Salah H. Al-Buloushi. International Journal of Engineering Research and Applications
www.ijera.com
ISSN: 2248-9622, Vol. 16, Issue 5, May 2026, pp 18-27

RESEARCH ARTICLE OPEN ACCESS

Advanced Design Optimization of Marine Propellers for Minimizing Cavitation and Improving Efficiency

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ABSTRACT
This paper aims to investigate several designs of the marine propellers to minimize cavitation and improve efficiency. Many design parameters can affect propeller efficiency, produce thrust flow rate, suction pressures, and cavitation occurrence. The most important design parameters are chord length, rake angles and pitch ratio. Different propellers were investigated with different geometry. Efficiency was calculated after measuring the thrust force and torque at certain rotation speed and ship speed using data logger. So, optimum design and propeller geometry was obtained, and simulation was conducted to check the cavitation possibilities with changing in the design parameters. The cavitation had occurred significantly near to the middle part of the blade which leads to pressure decreasing and vapor formation. So, the optimum design has higher chord length, high rake angle, low pitch ratio at the mid blade length to enhance the pressure distribution and reduce cavitation.
Keywords: Propeller optimum design, cavitation, pitch ratio, hull, rake angle, chord length, energy saving in ships, marine fuel consumption, CO2 emission in marine ships

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Date of Submission: 01-05-2026 Date of acceptance: 09-05-2026

I. Introduction

One of the most common transportations is ships. It represents around 3% of greenhouse gas emission [18]. The new regulations restrict the amount of greenhouse gas emissions produced from diesel fuel burning in the marine diesel engines. As the propeller torque decreases, the fuel consumption in diesel engines will be decreased.

A marine propeller is a mechanical device used to change the kinetic energy to axial flow rate to push a vessel through water. It consists of certain numbers of blades installed on the hub, which rotates to create negative pressure at the impeller inlet, suck the water flow rate toward the discharge side, producing axial thrust [5].

Propeller efficiency is affected by many factors such as geometry, pitch, blade length, and material. The propeller components are shown in Figure 1.1. The hub is the central part of the propeller, fixing to the shaft that drives the rotation force from the marine diesel engine. Many researchers studied the possibilities of enhancement of propellers to decrease the water resistance which is produced by cavitation at many regions on the blade airfoil. As shown in Figure 1.2, Several researches were carried out at inlet area of the propeller region (I), to decrease the drag force.

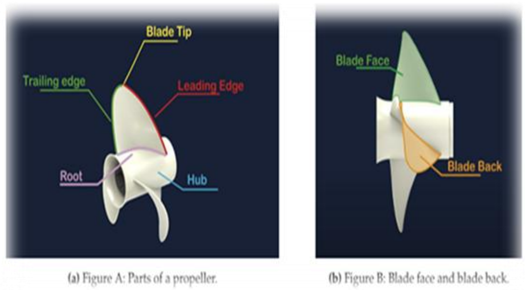


Figure I-1 propeller components

Other researchers studied in region (II) at the blade exit region to overcome the required torque and have higher flow rate to decrease cavitation possibilities.

The most important parameters which affect propeller efficiency such as chord length, skew, rake, and pitch. Changing these parameters influences propeller capacity, fuel consumption, and cavitation. Chord length is the straight line that connect between the leading edge and trailing edge. Skew is the curvature of the blade, and rake is the angle between the blades relative to the central hub; it can assume positive and negative values. Pitch describes the water displacement when propellers move forward in one complete revolution. All these parameters are shown in figure 1.3.

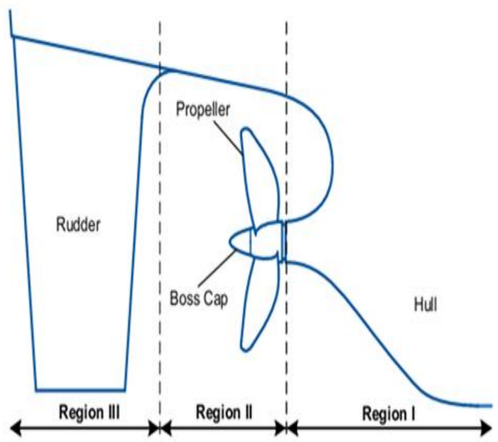


Figure I-2 Suction, discharge, and rudder regions for ship energy saving

On the other hand, propeller boss cap fins are located as guide-vanes at the inlet which used to decrease the flow separation and vortices formed by the propeller rotation. It is used to reduce the required torque and increase efficiency as shown in figure 1.4. Some types of propellers have constant pitch which has constant attack angle while there are other types that have variable (controllable) pitch which can change the load and thrust flow rate according to the required load. Pitch ratio is the ratio of its pitch to its diameter. Higher pitch ratio can reduce cavitation risk by increasing the area exposed to water pressure distribution. However, excessive pitch ratio may cause deficiency.

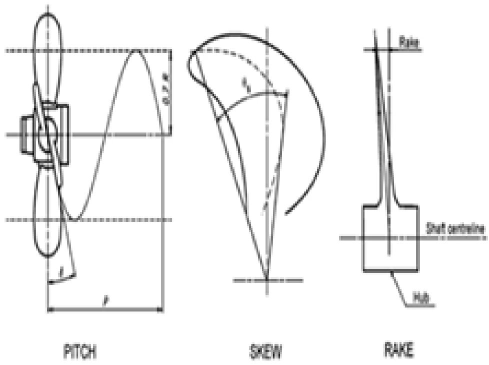


Figure I-3 Geometric parameters of propellers blades; pitch, skew, and rake angle

Cavitation is a phenomenon in fluid dynamics where vapor bubbles are formed in a liquid due to pressure drop below the liquid vapor pressure. When these bubbles collapse due to impact with the propeller or increase the exposed pressure, caused rubbing, noise, and vibration in propellers [6].

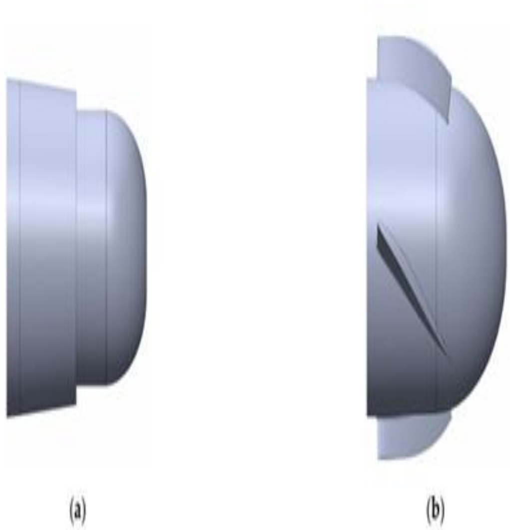


Figure I-4 The original boss cap vs. the new cap with optimized fins

There are many cavitation types on marine propellers as below and as shown in Figure 1.5:

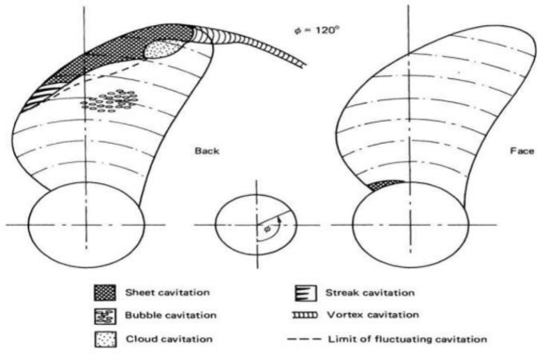


Figure 2.3: Classification of cavitation types [4].

Figure I-5 Cavitation types

1. **Sheet Cavitation**: vapor formed on the blade suction side at the leading edges due to high angle of attack and excessively high flow rate.
2. **Bubble Cavitation**: vapor bubbles formed on the blade surface which cause lower efficiency.
3. **Cloud Cavitation**: vapor bubbles that grow and collapse rapidly which cause strong propeller erosion.
4. **Hub Vortex Cavitation**: vapor formed at the suction eye where vortices developed.

Based on the above, the blade geometries were investigated and both cavitation and efficiency were observed and calculated where different chord length, pitch ratio and rake were investigated.

II. Literature Review

Several studies were carried out to enhance the propeller design and improve efficiency. CHIHARU etal [39] studied the effect of reaction fins and stator fins in the propeller produced torque by CFD modeling. Figure 2.1 showed the flow rate to the propeller with and without reaction fins. The results show that the reaction fins move water in the opposite direction of rotation. The fin-mounting angle can be optimized based on these results.

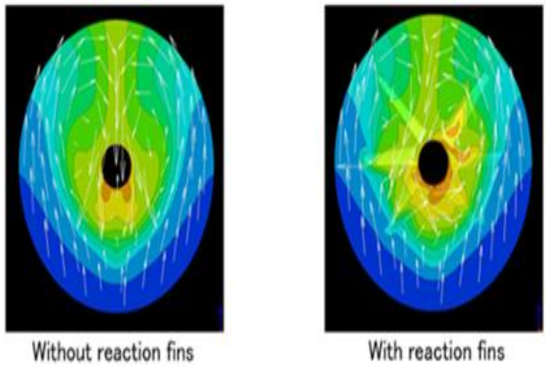


Figure II-1 Flow distribution of the propeller surface with and without reactions fins

Figure 2.2. shows the cavitation possibilities for two different propellers, A and B. For propeller A, sheet cavitation was noticed on the inlet, and face cavitation was observed on the discharge side. Propeller B prevents the occurrence of face cavitation and has a low risk of cavitation erosion where no face nor sheet cavitation. The results were verified by computational fluid dynamics CFD.

On the other hand, stator fins were investigated. Figure 2.3. showed the CFD results for a propeller with installed stator fins. There was a decay in pressure on the suction region of the stator fins and an increase of pressure at the rudder leading edge. So, the risk of cavitation decreased.

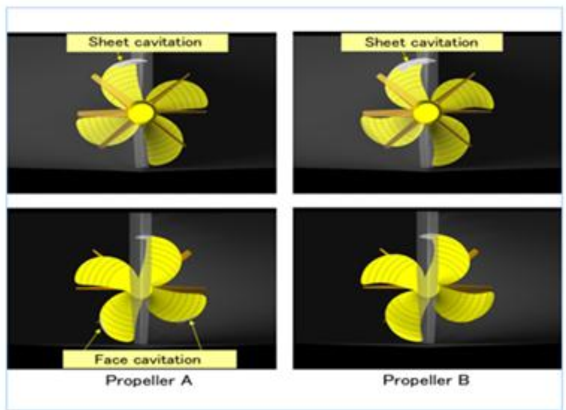


Figure II-2 Comparison of cavitation occurred for propellers A and B

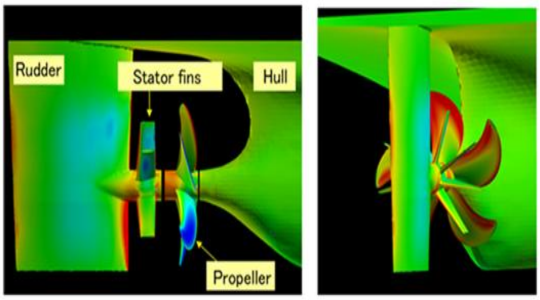


Figure II-3 Pressure distribution around the propeller with installed stator fins

Yin etal [40] studied the effect of inlet guide vanes (boss cap fins BCF) in enhancement of the ship propeller efficiency. The thrust, torque, and efficiency obtained from the experiments were used to validate the CFD model. Different boss cap fins designs were investigated by CFD and the results and experimental data under different test conditions are summarized in Table 2.1. From the results shown in figure 2.4, Yin etal determined the best values of rake, thickness, chord length, and span height according to CFD results.

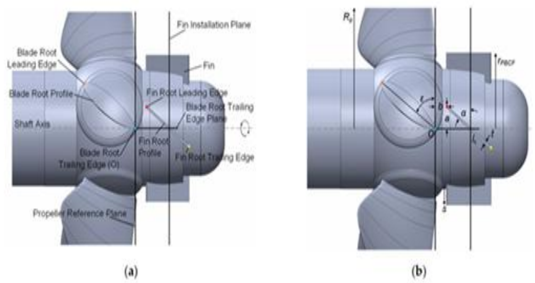


Figure II-4 Propeller with PBCF.
(a) Profile, axes, and points. (b) PBCF sizing and installation parameters

Table II-1 Validation of CFD with testing of the original propeller / rudder system

Ship (or Water Inflow) Speed, V_S [m/s]	2.02	2.08	2.13	2.19	2.25	2.30	2.36	2.42	2.47
Deviation in thrust coef., $\frac{(K_{T,CFD}-K_{T,exp})\times 100}{K_{T,exp}}$ [%]	0.6	0.7	1.0	1.4	1.3	1.5	1.8	1.7	1.9
Deviation in torque coef., $\frac{(K_{Q,CFD}-K_{Q,exp})\times 100}{K_{Q,exp}}$ [%]	1.1	1.2	1.5	1.8	1.8	1.9	2.1	2.1	2.3
Deviation in propeller eff., $\frac{(\eta_{0,CFD}-\eta_{0,exp})\times 100}{\eta_{0,exp}}$ [%]	−0.5	−0.5	−0.5	−0.4	−0.5	−0.4	−0.4	−0.4	−0.3

III. Research Methodology

An experimental investigation will be conducted for different propellers with different parameters followed by instruments that measure the efficiency and simulate the cavitation occurred. The propeller parameters that will be changed and tested are:

- Chord length
- Rake angles
- Pitch ratio

3.1. Select the propellers operating regions

Now, it is required to determine the no. of blades, rotation speed, and rotor diameter according to the required thrust force and ship speed. As shown in figure 3.1, the drag force represents the resistance of the ship motion. The design parameters were selected to be 260 N for the required thrust and 7.2 m/s for the ship speed, the area at the bottom of the curve. This point was selected because it has lower drag with suitable velocity. Consequently, and from figure 3.2, the propeller manufacturer recommends propeller diameter range 0.2− 0.4 m, the range for the number of blades was 2− 4 and the rotation speed was 2000−10000 Revolutions Per Minute (RPM).

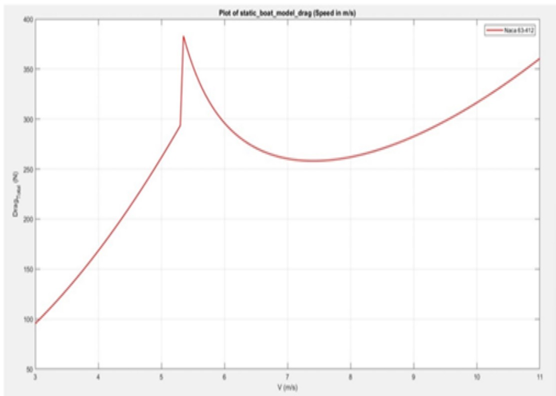


Figure III-1 Drag coefficient vs. vessel speed curve

From figure 3.3, the efficiency curves are shown for diameters greater than 0.36 m. As the diameter increases, there is hydrodynamically instability where assumptions about water flow conditions, attack angle, and cavitation may no longer hold. Thus, the values chosen to begin the study were: number of blades, 2; rotation speed (RPM), 2000; and rotor diameter (m) is 0.2. The propeller 3D drawing is shown in figure 3.4.

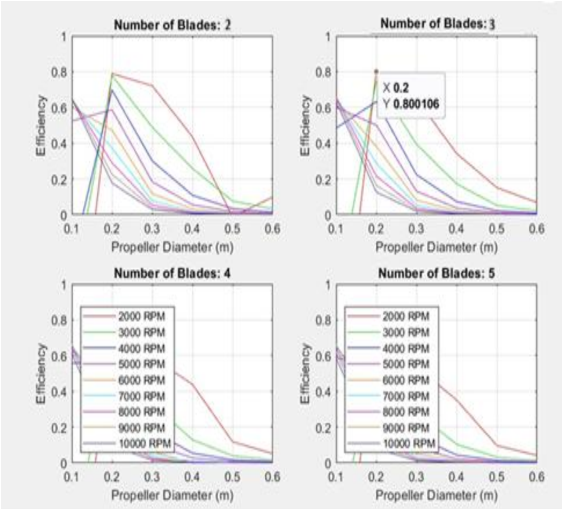


Figure III-2 Parametric analysis of propeller efficiency vs rotational speed for small hub diameter

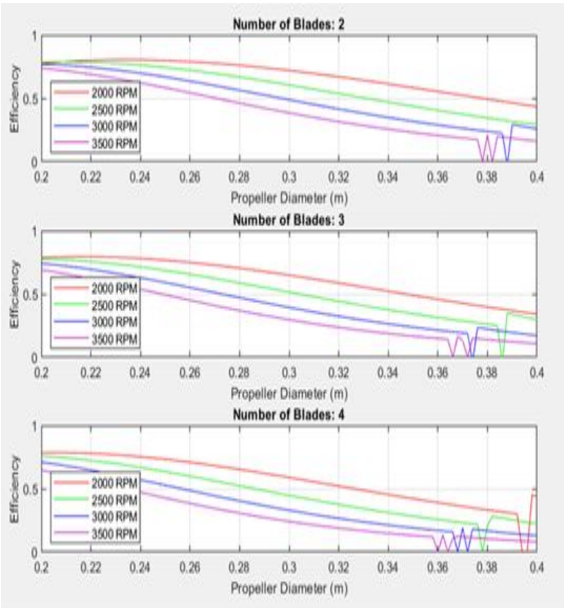


Figure III-3 Parametric analysis of propeller efficiency vs rotational speed for large hub diameter

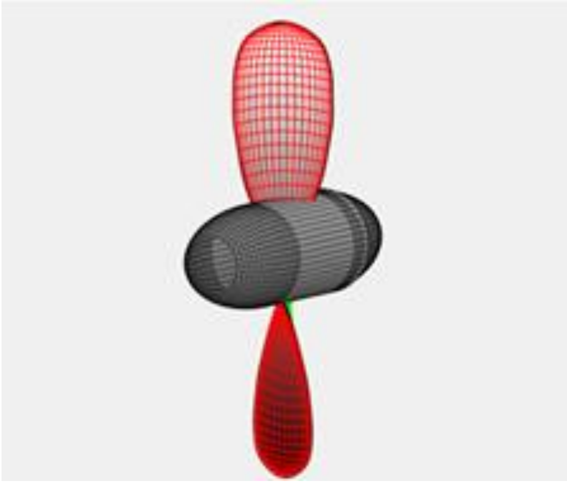


Figure III-4 3D propeller model (original design)

3.2. Instrument used

To measure efficiency, equation 3.1. is used as below:

$$\eta = \frac{Va \quad T}{2\,\pi\, w\, Q} \qquad \text{equation 3.1}$$

Where Va: ship speed (m/sec)

T: Thrust force (N)

W: Rotational speed (RPS)

Q: Produced torque (N.m)

The ship speed was measured by electromagnetic sensor that was installed on the hull which creates a magnetic field and measures the voltage generated by water moving through it. Both torque and thrust force were measured by using a dedicated thrust stand equipped with a load cell.

IV. Results and discussion

4.1. Optimization of Chord length

The first change was the chord length of each blade section. Different chord lengths were investigated, and the efficiency was calculated for each chord length. The optimum chord was found 6.5 cm which increased efficiency by 0.5% as shown in figure 4.1. As the chord length increases, the contact area between the blade and the cut water increases, consequently, the thrust and efficiency increased. However, in excessive chord length, several swirling and flow circulation occurred. It means that the circulating flow consumes power to keep the swirling and no gain power in the thrust directions.

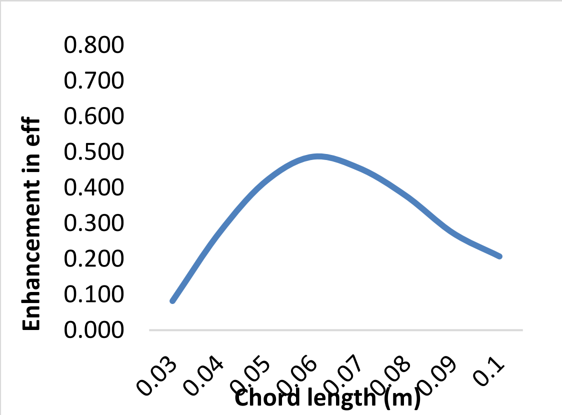


Figure IV-1 Chord length effect on propeller efficiency

4.2. Optimization of Rake angle

The second change was the rake angle which changed from -15° to +15° and the efficiency was calculated for each angle. The optimum rake angle was found 5° which increased efficiency by 0.5% as shown in figure 4.2. Increasing rake angle means increasing the attack angle and more flow rate directing toward thrust or axial direction. However, excessive rake angles cause more swirling and eddies at the propeller inlet and decrease the thrust force and efficiency.

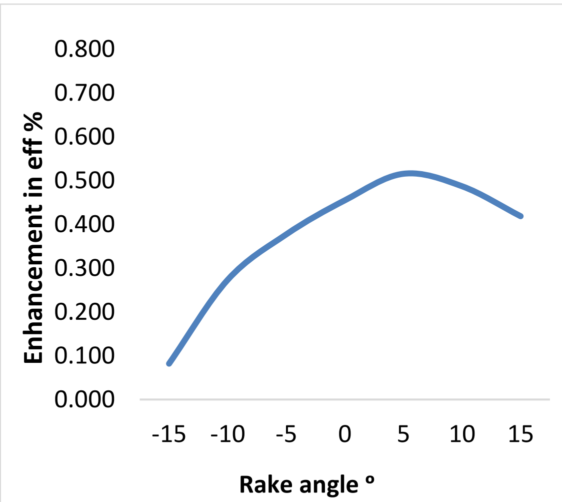


Figure IV-2 rake angle effect on propeller efficiency

4.3. Optimization of Pitch ratio

The third change was the pitch ratio which changed from 0.6 to 1 and the efficiency was calculated for each ratio. The optimum pitch ratio was found 0.6 (the smallest one) which increased the efficiency by 0.45% as shown in figure 4.3. Excessive pitch adjustments may cause efficiency reduction and require balance between thrust production and cavitation.

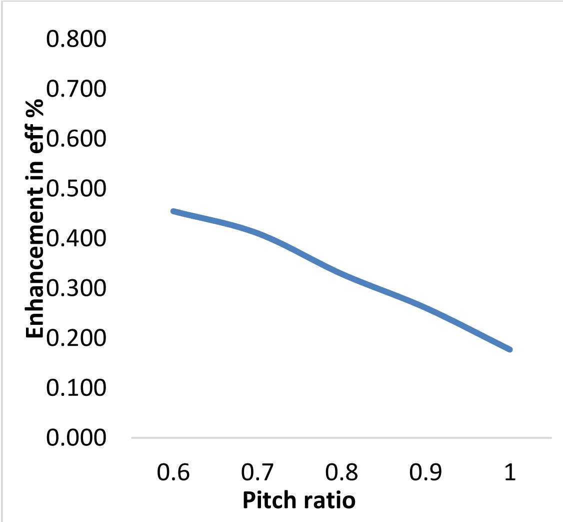
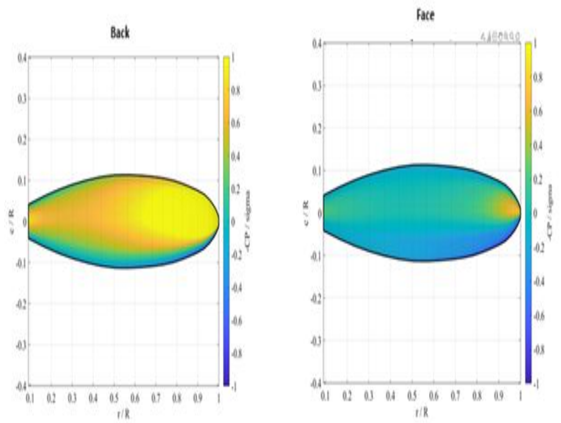


Figure IV-3 pitch ratio effect on propeller efficiency

4.4. Cavitation Study in small chord length and rake angle

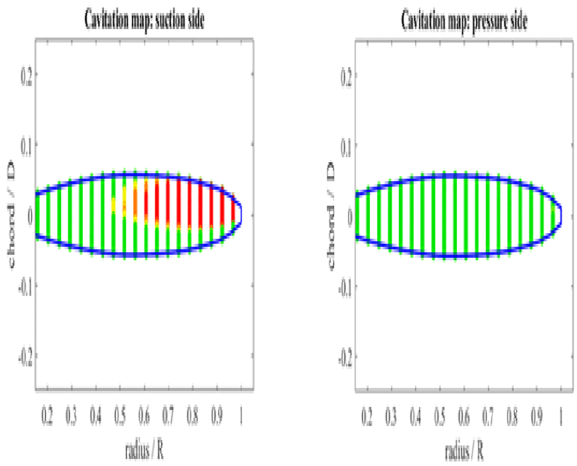
MATLAB program was developed and was used to proceed with the cavitation analysis by formulating the blade profile, suction pressure and discharge pressure. Both Figure 4.4 and Figure 4.5 show the cavitation occurring along the blade at the suction and pressure sides. In the first figure, the x-axis represents the original radial position along the blade, and the y-axis represents the normalized chord length, showing the blade cross-section. The color scale represents σ factor. σ factor is dimensionless parameter, which used as a cavitation indicator at different blade section. Higher σ factor marked in yellow mean close to or below the vapor pressure and higher cavitation risk. Lower values (blue) indicate higher pressure, meaning less cavitation risk.

On the other hand, in figure 4.5, the blade is divided into sections with a different color scheme, and the y-axis represents the original chord length. Green shows areas where cavitation will not occur, whereas red shows areas where cavitation will occur. This is due to the rapid decay in chord at the tip. The blade loses area too quickly at the mid blade length (0.6 L), which causes high pressure gradients, low surface pressures, and cavitation possibilities.



(a) Suction side. (b) Pressure side.

Figure IV-4 Cavitation analysis

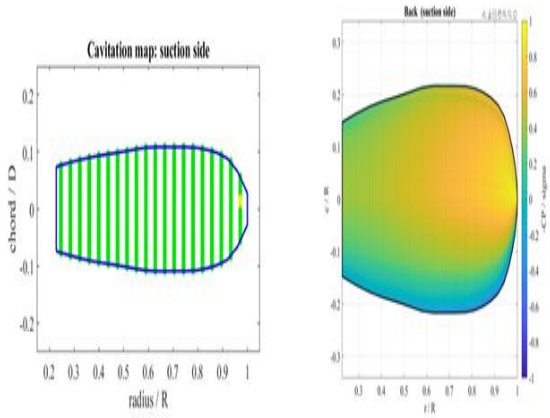


(a) Suction side. (b) Pressure side.

Figure IV-5 Cavitation map

4.5. Cavitation Study with the optimum chord length and rake angle

The optimum chord length, rake angle, and pitch ratio were obtained at sections 4.1, 4.2, and 4.3. Cavitation simulation was checked, and no less cavitation effect was shown in figure 4.6. A more significant chord at mid-span improves load distribution and reduces cavitation. Also, to minimize tip vortex cavitation, the chord length near the tip could be reduced.



(a) Figure A: Cavitation map. (b) Figure B: Cavitation analysis.

Figure IV-6 Cavitation map and cavitation analysis after new geometry corrections: Suction side

V. Conclusion

This study lays out an experimental investigation and simulation approach to have the optimum propeller design; chord length, rake angle, and pitch ratio which increase the efficiency and decrease cavitation possibilities. The results were concluded as below:

- The optimum chord was found 6.5 cm which increased efficiency by 0.5%. As the chord length increases, the contact area between the blade and the cut water increases, consequently, the thrust and efficiency increased. However, in excessive chord length, several swirling and flow circulation occurred, and efficiency will be decreased.
- The optimum rake angle was found 5^o which increased the efficiency by 0.5%. Increasing rake angle means increasing the attack angle and more flow rate directing toward thrust or axial direction. However, excessive rake angles cause more swirling and eddies at the propeller inlet and decrease the thrust force and efficiency.

- The optimum pitch ratio was found 0.6, which increased the efficiency by 0.45%. Excessive pitch adjustments may lead to efficiency losses, requiring a balance between thrust generation and cavitation mitigation.
- The optimum propeller geometry was investigated by simulation using MATLAB program and the cavitated area the blade that was observed in the original design was enhanced a lot with the new optimum design.

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