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Development of a High Performance Ducted Propeller

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SYNOPSIS

It is well known that a ducted propeller offers significant advantages for the bollard pull performance of tugboats. Studies about nozzle and propeller shape have been done for some time, and a Ka series propeller and a conventional 19A nozzle are used ordinarily for a ducted propeller. In recent years, the demand for energy saving has increased because of the rise in oil prices, and a corresponding high bollard pull performance demand for tugboats at the same horsepower. To meet this demand, the most effective solution has been through the use of a high performance ducted propeller.

This paper describes the advanced design method of a ducted propeller which has high bollard pull performance. A nozzle section shape and a propeller were newly designed through a parametric study of the numerical simulation to have higher performance than a conventional ducted propeller. The optimum arrangement between nozzle and propeller combination was studied. In order to confirm high bollard pull performance of the improved ducted propeller, open water tests were carried out in a towing tank at Akishima Laboratories (Mitsui Zosen) Inc.

In addition, we researched Propeller Boss Cap Fins (PBCF) for ducted propellers. The tank test was carried out in various combinations of key parameters of PBCF. After the evaluation of the test results, the ducted propeller with high bollard pull performance was designed for actual tugboats.

The newly designed ducted propeller is equipped for the ‘Z-Peller’ of our product, which is a propulsor for a workboat. Full-scale bollard pull tests have been conducted in the field. This paper will also present the field test results showing a higher bollard pull performance than a conventional ducted propeller.

INTRODUCTION

Ducted propellers are classified into two general groups–cruising type (free-running type) for supply or transport vessels and high-power types for ocean and harbour tugboats. Conventional ducted propellers have ordinarily been composed of a 19A nozzle and Kaplan propeller. However, in recent years, it has become increasingly difficult to meet market demands for ducted propellers based on this conventional composition. For cruising-type ducted propellers, efforts to meet market requirements have led to the development of high-efficiency nozzles, such as the HR nozzle.

Demand for high-power ducted propellers with high bollard pull performance continues to rise yearly, spurring improvements in performance. In response to this demand, we developed the advanced design method of a high-power type ducted propeller with high bollard pull performance. This paper shows how the performance of the newly-designed ducted propeller was evaluated with full-scale test results and led to the successful commercialisation of this new type of ducted propeller.

DESIGN OF DUCTED PROPELLER

The target of this paper was to develop a new ‘Z-Peller’, by improving the bollard pull performance of the existing one. *Table 1* shows design conditions.

Engine Output	Prop.Dia	Bollard pull Thrust [ton] *	
[kW/min-1]	[m]	Existing model	**New designed model**
2206 / 750	2.7	75.0 ⇨	**Over 80.0**

Table 1: Design condition.
**at twin Z-Peller*

The following three aspects were investigated to develop a new ducted propeller:

- Nozzle shape;
- Propeller shape;
- Interaction between the nozzle and the propeller.

Nozzle shape design

To develop a new nozzle with bollard pull performance exceeding conventional nozzles (19A), we investigated the 19A-based nozzle shape, in particular the parameters of camber and thickness distributions in the nozzle fore/aft part. In addition to nozzle performance, ease of manufacturing was also considered. We used both theoretical and computational fluid dynamics (CFD) calculations to analyse various shapes. The theoretical method is preferable for parametric studies for shape analysis because it tends to reduce the time required for calculations. We performed theoretical calculations based on the Vortex Lattice Method (VLM), often used to calculate propeller characteristics, applying it to explore new nozzle shapes. We evaluated nozzle thrust per unit of propeller thrust (KTD/KTP), comparing this aspect to performance provided by conventional nozzles.

Since the theoretical method does not permit detailed evaluations of flow near the nozzle, we used CFD at the final stage to perform detailed performance evaluations. We used commercial finite-volume code STAR-CD Ver.3.26 fluid analysis software for CFD analysis with a simplified two-dimensional axially symmetric model that provides propeller thrust as the body force. An even thrust inside the nozzle was provided as the body force. The calculation conditions are shown in *Table 2*. The generated meshes for the calculation are shown in *Figure 1*. *Figure 2* shows the shape of the newly-designed nozzle.

Analysis Solution	2D Steady-State SIMPLE method
Discrete Scheme	QUICK
Turbulence Model	k-ω SST High-Reynolds Number model
Reynolds number	$Rn=6\times10^5$
Generated meshes	Approx. 45000 cells(hybrid mesh)

Table 2: Calculation condition for 2D analysis.

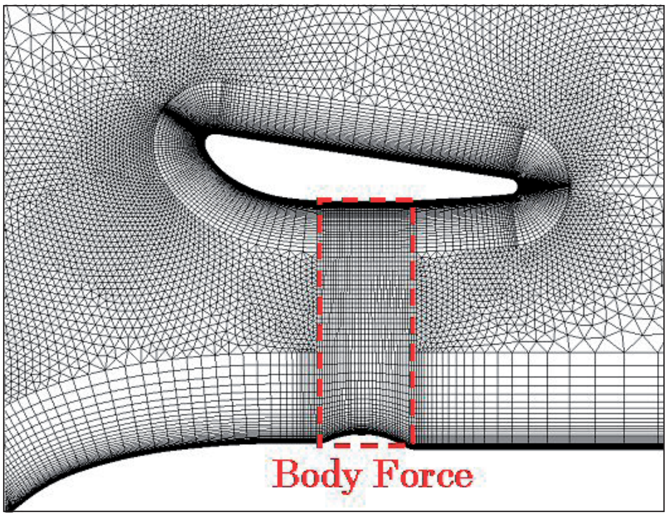


Figure 1: Calculation Meshes for 2D Analysis.

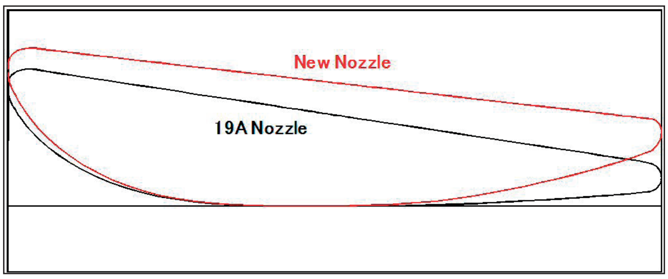
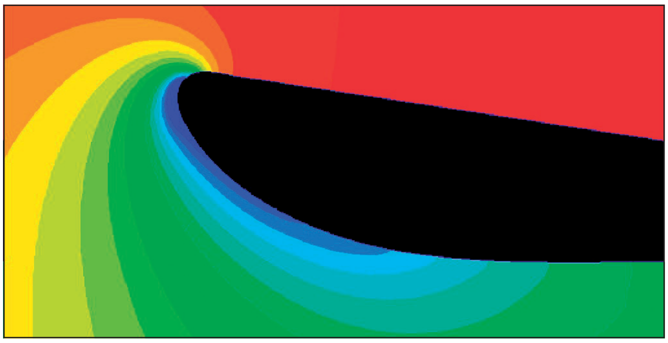
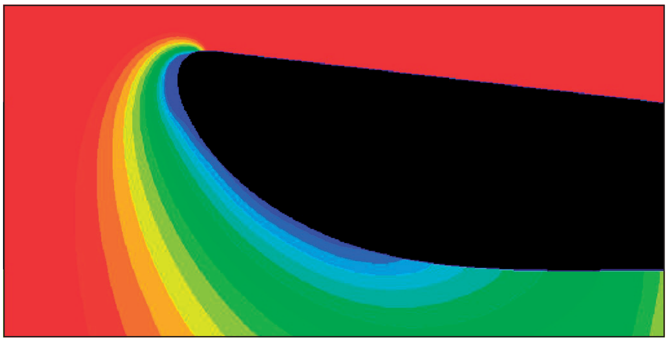


Figure 2: New designed nozzle shape.

Figure 3 compares CFD calculations (of the bollard pull condition) for the conventional nozzle and the new nozzle, confirming higher negative pressure at the fore part of the new nozzle. Since the nose height of the new nozzle is greater than the 19A nozzle, the pressure-receiving area and nozzle thrust is larger. This results in an approximate improvement of 4.5 per cent for KTD/KTP over the conventional type.



Conventional nozzle (19A).



Newly designed nozzle.

Figure 3: Comparison of pressure distribution.

Propeller shape design

Propeller shape is another aspect that must be investigated to achieve high performance in a ducted propeller. For higher performance of the propeller itself, we should investigate the wing-section of the propeller, its profile (width/skew distributions), and pitch distribution.

For open propellers of several vessels, the NACA wing section was adopted to improve propeller performance. This shape also offers advantages over conventional Kaplan propellers with respect to cavitation performance. By selecting a skew distribution to maximise cavitation performance, we can prevent the appearance of bad cavitation. With respect to propeller width distribution, an effective approach is to widen the propeller tip area to increase interference between the nozzle and the propeller. In this study, based on extensive experience, we selected a skewed Kaplan type profile, the standard shape of the Z-Peller, without the problem in cavitation performance, and the propeller wing section was changed to NACA wing section.

Next, pitch distribution was studied. For ducted propellers, in contrast to open propellers, the ideal shape is one that provides the highest accelerated inflow into the nozzle to maximise nozzle thrust. The key to the higher performance of a ducted propeller is propeller-induced velocity in the area close to the nozzle.

We investigated two type pitch distributions (*Figure 4)* differing in propeller-tip loads to evaluate changes in propeller performance with respect to changes in induced velocity by using theoretical and CFD calculations. We used the newly-developed nozzle described in the previous section, setting the propeller so that the propeller generator line aligned with the centre of the nozzle. The mean pitch ratio was selected so that the VLM-based theoretical calculations generated the same propeller thrust value on the bollard pull condition for each propeller operating inside the nozzle.

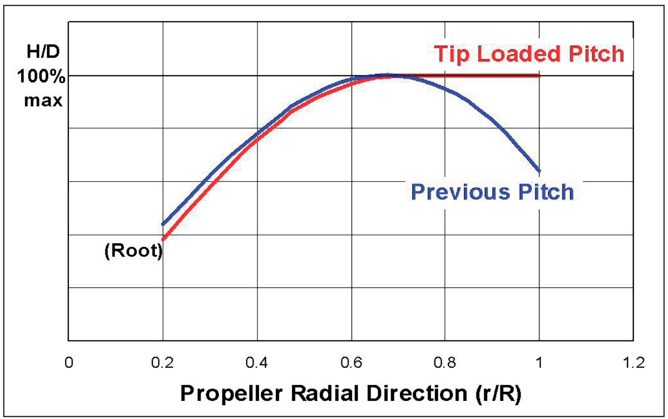


Figure 4: Propeller pitch distribution.

Figure 5 shows the results of VLM calculations of radial thrust distributions for the two propellers in the bollard pull condition, clearly showing the high thrust of the tip-load type pitch-distribution propeller near the nozzle.

Figure 6 shows the results of calculations in which this thrust distribution is used as the radial distribution of body force in the two-dimensional CFD propeller model investigated in the previous section. Comparing pressure distributions at the nozzle fore part confirmed higher negative pressures with the tip-loaded pitch propeller. We achieved improvements of approximately one per cent for KTT/10KQ, an indicator of propeller efficiency of the bollard pull condition.

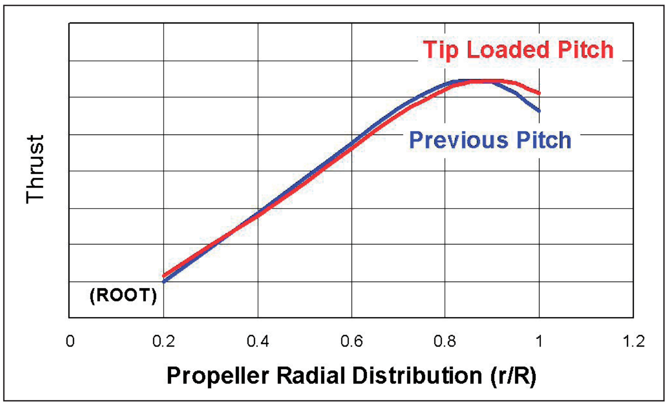


Figure 5: Radial propeller thrust distribution.

Conventional pitch propeller.

Tip loaded pitch propeller.

Figure 6: Comparison of pressure distribution with propeller tip load.

Interaction between the nozzle and propeller

We investigated the effects of propeller pitch distributions and how changes in this parameter affected inflow velocity into the nozzle. The geometric composition of the nozzle and the propeller was another closely investigated issue. In ducted propellers, the clearance between the propeller tip and the straight section inside the nozzle affects performance significantly. If the position of the propeller tip departs from the straight section inside the nozzle, performance declines. We investigated the effects of the clearance between the propeller and the nozzle using a three-dimensional CFD model that considered the geometric shape of the propeller correctly. For this aspect of our study, we combined the newly-developed nozzle with a tip-loaded pitch propeller. The propeller was moved ±10 per cent of the nozzle length across the nozzle centre so that the propeller tip departed from the straight section inside the nozzle. We used the STAR-CD multi-reference frame (MRF) function for analysis, performing calculations for a single propeller blade to which the cyclic boundary condition was adopted. The generated meshes for 3D Analysis are show in *Figure 7*. The calculation conditions are shown in *Table 3*.

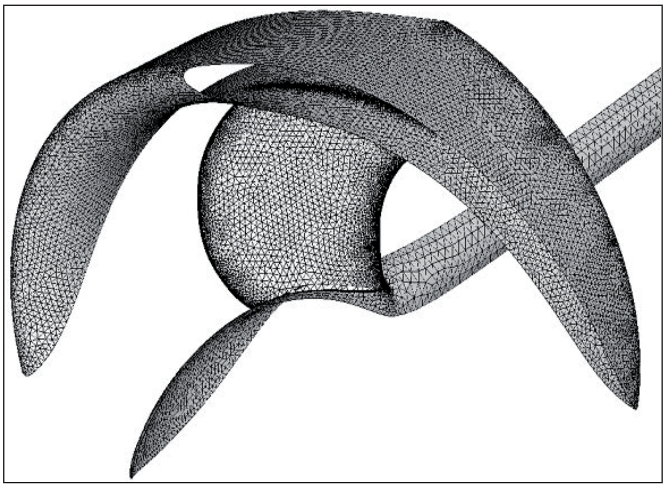


Figure 7: 1/4 Cycle model for 3D analysis.

Analysis Solution	3D Steady-State SIMPLE method
Discrete Scheme	QUICK
Turbulence Model	k-ω SST High-Reynolds Number model
Reynolds Number	$Rn=6\times10^5$
Generated Meshes	Approx. 1,700,000 cells(non-structured mesh)

Table 3: Calculation conditions for 3D analysis.

Figure 8 shows the changes in ducted propeller characteristics. Positioning the propeller forward accelerates inflow velocity along the nozzle leading edge, increases negative pressure at the nozzle fore part, and increases nozzle thrust. However, it also accelerates flow inside the nozzle, reducing the propeller's thrust and torque. *Figure 9* shows the resulting velocity distributions inside the nozzle and propeller surface pressure distributions in the bollard pull condition.

Positioning the propeller towards the rear weakens inflow acceleration at the nozzle fore part and reduces nozzle thrust. Additionally, since increasing the clearance between the nozzle and the propeller tip weakens flow acceleration in the propeller tip, it reduces not only propeller surface negative pressure, but also propeller thrust and torque.

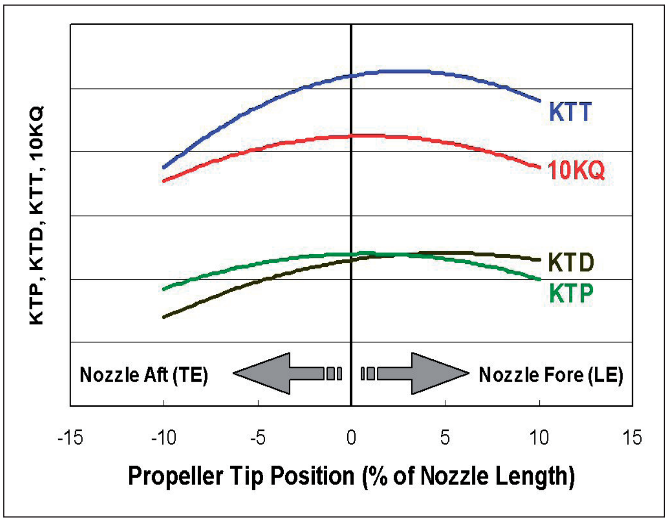
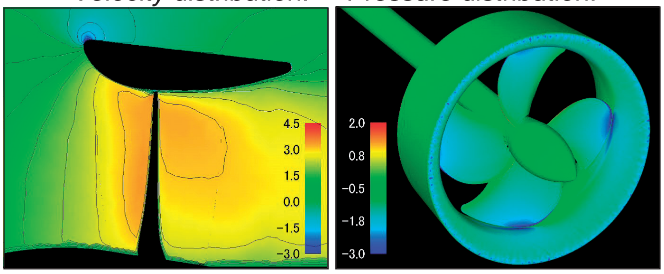
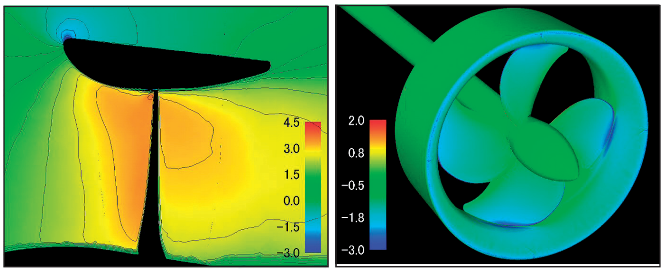


Figure 8: Calculation results of ducted propeller characteristics.

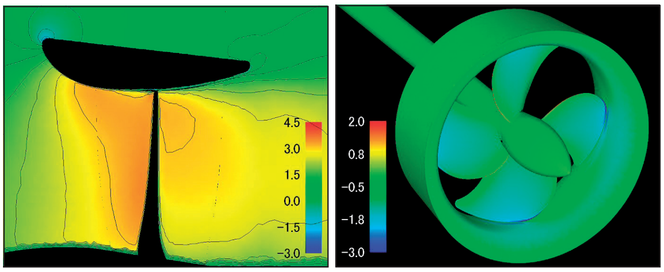
Velocity distribution. Pressure distribution.



Nozzle centre position + 10 per cent nozzle length.



Nozzle centre position.



Nozzle centre position - 10 per cent nozzle length.

Figure 9: Comparison of propeller tip position.

Figure 10 shows KTT/10KQ values at each propeller tip position. KTT (=KTP+KTD) is a total thrust coefficient and KQ is a propeller torque coefficient. When the propeller is located towards the rear, bollard pull efficiency declines dramatically; when the propeller is located toward the front, bollard pull efficiency increases. This suggests that the optimal position for the propeller is forward of the centre of the nozzle. The ideal propeller configuration maximises interference between the nozzle and the propeller.

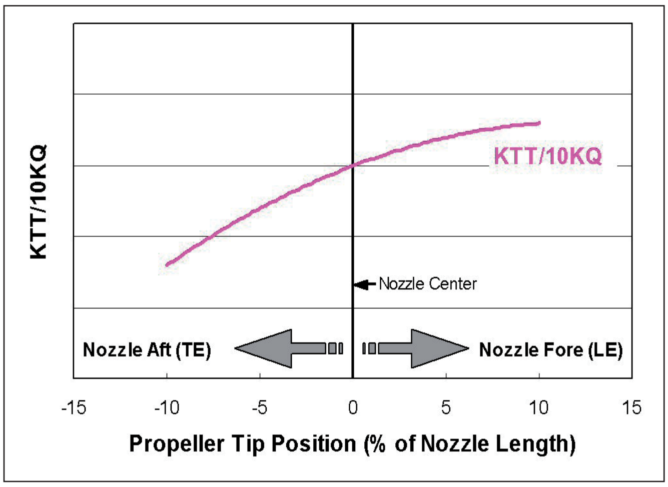


Figure 10: Calculation results of bollard pull efficiency.

The next section discusses the validity of new design method through model tests.

Model Tests

To evaluate performance of the newly designed nozzle and tip-loaded type propeller, we performed model tests using a towing tank at Akishima Laboratories (Mitsui Zosen) Inc. For this model propeller, we selected a mean pitch ratio that met the design conditions. *Figure 11* is a photograph of ducted propeller model.

The ducted propeller open test (POT) was carried out with a Reynolds number $Rn=6x10^5$. The test was performed with the propeller rotation kept constant. *Figure 12* shows the test results (bollard pull condition) when the propeller tip position is varied to confirm the effects of the relative position of the nozzle and propeller. These results confirm the changes in KTT/10KQ as the position of the propeller tip is varied and evaluates the validity of the CFD analysis.

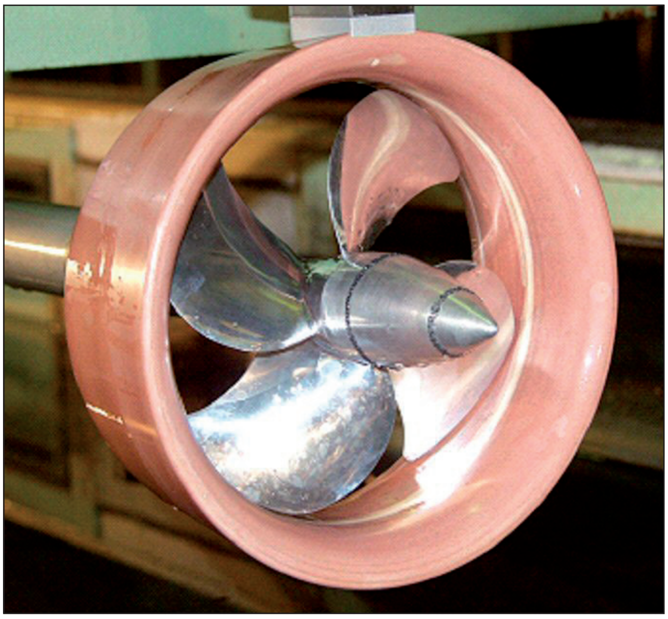


Figure 11: Ducted propeller model.

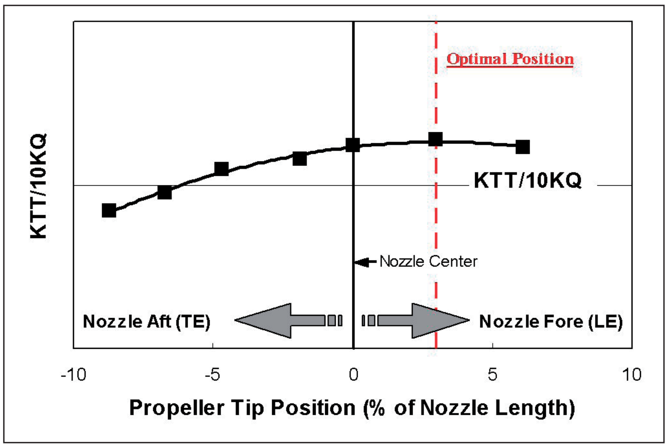


Figure 12: Model test results of bollard pull efficiency.

We found that with the optimal propeller position, the propeller tip is about three per cent of the nozzle length in front of the nozzle centre. Since the centre of the straight section inside the newly designed nozzle lies 47 per cent of the nozzle length from the nozzle leading edge, this position is equal with optimal position of the propeller tip. As a guide for ducted propeller design, the position of the propeller tip should be arranged on the centre of the straight section inside the nozzle. When the propeller tip is at the optimal position, bollard pull thrust (twin ducted propellers) at design condition (2206 kW) is improved slightly over 5.5 per cent (estimated by tank test results) compared with conventional design. This showed that the target performance of 80 tonnes bollard pull thrust was satisfied (see *Figure 13*).

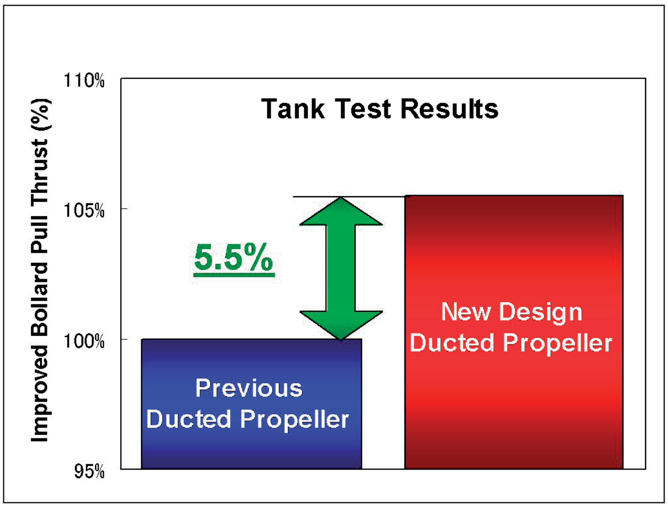


Figure 13: Comparison of bollard pull thrust.

PBCF FOR DUCTED PROPELLER

PBCF (Propeller Boss Cap Fins) is a boss cap with small fins (*Figure 14*) that is well known to have increased the efficiency of a propeller. Almost all the research and development work on PBCF has been reported through technical articles published by Mitsui OSK Techno-Trade Ltd, West Japan Fluid Engineering Laboratory Co Ltd and the Mikado Propeller Co Ltd.

Figure 14: Propeller boss cap fins.

To pursue further performance improvement, we researched information about PBCF for ducted propellers and found many articles. However, most of the information about PBCF was for open propellers: there is no information about PBCF for ducted propeller.

There are fundamental differences in propeller characteristics between open propeller and ducted propellers. So we had to conduct the tank test to confirm the effectiveness of PBCF.

The aim was to ascertain the effectiveness of PBCF and find the optimum fin shape for ducted propellers.

Figure 15 shows key parameters of PBCF. The tank test was carried out in the varied combinations of key parameters of the PBCF (see *Figure 16*).

Fs	Fin shape
Cs	Cap shape
α	Pitch angle
a	Gap length

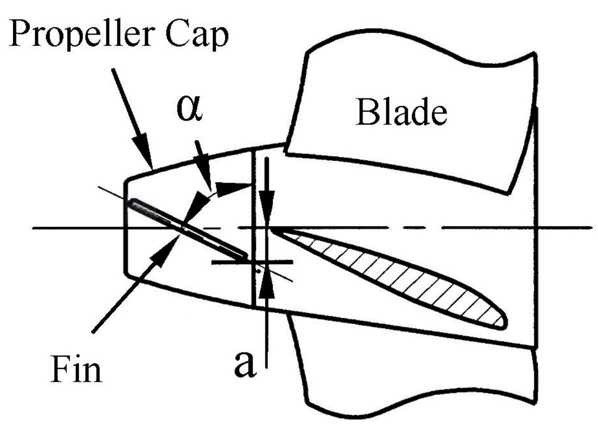


Figure 15: Key parameters of PBCF.

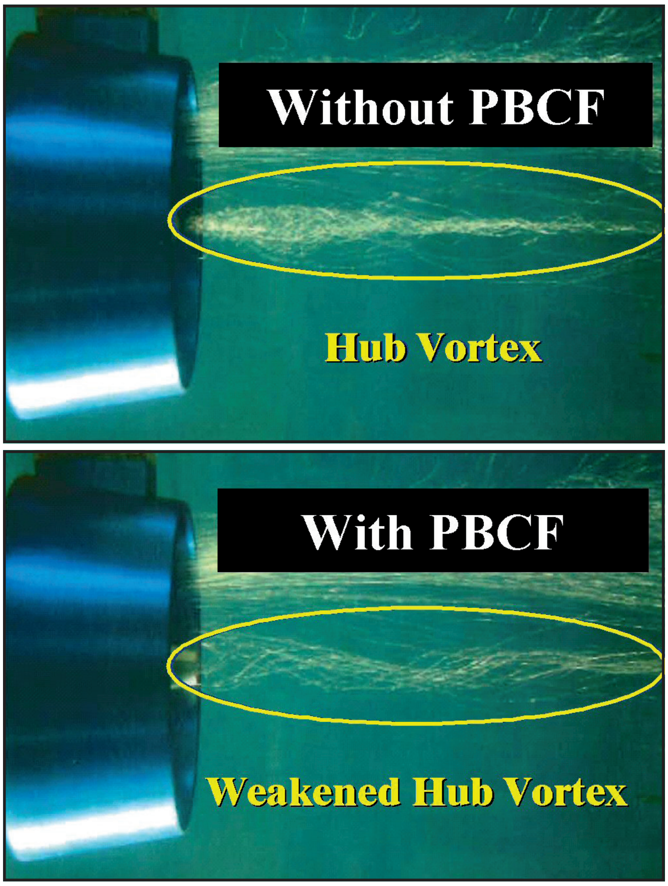


Figure 16: Visualisation test of a stream.

Figure 17: PBCF Models

After much experimentation, we found the optimum fin shape and relative position. By fitting optimised PBCF, the bollard pull performance was improved by at least 1.5 per cent at bollard condition. This improvement was primarily from a propeller thrust increase.

BOLLARD PULL PROGNOSIS

Figure 18 shows a final bollard pull prognosis from study results. If the newly designed ducted propeller and PBCF are used together, bollard pull performance will improve by more than 7 per cent from the existing model. The results of the study clearly showed that the bollard pull prognosis became over 80 tonnes. We confirmed this performance improvement, and have a prospect of actually putting it to use.

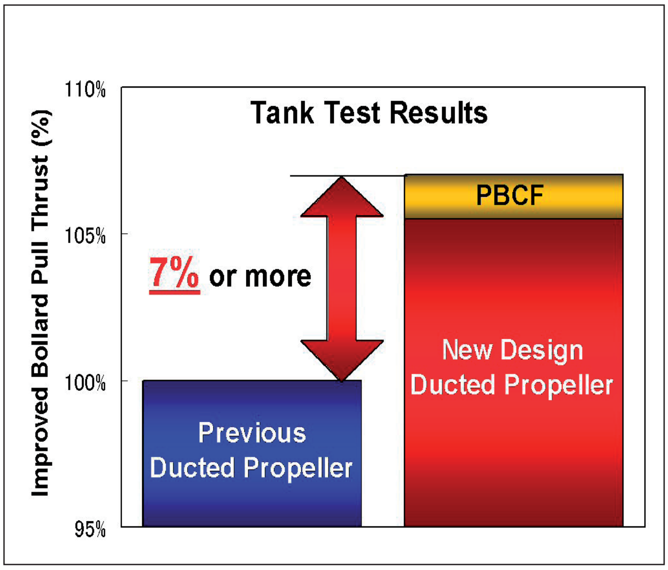


Figure 18: Bollard pull prognosis from study.

FIELD TESTS

We also performed field tests to evaluate the validity of new ducted propeller design method and model tests. The field test was carried out in Batam, Indonesia in June 2008. This bollard pull test was carried out for tugboats, each equipped with Z-Pellers applying the new ducted propellers and PBCFs.

Figure 19 is a photograph of newly designed ducted propeller at full-scale dimension.

Figures 20 and 21 are the first vessel equipped with new ducted propeller and a shot of the bollard pull test.

Figure 19: New design ducted propeller at full-scale.

Figure 20: First vessel equipped with new designed ducted propeller.

Figure 21: Scene of a field test.

It was necessary to perform corrections that took account of the test environment (wind, tide, water depth, fuel property, etc) to derive a reasonably accurate value for bollard pull. As a result of a detailed analysis, the bollard pull thrust at the design point in the ahead pull condition was more than 82 tonnes. We obtained gratifying results and had surpassed our original goal.

CONCLUSION

- To achieve the bollard pull performance target, we designed a new ducted propeller based on theoretical calculation and computational fluid dynamics, then evaluated the new design method through field tests;

- To optimise the nozzle shape for higher bollard pull performance, we performed a parametric study based on theoretical calculation and CFD. The performance improvement of the nozzle alone was confirmed compared to the conventional 19A type;

- To increase ducted propeller performance, we investigated tip-loaded pitch propellers. With such propellers, the negative pressure at the nozzle fore part increased with a larger induced velocity. The resulting efficiency was greater than with conventional ducted propellers;

- Using CFD, we also investigated the arrangement and clearance between the propeller and nozzle, finding that efficiency declined when the propeller tip was located behind the straight section inside the nozzle. We also found that positioning the propeller tip forward would maximize propeller efficiency;

- We found that the relative positions of the propeller tip and the straight section inside the nozzle served as indicators for the ducted propeller design;

- We confirmed the effectiveness of PBCFs in bollard pull performance for a ducted propeller;

- To evaluate the validity of the new design method for the new ducted propellers, we performed field tests. The bollard pull thrust reached was 82 tonnes. This showed approximately an 8 per cent improvement from the existing model. This result surpassed the design target of 80 tonnes and finally led to the commercial introduction of the new Z-Peller model;

- This improvement of thrust per unit output power leads to fuel consumption reduction and helps to cut CO^2 generation.

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