A Study on Seven-bladed Propeller for High-speed Ships by CFD

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ABSTRACT

Japan's National Maritime Research Institute (referred to as NMRI) et al. developed propeller design charts for determining propeller particulars, known as the MAU series, which are frequently used for commercial ships. Figures 1 and 2 show the MAU series propeller profile and design chart. Subsequently, advanced propeller design charts based on the MAU series were developed by model tests and CFD using innovative propellers, emphasizing blade section, propeller profile, blade area, etc. Yamasaki *et al.* (2013), for instance, developed propellers with minimized blade area (Fig. 3)[5)6)] and Okazaki *et al.* (2019) developed propellers with backward tip rake (Fig. 4)[7)]. Designing propellers with design charts will have a maximum blade count of 6 blades, due to the unavailability of design charts for 7-bladed propellers. However, a 7-bladed propeller might be advantageous when the propeller diameter is severely constrained, such as on a roll-on/roll-off ship (referred to as ro-ro ship). In this research, the authors developed 7-bladed propeller design charts by conducting model experiments, which were then used to design the propellers for high-speed merchant vessels. CFD calculations were carried out to compare the performance of the propellers with different numbers of blades, and it was found that the 7-bladed propeller was superior in terms of efficiency, cavitation performance, and risk of hull vibration when there is a substantial limitation on the propeller diameter.

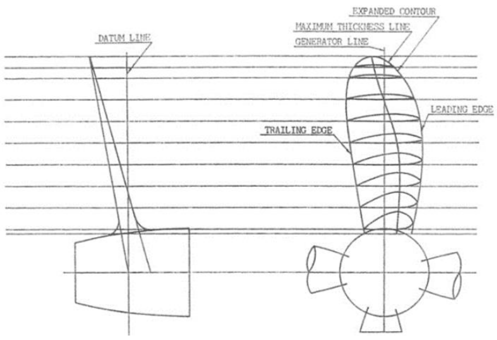


Figure 1. MAU series propeller[2)]

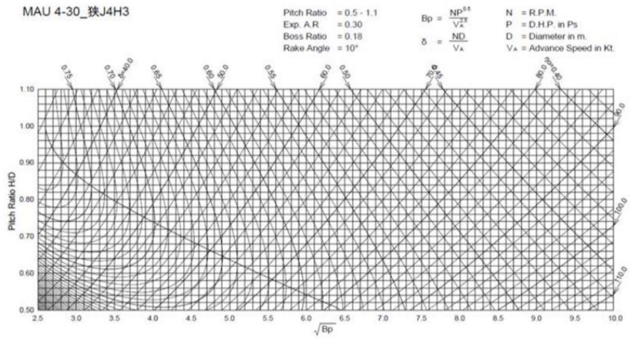


Figure 2. Propeller Design chart of MAU series[2)]

Figure 3. Minimized blade area propeller (right side) [5)6)]

Figure 4. Backward tip rake propeller[7)]

Keywords: Seven-bladed propeller; Propeller design chart; Propeller open water characteristics; CFD

NOMENCLATURE

ρ	Fluid density [kg m^{-3}]
V_A	Propeller advanced speed [m s^{-1}]
n	Propeller rotational speed [rps]
D	Propeller diameter [m]
T	Propeller thrust [N]
Q	Propeller torque [N m]
J	Propeller advanced ratio [-]
K_T	Thrust coefficient [-]
K_Q	Torque coefficient [-]
η_O	Propeller open-water efficiency [-]
$C_{0.7R}$	Propeller chord length at 0.7 radius from the propeller axis [m]
ν	Kinematic viscosity [m^2 s^{-1}]
R_{NK}	Kempf's definition of Reynlods number [-]
F_S	Surface Force [kPa]
CFD	Computational Fluid Dynamics
TEU	Twenty-foot Equivalent Unit

1. INTRODUCTION

In recent years, it has become common practice to reduce both the ship's speed and the propeller's rotational speed in an effort to reduce fuel oil consumption. As a result, the design specifications and constraints of the propeller have changed drastically. By altering propeller design conditions, for instance, the optimal diameter would increase. In general, propeller designers must consider not only the efficiency of propellers in open water but also cavitation performance, including surface force, which is the fluctuation in pressure amplitude on the hull bottom near the propeller that also causes hull vibration. If the propeller's diameter is increased, the clearance between the propeller tip and the hull's surface will narrow, resulting in an increase in surface force. Consequently, unwanted hull vibration could occur. In this situation, increasing the number of blades may be advantageous, as increasing the blade count will reduce the optimal diameter of the propeller. When designing a propeller, the blade count must be selected from a range of options, most commonly starting from 3-blade up to 6-blade charts. Especially in the case of a ro-ro ship, the propeller diameter limitation for maintaining adequate clearance is frequently too small compared to the optimal diameter. Therefore, propeller designers occasionally require a design chart with more blade numbers. In light of this, model experiments were conducted to determine the propeller characteristics (J (1), K_T (2), K_Q (3), and η_O (4)) of 7-bladed propellers, and design charts for 7-bladed propellers were developed. In addition, a 7-bladed propeller was designed for a 5000 TEUs container ship and a ro-ro ship using the newly developed chart. In addition, CFD calculations were carried out to compare the propeller efficiency and cavitation performance of 6-bladed and 7-bladed propellers for ro-ro ships.

$$J = \frac{V_A}{nD}, \tag{1}$$

$$K_T = \frac{T}{\rho n^2 D^4}, \tag{2}$$

$$K_Q = \frac{Q}{\rho n^2 D^5}, \tag{3}$$

$$\eta_O = \frac{K_T J}{K_Q 2\pi}, \tag{4}$$

2. DESIGN CHARTS DEVELOPMENT OF SEVEN BLADED PROPELLER

2.1 Basic Propeller Design Charts

During the initial design phase, the optimal diameter of the propeller was determined by using propeller design charts. In Japan, the MAU series is widely used and is known for its extensive range of propeller particulars and advance coefficient J, having developed upon numerous model experiments with 3, 4, 5, and 6-bladed model propellers (see Table 1). Consequently, MAU series design charts are very beneficial for determining propeller main particulars. On the other hand, Yamasaki *et al.* (2018) developed new design charts using laminar flow blade sections (referred to as the N-series). The N-series blade section has a contemporary shape, making it a more effective chart for the later stage of design. The N-series design charts were developed by conducting model experiments and CFD calculations while keeping the Kempf's definition of Reynolds number (referred to as R_{NK}, defined as in Equation 5) constant to 6.0x10^5 to exclude any effects due to a change in Reynolds number. In addition, the optimal diameter of the N-series is slightly bigger in comparison to the MAU series.

$$R_{\mathrm{NK}} = \frac{C_{0.7R}\sqrt{{V_A}^2 + (0.7\pi D)^2}}{\nu}, \tag{5}$$

Table 1. Chart range of MAU series

Number of blades	3	4	5	6
Expanded area ratio	0.30, 0.50	0.40, 0.55, 0.60	0.50, 0.65, 0.80	0.55, 0.70, 0.85
Pitch ratio	0.4～1.2	0.5～1.6	0.4～1.6	0.5～1.5
Boss ratio	0.18			
J	0.0～1.0			

2.2 Development of Propeller Design Charts for 7-bladed Propellers

As previously stated, it is common to have the optimal propeller diameter bigger than the maximum allowable diameter when designing propellers for high-speed ships, such as ro-ro ships. By designing a propeller with more blade count, a smaller optimal diameter will be available, thus higher performance can be expected. In order to develop propeller design charts with more blade counts, the authors conducted model tests using 7-bladed propellers. The range of model experiments conducted is outlined in Table 2, and the model propeller is shown in Figure 5. These model experiments were conducted at AKISHIMA LABORATORIES INC. The towing tank was used for propeller open water testing, and Figure 6 shows the equipment used to measure the open water characteristics of the propellers. R_{NK} was kept constant to 6.0x10^5 for the exclusion of Reynolds effect in the model test. Using all of the K_T and K_Q measurement results, a multiple regression analysis was conducted to develop the propeller design charts.

Table 2. Chart range of 7-bladed propeller

Number of blades	7
Expanded area ratio	0.49,　0.60,　0.75,　0.90
Pitch ratio	0.7～1.3
J	0.0～1.0

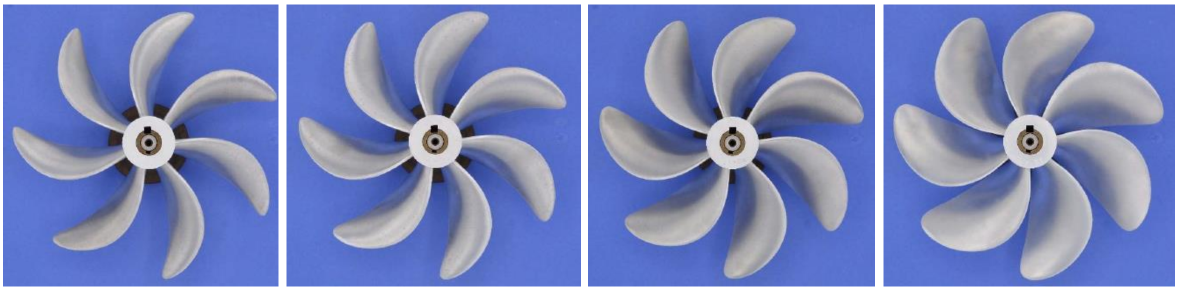


Figure 5. 7-bladed propeller series for model test

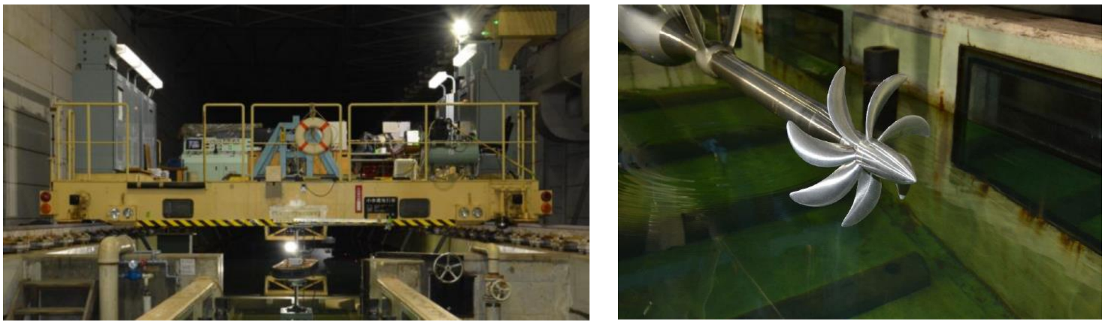


Figure 6. Measurement equipment for propeller open characteristics[8]

2.3 Trend of Performance and Particulars for Different Number of Blades

First, the propeller for a 5000 TEUs container ship was designed to investigate the propeller particulars and efficiency for each number of blades. According to the propeller design conditions, the maximum surface force should be no more than 4.2 kPa, with no limitation on the propeller diameter and skew angle. The results of the calculations for propeller particulars and performance for each number of blades are displayed in Table 3. The open-water propeller efficiency was calculated using the design chart, while the surface force was estimated with an empirical calculation based on the method by Holden (1979). The optimal diameter, expanded area ratio, and skew angle all decrease as the number of blades increases. In this calculation condition, the 6-bladed propeller's open water efficiency was superior to that of others. Nonetheless, if there is a substantial limitation on propeller diameter, there is a possibility that the diameter of the 6-bladed propeller would have to be reduced. Therefore, the open water propeller efficiency of the 6-bladed propeller would decrease, making the 7-bladed propeller advantageous. Additionally, in the case of 7-bladed propellers, the skew angle can be kept to a minimum, allowing thinner blade thickness due to less stress on the blades. This allows the propeller to have reduced material and weight. This investigation suggests that adopting a 7-bladed propeller in an actual project may be advantageous to increase overall efficiency.

Table 3. Propeller particulars and performance for each number of blades

Number of blades	4	5	6	7
Optimum propeller diameter (m)	10.70	10.44	10.11	9.98
Expanded area ratio	0.65	0.66	0.59	0.58
Skew angle (deg.)	37.5	31.7	29.7	26.5
Ship speed (knot)	21.93	22.04	22.10	22.05
η_O	0.802	0.815	0.822	0.817
F_S (kPa)	4.2	4.2	4.2	4.2

3. PROPELLER DESIGN FOR RO-RO SHIP

3.1 Design Condition for 6- and 7-bladed Propellers

As the above calculation suggested the advantageous possibility of adopting a 7-bladed propeller, 6-bladed and 7-bladed propellers were designed for a past ro-ro ship project. For the propeller design conditions, the limitation of propeller diameter was 5.4m, with a maximum surface force of 3.7kPa, and the skew angle was to be adjusted in order to keep the surface force below the maximum value. The expanded area was to be determined by assessing the cavitation pattern. These design conditions are the same conditions used for the actual project.

3.2 Comparison of Propeller Particulars

The calculated propeller particulars are shown in Table 4. The optimum propeller diameter was 5.57m for the 6-bladed propeller and 5.41m for the 7-bladed propeller. Compared to the 6-bladed, the difference between the 5.41m optimal diameter of the 7-bladed and the 5.4m maximum diameter was minimal. By cavitation calculation, the expanded area ratio and skew angle of the 7-bladed propeller were identical to those of the 6-bladed propeller.

Table 4. Comparison of propeller particulars (6- and 7-bladed)

Number of blades	6	7
Propeller diameter (m)	5.40	5.40
Expanded area ratio	0.80	0.80
Skew angle (deg.)	36.0	36.0
For reference Optimum propeller diameter (m)	(5.57)	(5.41)

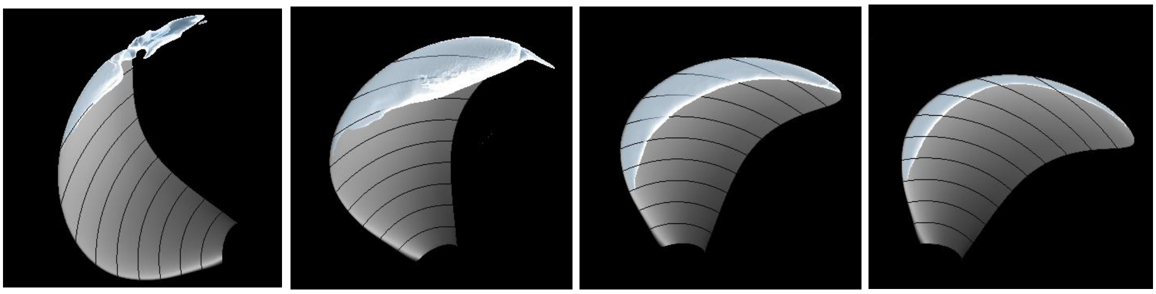
Figure 7. Propeller profile of 6- and 7-bladed for ro-ro ship

3.3 Comparison of Propeller Performance

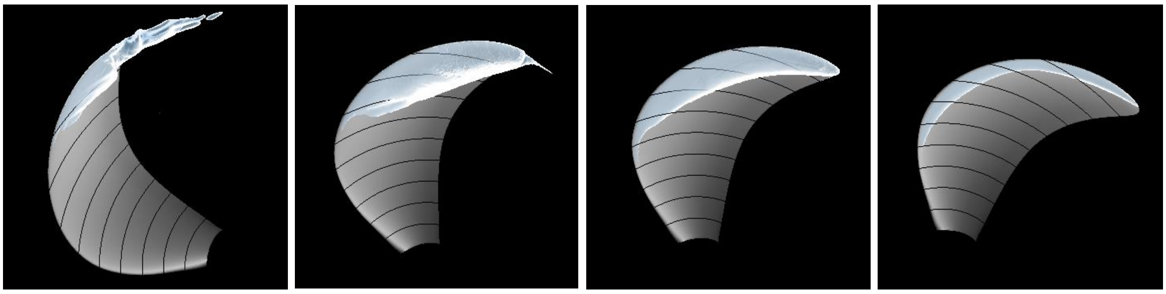
CFD calculations were carried out to compare the open water efficiency, cavitation pattern, and surface force between the 6- and 7-bladed propellers. RANS calculations were performed by using the software CRADLE SCRYU/Tetra[10)] which is a commercial CFD code based on a finite volume method with an unstructured grid. Table 5 shows the comparison of performance for both propellers. The results of this calculation indicate that the 7-bladed propeller's open water efficiency was 0.6% greater than that of the 6-bladed propeller. In addition, there was a difference of 0.02 knots in ship speed. Regarding propulsion performance, the 7-bladed propeller proved to be effective when there was a diameter limitation. Next, Figure 8 displays the results of the CFD cavitation pattern calculation. It was confirmed that the cavitation pattern of the 7-bladed propeller vanished quiet smoothly. On the other hand, the 6-bladed's cavitation disappearance was somewhat unstable. According to these calculations, there was no risk of cavitation erosion for the 7-bladed propeller. Furthermore, despite the fact that the first order blade frequency of surface force was at the same level for both propellers, the second and third order frequencies of 7-bladed propellers were lower than the 6-bladed, confirming a lower risk of hull vibration generation, making the 7-bladed propeller superior to that of the 6-bladed propeller in terms of efficiency, cavitation performance and hull vibration.

Table 5. Comparison of propeller performance by CFD

Number of blades	6	7
Ship speed (knot)	22.41	22.43
η_O	0.670	0.674
1st/2nd/3rd order of F_S (kPa)	3.7 / 1.7 /1.3	3.7 / 1.4 / 0.6



Cavitation observation of 6-bladed propeller by CFD



Cavitation observation of 7-bladed propeller by CFD

Figure 8. Comparison of cavitation pattern by CFD

4. CONCLUSIONS

In this study, the authors develop new design charts for 7-bladed propellers and investigated its viability. Consequently, the following conclusions were drawn:

1) In the case of designing the propeller for the 5000 TEUs container ship, the open water efficiency of a 6-bladed propeller was higher than that of a 7-bladed propeller. Nevertheless, if there was a substantial limitation on propeller diameter, the diameter of the 6-bladed propeller would have to be reduced, thus decreasing its efficiency and rendering a 7-bladed propeller preferable.

2) Next, propellers with 6- and 7 blades were designed for the ro-ro ship project. The 7-bladed propeller was 0.6% more efficient than the 6-bladed propeller. Additionally, there was a difference of 0.02 knots in ship speed.

3) The cavitation that occurred on the 7-bladed propeller vanished quiet smoothly, as opposed to the somewhat unstable cavitation disappearance on the 6-bladed propeller. For the subject ship, CFD calculations confirmed that the 7-bladed propeller had a lower cavitation risk and a smoother cavitation pattern.

4) The surface force of both 6- and 7-bladed propellers was also then calculated with CFD for the subject ro-ro ship. Although the 1st-order blade frequency of surface force was at the same level for both propellers, the second and third order frequencies of 7-bladed propellers were less than those of the 6-bladed, confirming a lower risk of hull vibration generation and superior cavitation performance.

5) The effectiveness of the 7-bladed propeller for ships with a substantial difference between the optimal diameter and the limited diameter, such as ro-ro ships, has been confirmed.

Nakashima Propeller hopes to install the newly developed high-performance 7-bladed propeller on high-speed commercial vessels in the near future.

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