nojiri et al. reported the results of more systematic experiments regarding four, five and six-bladed propellers. The measured increase of the propeller efficiency was from 1 to 1.5% [4]. On the other hand, Ouchi reported the results of full scale analyses for 12 different vessels, in which the average energy-saving effect of PBCF was 5.4% [3]. Hansen et al. reported that the analysis of the sea trials showed 3.5% and 4% reduction in shaft horsepower in ballast and in full load condition [5]. Nojiri et al. also showed the results of full scale analyses for 16 different vessels, in which the energy-saving effect ranges from 2 to 10% with the average being approximately 5% [4]. Those results suggest that the energy saving effect of PBCF is larger in full scale than in model scale. Kawamura et al. reported results of CFD computations were carried out in order to investigate the reasons for the difference in the effects of PBCF in model test and in full scale data [6,7]. They presented the computed effect in the propeller efficiency, which around 2% is still smaller than the reported value in sea trial and fleet data. The authors have also been studying the possibility of Experimental Fluid Dynamics(EFD) and Computational Fluid Dynamics(CFD) on the performance evaluation of PBCF and propeller [8,9]. In precious study, the authors discussed the various validations for the effect of PBCF, and we confirmed that the effect of PBCF in a uniform flow and an imaginary wake was qualitatively well estimate, but the difference in effect for the propeller efficiency between full scale and model scale were not sufficiently explained. So, the authors performed EFD and CFD regarding PBCF operating behind simulated full-scale ship wake, and discussed the reason of the difference in the gain between the full scale and model scale. Furthermore, we were carried out the experiments.
on the combined effect of PBCF and other energy saving devices (ESD). The measurement results demonstrated the effectiveness of the combination of the PBCF and other ESD for EEDI improvement. And we described the reduction effect of underwater radiation noise by PBCF.

2. PBCF PERFORMANCE IN FULL-SCALE

2.1 REVERS PROPELLER OPEN TEST

The reverse propeller open test (rev-POT) of PBCF without/with simulated full-scale ship wake was carried out in the cavitation tunnel at Akishima Laboratory. The arrangement of reverse propeller open test was shown in Figure 2.

![Figure 2: Reverse Propeller Open Test (rev-POT)](image1)

2.2 FLOW MEASUREMENT

The difference of flow pattern without/with the PBCF behind simulated full scale ship wake was measured by using the stereo particle image velocimetry (SPIV). And it is discussed that the influences of simulated full scale ship wake for PBCF. The SPIV set-up is shown in Figure 3 and the SPIV system configuration was shown in Table 1. The SPIV set up consisted of two CCD cameras located in both sides of the cavitation tank and the Nd-YaG laser to generate the light sheet to the measurement plane. The area of measurement was W300×H300mm [10].

![Figure 3: Arrangement of Stereo PIV System](image2)

<table>
<thead>
<tr>
<th>Camera</th>
<th>ImagerProX 2M</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>(1600×1200pixel, each being a square of side 7.4μm)</td>
</tr>
<tr>
<td>Camera lens</td>
<td>Ai AF Zoom-Nikkor 24-85mm f/2.8-4D IF</td>
</tr>
<tr>
<td>Measurement area</td>
<td>W300mm×H300mm</td>
</tr>
<tr>
<td>Laser</td>
<td>DPIV-L200 200mJ</td>
</tr>
<tr>
<td>Seeding Particles</td>
<td>Silver Coated Hollow Glass Spheres: diam 14μm</td>
</tr>
<tr>
<td>PIV analysis</td>
<td>Lavision FlowMaster DaVis8.1.3</td>
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</tbody>
</table>

2.3 MODEL PROPELLER

The practical high-skew marine propellers were applied in the several model tests. Figure 4 and 5 shows the principal particulars of the model propeller P664R and P668R. The model of PBCF was designed for the several model propellers.

![Figure 4: Model Propeller P664R](image3)

<table>
<thead>
<tr>
<th>MPNo. P664R</th>
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<tbody>
<tr>
<td>Propeller Diameter</td>
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<td>Number of Blades</td>
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<td>Mean Pitch Ratio</td>
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<td>Expanded Area Ratio</td>
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<tr>
<td>Boss Ratio</td>
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<td>Turning Direction</td>
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![Figure 5: Model Propeller P668R](image4)

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<th>MPNo. P668R</th>
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<tr>
<td>Propeller Diameter</td>
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<td>Turning Direction</td>
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2.4 FULL SCALE SHIP WAKE SIMULATION

In assessing the ESD performance of the full scale ship, the flow field of stern is very important. Figure 6 shows the CFD analysis results of wake distribution in model Re=10^7 and full scale ship Re=10^9. It was confirmed that very different wake between model and full scale was obtained, as full scale ship wake against model wake [11]. Therefore, to estimate the energy saving effect of PBCF, the propeller inflow is very important and it is necessary to consider full scale ship wake. So, we estimated two type of Full scale ship wake distribution at the propeller plane in the towing condition.

The full scale ship wake flow in cavitation tunnel was simulated by a wire mesh screen method which was installed upstream the propeller. The arrangement of wire mesh screen in cavitation tunnel was shown in Figure 7.

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Figure 6: Comparison of wake distribution between model Re =10^7 and full scale ship Re=10^9.

The wire mesh screen method is usually used for the simulation of ship wake on the cavitation test. This simulation method is very effective in reproducing the designated ship wake distribution in cavitation tunnel.

Figure 7: Arrangement of Wire mesh screen

Two type of simulated full scale ship wake in cavitation tunnel was shown in Figure 8. Ship-A wake is the full form ship and ship-B wake is the relatively slender ship.

Figure 8: Simulated wake distribution in cavitation tunnel.

2.5 FLOW MEASUREMENT RESULTS

To confirm the effect of performance improvement of PBCF, the propeller slipstream was measured using SPIV. The test condition was shown in Table 2. The constant loading method is employed for the reversed POT.

Figure 9 shows the measurement results of the propeller slipstream of P668R without and with PBCF in uniform flow. It was confirmed that the strong hub vortex behind the propeller boss in without PBCF. On the other hand, it was confirmed that the hub vortex was disappeared with PBCF. Figure 10 shows the measurement results of the propeller slipstream of P668R without and with PBCF in full scale ship wake A. It was confirmed that the hub vortex behind the propeller boss in full scale ship wake A was stronger than uniform flow in without PBCF. And, it was confirmed that the hub vortex was disappeared with PBCF.
Figure 10: Comparison of Velocity (left) and Vorticity (right) distribution behind P668R in Ship Wake A.

Figure 11 shows the comparison of the energy-saving effect of PBCF. The energy-saving effect of PBCF was obtained around 2 to 3% in uniform flow. The energy-saving effect of PBCF was achieved more than 4% in ship wake A, almost same magnitude of energy saving effect of PBCF in full scale.

Figure 11: Comparison of the energy-saving effect of PBCF for propeller P668R.

Figure 12 shows comparison of velocity and vorticity distribution behind propeller boss cap of P644R in uniform flow. Figure 13 shows comparison of velocity and vorticity distribution behind propeller boss cap of P644R in ship wake B. As with case of propeller P668R, it was confirmed that the hub vortex was disappeared with PBCF in uniform flow and in ship wake B. Figure 14 shows the comparison of the energy saving effect of PBCF for P664R. The energy-saving effect of PBCF was obtained around 2 to 3% in uniform flow. The energy-saving effect of PBCF was achieved more than 3% in ship wake B, almost same magnitude of energy saving effect of PBCF in full scale.
Thus, it was confirmed that the difference in effect for the propeller efficiency between full scale and model scale was reduced by taking into account the full scale ship wake. To estimate the energy saving effect of PBCF in full scale, it is important to be close the load of the propeller to the condition in full scale. Especially, the inflow distribution of propeller is very important to estimate the energy saving effect of PBCF in full scale.

2.6 CFD Calculation

The present work uses OpenFOAM OpenSource CFD tool to compute the incompressible flow field around the propeller and PBCF in reversed POT. In this study, pimpleDyMFoam is an unsteady solver for incompressible fluids on a moving mesh using the PIMPLE (merged PISO-SIMPLE) algorithm with AMI (Arbitrary Mesh Interface) techniques. The governing equations are the Reynolds-Averaged Navier-Stokes equations and the $k\omega$ – $SST$ model was used for turbulence modelling.

Figure 15 and Figure 16 shows the comparison of streamline behind propeller boss cap for propeller 668R in uniform flow and in ship wake A. The hub vortex behind propeller boss cap was generated and the efficiency loss has occurred without PBCF. On the other hand, it was confirmed that the hub vortex was disappeared and the energy saving effect was achieved by PBCF. And the energy saving effect in ship wake A is increased compared with uniform flow.

Furthermore, the comparison of isosurface of vorticity distribution around propeller was shown in Figure 17 and Figure 18. From these results, it was confirmed that the hub vortex in ship wake A was larger than in uniform flow and the hub vortex was disappeared by PBCF. Especially, it was recognized that PBCF is better ESD to decrease the efficiency loss by the hub vortex.
3. **COMBINED EFFECT of PBCF AND OTHER ENERGY SAVING DEVICE.**

Due to global warming and exhaustion of fossil fuels, measures in the maritime industry to reduce greenhouse gas (CO2) and to cope with fuel consumption regulations are becoming important issues. Therefore, the development of the high-performance energy-saving device is expected. The experiments regarding the combined effect of PBCF and typical ESD were conducted in the large towing tank at Akishima Laboratory. It is confirmed about the influence of the interaction between PBCF and other ESD. Figure 19 shows the combination was used in the experiments, which PBCF, PBCF with Rudder Bulb-Fin(RBF), PBCF with Duct and PBCF with Duct and RBF.

![Figure 19: Combination of PBCF and typical ESD](image)

Figure 20 and Figure 21 shows the comparison of velocity and vorticity distribution behind propeller was measured by SPIV. In both conditions without and with duct, the hub vortex is generated by rotating propeller. And, it was confirmed that the hub vortex was disappeared by PBCF. Since these experiments regarding the combined effect of PBCF and typical ESD were carried out in the model wake, it is expected that the energy saving effect is further improved in the full scale wake. Figure 22 shows the comparison of the energy saving effect of combination between PBCF and typical ESD by considering the energy saving effect in full scale wake. By combining PBCF and other ESD, it was predicted that more energy saving effect was achieved and more than 6% gain was obtained in case of PBCF+DUCT+RBF.

![Figure 21: Velocity(left) and Vorticity(right) distribution behind propeller with Duct](image)

![Figure 22: Comparison of the energy saving effect of combination between PBCF and typical ESD.](image)

4. **UNDERWATER RADIATION NOISE**

From the influence of radiation noise from the merchant ships to marine life attracted global attention, the development of underwater radiation noise reduction techniques have been important. Especially, the various
cavitation generated from propeller is main noise source from the ship, the reduction of these cavitation is important. The experiment regarding the underwater radiation noise was conducted in cavitation tunnel at Akihima Laboratory. Figure 23 shows the results of cavitation observation without and with PBCF. It was confirmed that the hub vortex cavitation was disappeared by PBCF. Figure 24 shows the comparison of the sound pressure level (SPL) between condition without and with PBCF. In PBCF equipped condition, the underwater radiation noise was confirmed to be reduced by around 5db in range from 100 to 1kHz. As a result, it was confirmed that PBCF is an effective device to reduce the underwater radiation noise.

![Figure 23: Comparison of cavitation observation without and with PBCF for propeller.](image)

5. **CONCLUSIONS**

SPIV measurements and CFD computations were carried out in order to investigate the reasons for the difference in the energy saving effects of PBCF in model test and in full scale data. It was confirmed to evaluate the full scale energy saving effect of PBCF by taking into account the propeller inflow in the real ship. As results, it was suggested that EFD and CFD analysis using simulated full scale ship wake is effective to estimate the energy saving effect of PBCF in full scale. And the effect of energy saving was confirmed to increase in combination with PBCF and other ESD. Also, it was confirmed that the effectiveness of the combination of PBCF and other ESD for EEDI improvement. Furthermore, it was confirmed that PBCF is an effective device to reduce the underwater radiation noise from the cavitation test.

6. **ACKNOWLEDGEMENTS**

The authors would like to express their gratitude to Dr. Chiharu Kawakita at Fluid Control Research Group, Fluids Engineering & Hull Design Department, National Maritime Research Institute for his cooperation and support to the study.

7. **REFERENCES**


8. AUTHORS BIOGRAPHY

Koyu Kimura holds the current position of Director of Research&Development Division at Akihima Laboratories (Mitsui Zosen) Inc. He is responsible for R&D and design of hull form, propeller, ESD at Akishima Laboratory. His previous experience includes hull form, propeller design and R&D on propeller cavitation noise in Akihima Laboratories (Mitsui Zosen) Inc.

Satoko Ando holds the current position of Assistant Manager of Marine Engineering & Hydrodynamics Department at Akihima Laboratories (Mitsui Zosen) Inc. She is responsible for R&D and design of propeller, ESD at Akishima Laboratory. Her previous experience includes propeller design and R&D on propeller cavitation noise in Akihima Laboratories (Mitsui Zosen) Inc.

Shirou Ono holds the current position of general manager-technical of PBCF Department at MOL Techno-Trade, Ltd. He is responsible for R&D and sales of PBCF at MOL Techno-Trade. His previous experience includes ship basic design and R&D works and on ship’s performance in rough sea, in Mitsui O.S.K. Lines, Ltd.

Susumu Takeuchi holds the current position of technical advisor for PBCF Department at MOL Techno-Trade, Ltd. He is responsible for R&D and sales of PBCF at MOL Techno-Trade. His previous experience includes ship planning, designing and construction of new-building vessels in Mitsui O.S.K. Lines, Ltd.

Norimichi Asanuma holds the current position of general manager for Technical Innovation Team, Technical Division at Mitsui O.S.K. Lines, Ltd. He is responsible for R&D of technologies for reducing environmental impact like PBCF. His previous experience includes ship planning, designing and construction of new-building vessels and maintenance of existing vessels in Mitsui O.S.K. Lines, Ltd.

Yoshikazu Tanaka holds the current position of managing director at MOL Techno-Trade, Ltd. He is responsible for R&D Promotion and PBCF development. His previous experience includes ship basic design and R&D works and on ship’s performance in rough sea, in Mitsui O.S.K. Lines, Ltd.