A Development of a Propeller with Backward Tip Raked Fin

Yasuhiko Inukai

Japan Marine United Cooperation, Tokyo, Japan

ABSTRACT
This paper introduces the new concept of a propeller with backward tip raked fin. While we investigated the hydrodynamic characteristics of tip raked propeller, we found a remarkable effect by bending the blade in the tip region toward the pressure side, which can moderate the negative pressure on the suction side. This makes it possible to reduce a propeller blade area without a sacrifice of cavitation performance and improve the efficiency as a result. We designed a propeller with backward rake, i.e. bending the tip toward pressure side, for a container vessel. Propeller open water tests, cavitation observation and pressure fluctuation measurement have been carried out and the significantly higher efficiency compared with the conventional propeller was verified.

Keywords
Energy saving device, Tip raked propeller, Efficiency

1 INTRODUCTION
In order to reduce fuel oil consumption and greenhouse gases from ships, great efforts have been continuously made by a lot of researchers and accordingly many kind of energy saving devices and solutions have been developed. A tip raked propeller (TRP), on which we focus here, is one of such technologies pursuing higher propulsive efficiency. The concept of TRP comes from an analogy of a winglet fitted to an airplane wing, (e.g., Cone 1962), and applied to marine propeller by several researchers (Kappel & Andersen 2005, Suzuki 2002, Yamasaki 2005). Most successful example of TRP is "KAPPEL Propeller" developed by Kappel and Andersen (2005). KAPPEL propeller has the tip smoothly bended toward suction side and the higher efficiency compared with the conventional propeller has been confirmed by model and full scale tests. However, in spite of this superior performance, TRP has not been widespread over the world so far. One of the reasons is presumably the complexity on the geometry and on the design methodology. The author tried to design several TRPs in the past but didn"t success well for the lack of comprehensive understanding for TRP. To attain efficiency gain by TRP surely, it is essential to investigate its characteristics further and understand them deeper. This is our motivation of the study in the beginning.

We started with the study on a tip bended plate as a simplest example ofTRP. And then we investigated the optimum load distribution of TRP and its potential efficiency gain. Through these studies, we found that negative pressure area on the blade can be significantly reduced when bending the tip toward pressure side. Consequently, we came up with a concept of a propeller with backward tip raked fin (i.e. bending toward pressure side), which realizes reducing blade area without a sacrifice of cavitation performance, instead of applying forward tip rake like KAPPEL propeller. We carefully designed the propeller with backward tip raked fin (BTRP) for a container vessel and then propeller open water tests, cavitation observation and pressure fluctuation measurement were carried out. Accordingly 2.6% higher efficiency compared with the conventional propeller was verified and the better performance in wake field has been also verified.

This paper introduces the new concept of a propeller with backward tip raked fin and presents the results of the above calculation and model tests.

2 PLATE with BENDED TIP
At first, we studied the characteristics of a plate with bended tip at a right angle as a simplest example ofTRP. We calculated 4 plates shown in Figure 1 by vortex lattice method. Attack angles were changed from 1 degree to 12 degree. The drag coefficient was taken into account by equation (1), which was also used in the calculation of optimum load distribution and open water characteristic described later.

$$C_D = 0.01+0.03*(C_L-0.2) \quad \text{at } C_L > 0.2$$
$$= 0.01 \quad \text{at } C_L < 0.2 \quad (1)$$

Where, C_D = drag coefficient; C_L = lift coefficient

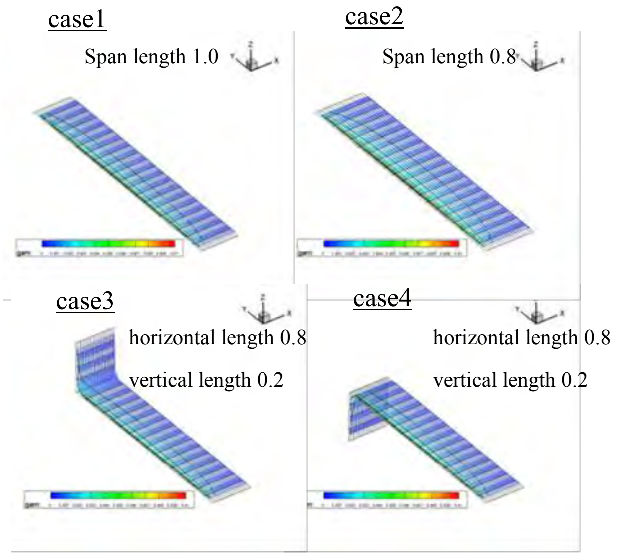

Figure 1: Calculated plates, case1; flat plate (total span length 1.0), case2; flat plate (total span length 0.8), case3; plate bending toward suction side (span length of horizontal part 0.8, span length of vertical part 0.2), case4; plate bending toward pressure side (span length of horizontal part 0.8, span length of vertical part 0.2)

The followings were found as the basic characteristics of a bended plate.

(1) The Figure 2 shows the lift and drag coefficient without considering viscosity. Regardless of the direction of bending tip (case3 and case4), lift coefficient increases and induced drag decreases compared with the plate of case2, which has the same horizontal span length, at the same attack angle. As shown in Figure 3, the circulations of the case3 and case4 are kept higher to the tip and these slopes of the circulation gets gentler at the tip. The former makes the lift coefficient larger and the latter makes the induced drag lower. It can be said these are fundamental benefits of bending tip. Note that the relation of lift and drag coefficient of bended plates is same with the plate of case 1 which has same total span length.

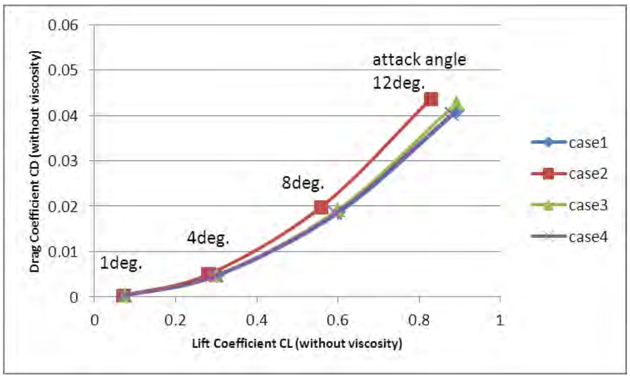

Figure 2: Calculated lift and drag coefficient without viscosity

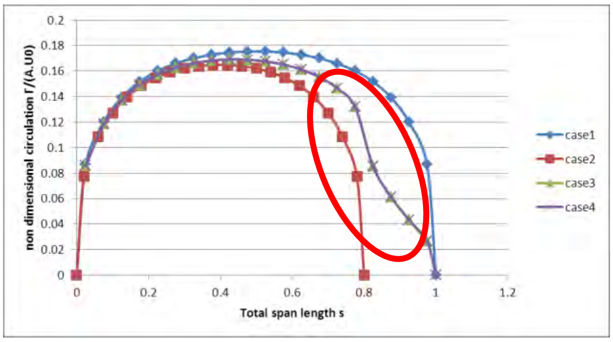

Figure 3: Span-wise circulation distribution

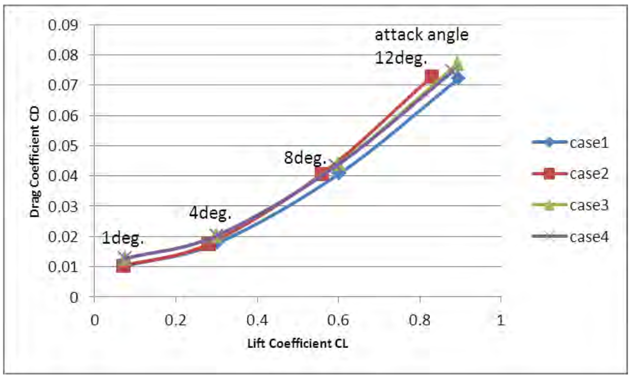

Figure 4: Calculated lift and drag coefficient with viscosity

(2) When considering the effect of the viscosity, the lift-drag ratio of case 3 and case4 cannot be improved compared with case 2 at low lift coefficient below 0.8(See Figure 4). The vertical part doesn't contribute to the lift and causes the drag increase. So, the viscous drag cancels the benefit mentioned in (1) unless the tip geometry was adequately designed.

(3) Regardless of the direction of bending tip, the circulation distributions of the plates agree completely each other and the lift-drag coefficient are almost same (See Figure 2 to 4). However, the pressure distributions of both cases are significantly different as shown in Figure 5 because the direction of the induced velocity at the tip is opposite (See Figure 6). When bending tip toward pressure side like case 4, the flow around the tip is decelerated due to the induced velocity. Accordingly the negative pressure area on the suction side at the vertical part of case 4 almost disappears.

This change of the pressure field by bending the tip toward pressure side becomes the key feature for design of BTRP as described later.

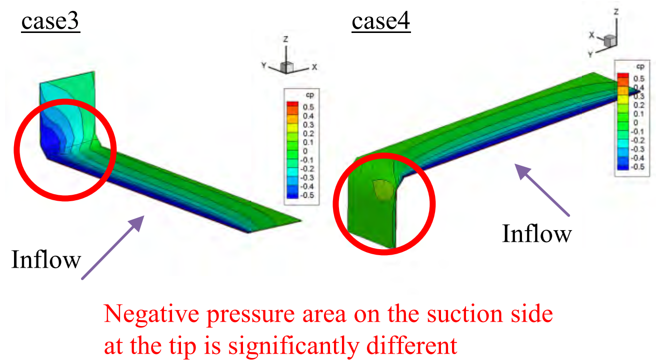

Figure 5: Pressure distribution on the suction side of case 3 and case 4 at attack angle of 12 degree

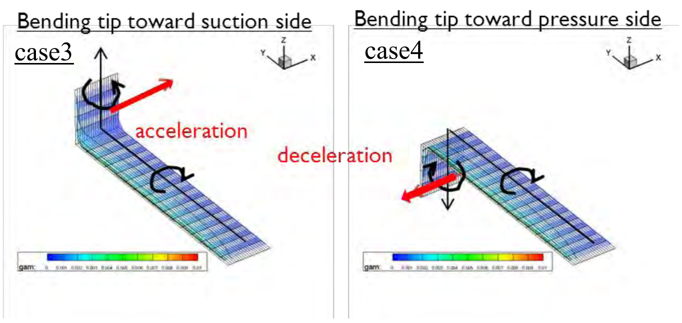

Figure 6: Direction of induced velocity at the tip of case 3 and 4

3 OPTIMUM LOAD DISTRIBUTION of TIP RAKED PROPELLER

Next, we investigated an optimum load distribution of tip raked propeller and considered its potential efficiency gain from a comparison with a conventional propeller without rake.

3.1 Calculation Method

Optimum radial load distribution, which enables the propeller to minimize the power with the required thrust, was calculated based on the vortex lattice method by reference to Olsen (2001) under the following assumption.

-The grids of the propellers and trailing wake sheets are aligned with the onset flow and the grid is not changed during the calculations.

-The profile drag is taken into account by equation (1).

-The chord-wise discretization of circulation density is equidistant.

-The inflow is homogeneous.

The attained optimum load distributions of conventional propellers, i.e. propeller without rake, agree well with those derived from Morgan‟s method (Eckhard & Morgan 1955) as shown in Figure 7. And Figure 8 shows an example of a comparison of the optimum load distribution between TRP and conventional propeller. It is found that TRP has lower peak of maximum circulation and gentle slope at the tip as pointed out by Andersen (2005).

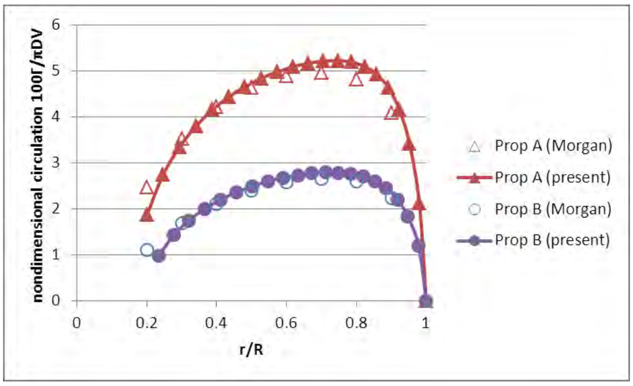

Figure 7: Comparison of optimum load distribution between the present method (Lines) and Morgan's method(dots)

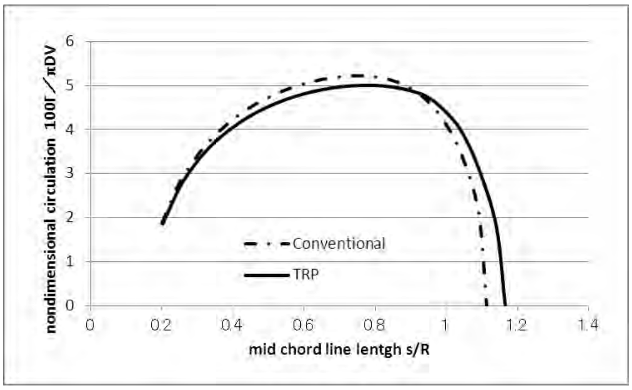

Figure 8: Comparison of optimum load distribution between the tip raked propeller (solid line) and conventional propeller (dotted line)

3.2 Parametric Study

An efficiency of a tip raked propeller was calculated with changing rake distributions parametrically as shown in Figure 9. The other configurations else rake distribution are kept same for simplicity.

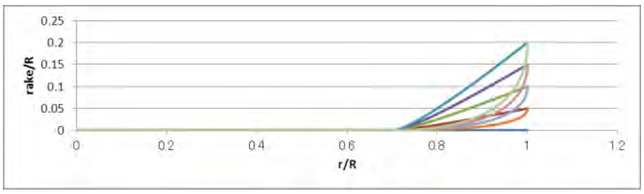

Figure 9: Varied rake distribution in the parametric study

Table 1 shows the results of calculated efficiency gain compared with no raked propeller designed for several kinds of vessels. Although the efficiency gains are 2-3% without consideration of viscosity, those reduced to 0-1% when taking into account viscosity. Especially propellers with low loading factor C_T like container vessel and ferry have no efficiency gain. These figures on efficiency gain are smaller than 2-5% gain of KAPPEL propeller claimed by Andersen (2005). The followings are presumable as the reasons.

(1) The flow field applied in optimization is different, wake field for KAPPEL propeller instead of homogeneous flow this time. Further, the claimed gain of KAPPEL propeller is not open water efficiency but propulsion efficiency including change of self-propulsion factors.

(2) The optimum propeller rotating speed of TRP propeller may differ from the conventional propeller, although the optimizations for both TRP and conventional propellers were carried out under the same rotating speed here.

Although we concentrated the improvement in open waterin the present study, the optimization must be expanded in wake field and the optimum propeller speed should be considered in near future.

Table 1: Efficiency gains of TRP compared with the conventional propeller, BTRP is backward tip raked propeller and FTRP is forward tip raked propeller

Kind of Vessel	VLCC	Bulk Carrier	Container	Ferry
Number of Blades	5	4	6	4
J	0.463	0.436	0.662	0.885
CT	2.615	2.355	1.081	0.576
Expanded Area Ratio	0.5	0.5026	1	0.58
Pitch Ratio at 0.7R	0.8	0.7138	0.9457	1.2
Boss Ratio	0.1602	0.1492	0.2011	0.263
BTRP (w/o vis.)	1.8%	2.1%	1.5%	1.8%
(with vis.)	0.3%	0.4%	0.0%	0.1%
FTRP (w/o vis.)	3.2%	3.4%	2.1%	2.2%
(with vis.)	0.7%	0.6%	-0.3%	-0.1%

4 CONCEPT OF BTRP

Thinking over how to improve efficiency surely by bending tip for all kind of propeller, we finally came up with a concept of a propeller with backward tip rake (BTRP). If pressure distribution on a blade can be improved when bending tip toward pressure side as mentioned at section 2, it is possible to reduce blade area without sacrifice of cavitation and improve efficiency as a result.

Based on this idea, a series of propellers were designed for a container vessel and their pressure distributions on the blades were calculated by a panel method "SQCM" developed by Ando (1995). The calculations were made for propellers working in homogeneous flow. Figure 10 shows a series of the calculated pressure distributions on the suction side. When decreasing blade area in 10% (propeller B), the negative pressure area increases naturally compared with the based propeller A. Then the tip of propeller B was bended toward pressure side without change of any other configurations (propeller C). The negative pressure area of propeller C decreases dramatically as intended. The reason is thought to be the same as mentioned for a bended plate at section 2. However, at this time the pressure distribution along the leading edge doesn't change in continuity and minimum pressure area appears at the mid chord (See Figure 11). It is forecasted that it causes too weak tip vortex, which leads to an unstable cavitation. To eliminate the unfavorable pressure distribution, nose-tail inclination (NTI) illustrated in Figure 12, which is used for KAPPEL propeller, was applied. For a conventional propeller the angle of incidence of the individual blade sections is described only by the pitch angle.

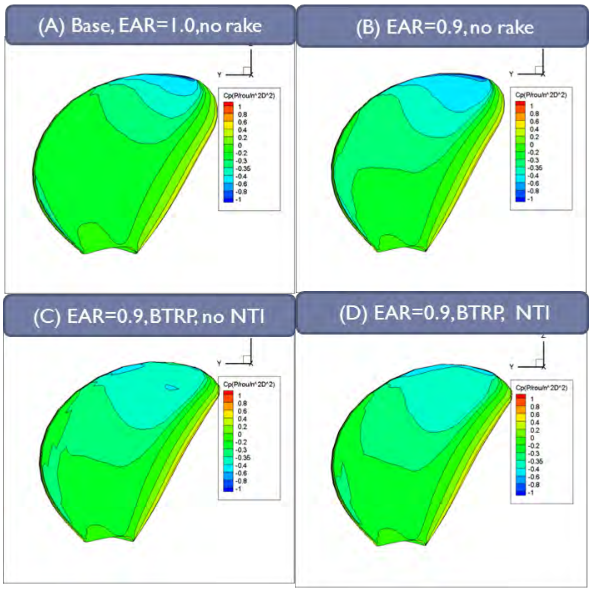

Figure 10: Calculated pressure distribution on the suction side of (A) original propeller, (B) propeller with 10% smaller blade compared with (A), (C) propeller applied backward tip raked to (B) and (D) propeller applied nose-tail inclination (NTI) to (C)

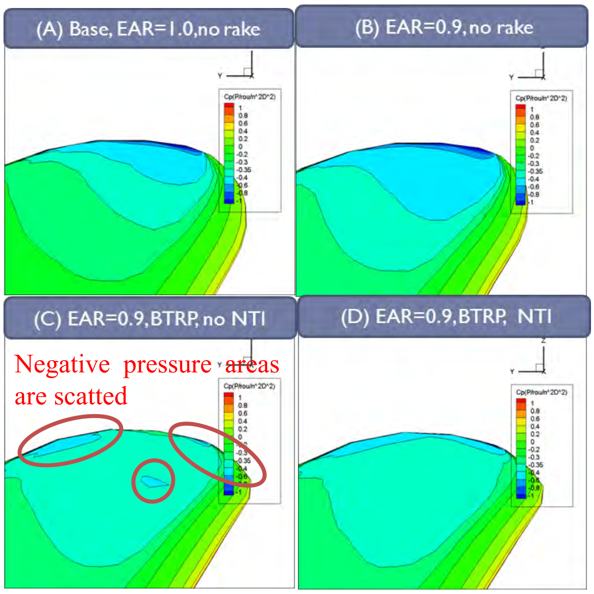

Figure 11: Closed look along the leading edge of pressure distribution in Figure 10

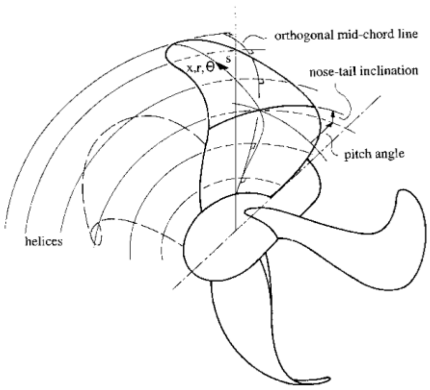

Figure 12: Geometry of the KAPPEL propeller (Andersen et al 2005)

On the other hand, for a tip raked propeller the radial flow influences the attack angle of the blade at the tip very much. In order to have an appropriate attack angle, it‟s necessary to apply a special definition of geometry like NTI, which enable the blade to incline with respect to cylindrical coordinates. The NTI was applied for propeller D whereas the other configurations were identical to the propeller C. It is found that the pressure distribution of the propeller D around the leading edge at the tip becomes more smoothly. Accordingly the negative pressure area of propeller D can be reduced in spite of 10% smaller blade area compared with propeller A, which leads better efficiency as described at next section.

5 DESIGN of BTRP and MODEL TESTS

We designed a BTRP for a 6,500 TEU container vessel. The principal dimension of the BTRP and conventional propeller are tabulated in Table 2. The designed BTRP was not only reduced blade area but also changed the other configurations (pitch, chamber and blade width etc) to get optimum circulation in homogeneous flow. As a result, 2.8% efficiency gain was expected by calculation. About half of the gain is due to reduction of blade area and the other half is due to the optimization of the geometry with use of the benefit of improved pressure distribution. In order to verify the performance, propeller models of the original and BTRP, of which diameter were 250mm, were manufactured and open water tests, cavitation observation and pressure fluctuation measurement were carried out.

Table 2: Dimensions of designed propellers (BTRP and Based conventional propeller)

	Base	TRP
Diameter (mm)	250	250
Number of Blade	6	6
Pitch Ratio at 0.7R	0.9457	0.9261
Expanded Area Ratio	1	0.9
Boss Ratio	0.2011	0.2011
Rake	None	Backward Rake
J	0.662	
CT	1.081	

Figure 13: Picture of the model of BTRP

5.1 Open Water Tests

Open water tests were carried out at IHI towing tank at Reynolds number of 6×10^5. Figure 14 shows the results of both propellers. 2.6% efficiency gain at design point was verified from the experiments.

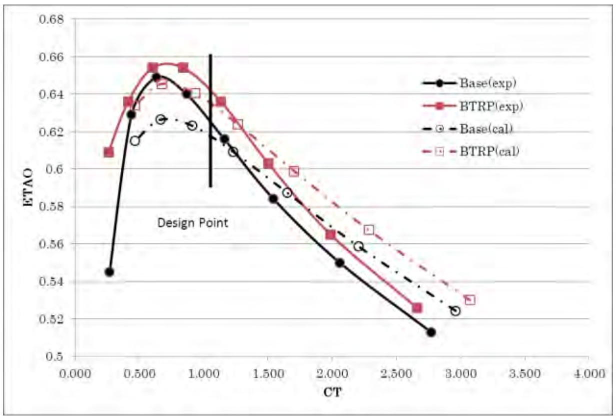

Figure 14: Comparison of efficiencies of BTRP and conventional propeller, experiment results are shown with solid line and calculation results are shown with dotted line

5.2 Cavitation Observation

Cavitation tests were carried out at IHI cavitation tunnel. Figure 15 shows the cavitation patterns of both propellers. The cavitation areas of both propellers are similar and no harmful cavitation was observed. Figure 16 shows the tip vortex sheds smoothly from the tip.

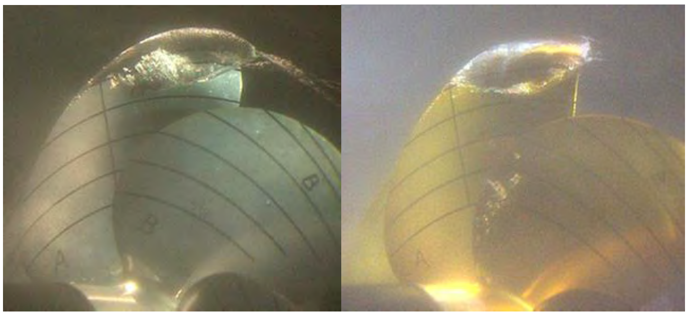

Figure 15: Comparison of cavitation pattern of BTRP (right) and conventional propeller (left)

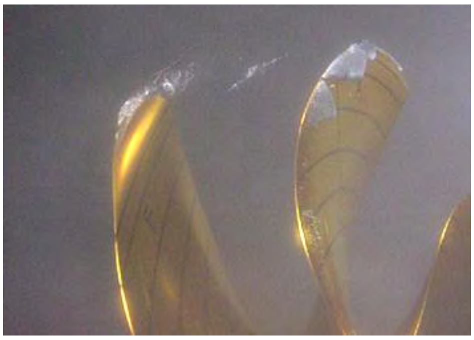

Figure 16: Picture of tip vortex of BTRP

5.3 Pressure Fluctuation

Figure 17 shows amplitude distribution of pressure fluctuation. Both 1st and 2nd blade frequency component are reduced compared with the conventional propeller.

Especially pressure fluctuation of 2nd blade frequency component was down by half. It can be implicated that the pressure distribution of BTRP is improved thanks to bending tip toward the pressure side.

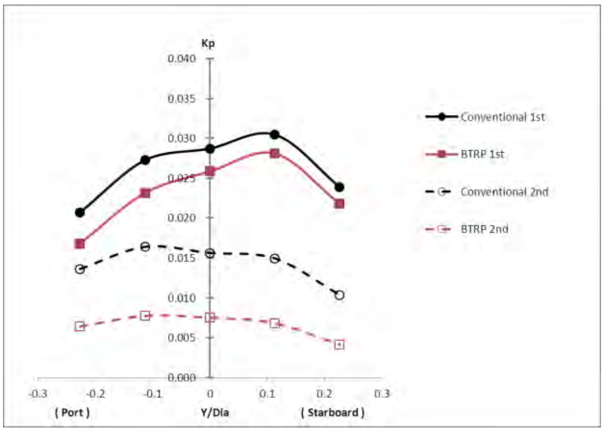

Figure 17: Comparison of pressure fluctuation of BTRP and conventional propeller, 1st blade frequency component are shown with solid line and 2nd blade frequency component are shown with dotted line

6 CONCLUSION

A propeller with backward tip raked fin (BTRP) has been developed in order to improve propeller efficiency. It is found that the negative pressure area on the blade can be significantly reduced when bending the tip toward pressure side. This realizes blade area smaller without a sacrifice of cavitation performance and consequently leads to higher efficiency. The model propeller of BTRP designed for a container vessel was manufactured and 2.6% higher efficiency compared with the conventional propeller was verified by model tests. Further, it is also confirmed that the pressure fluctuation of BTRP was reduced significantly.

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