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Research Article

Optimization Analysis of Screw Propeller Blade

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Abstract

Marine screw propeller is a fascinating invention. It transmits power by converting rotational motion into thrust force. The generated thrust creates pressure difference of fluid in the front and back surface of the propeller's blade for acceleration. In this project, the screw propeller, INSEAN E779A model was modified with the main objective to determine its optimized design that could achieve better performance during its operation. In determining the optimized design for the screw propeller blade, different modified models with various dimensions and properties were proposed and modelled in SolidWorks. Subsequently, Finite Element Analysis (FEA) was carried out to determine the Maximum von misses stress, strain, deformation and factor of safety along with flow analysis, velocity and pressure trajectories analyzed using Computational Fluid Dynamic (CFD). After comparing the analysis results, the optimized design for the screw propeller found in this project is having the dimensions of 3.0 mm thickness, 40° propeller blade twist angle, and 110° of angle between the leading edge and the propeller's hub. The Maximum Von Misses Stress was improved by 24.15%.

Keywords: Marine screw propeller, Finite Element Analysis (FEA), Computational Fluid Dynamic (CFD)

1. Introduction

A marine propeller acts like a wheel for vehicles but in water [1]. The propeller plays an important part in a ship to travel through the water by providing propulsion to the ship to move forward. Hence, the propeller must have good strength and longer lifespan and able to provide good thrust force.

A poorly designed propeller would cause the ship to move in slower speed and the generated vibration that passed through the shaft would cause damage to other connected parts such as bearings and seals. There were many Computational Fluid Dynamics (CFD) analyses conducted on propellers with different materials, designs and geometry dimensions in order to create the best quality propeller. Through the building of computational domain, meshing of the propeller and computational field and condition settings, the data of aerodynamic forces are then collected for performance analysis [2]. This study is aimed to determine the optimized design for the propeller *INSEAN E779A* model.

2. Literature Review

There are many dimensional factors such as the thickness and diameter of the blade will affect the propeller performance [3]. A thick propeller profile would yield higher Von Misses Stress but it would cause cavitation to happen. On another hand, the diameter of the propeller would decide its propulsion efficiency which the greater the diameter higher the efficiency of propulsion [4]. Generally, propeller with large diameter is required to be operating at lower shaft speed, otherwise it will not be beneficial from the aspect of the propulsion efficiency.

The number of blades in a propeller is another crucial factor to affect its performance which the lower the number of propeller blade, the greater the velocity of the ship due to lower torque and higher thrust force as the result of low blade drag in water [5]. On top of that, it is proven that 3-bladed and 4-bladed propellers are having better efficiency compared to 5-bladed and 6-bladed propellers.

A comprehensive study on the static and dynamic analysis of marine propeller using SolidWorks was carried out [6]. The finite element analysis on strength of the modelled propeller was determined with the result observed by simulating the deflection, Von Misses Stress, strain, and factor of safety on the propeller. Flow simulation was then done in CFD to compute the performance of the propeller with the flow trajectories analysis Thrust force in a propeller would cause the ship to move forward with the greater thrust force leads to higher velocity Hence, it is very important to compute the optimum thrust force generated when designing the propeller blade [7].

3. Methodology

In this paper, static simulation and flow simulation were conducted to find the optimized design of the propeller blade and then the performance was compared with the work by [6]. Firstly, SolidWorks was used to model the modified design of the propeller, INSEAN E799A model. Then, Finite Element Analysis (FEA) was carried out to analyze the factor of safety, maximum von misses stress, strain, and deflection by applying external load onto the blade and hub with fixed geometry shaft. With reference to [8], FEA based application was adopted for predicting marine propeller under steady state analysis with uniform thrust loading was adopted in this paper. Lastly, velocity and pressure trajectory flow analysis were computed to determine the propeller's performance in CFD.

Several changes were made in the dimensions of the modified propeller particularly the thickness, twist angle of propeller blade and angle between the leading edge and propeller–hub with the aim to improve its performance. Then, the performance analysis of the modified models was subsequently carried out and the result were analyzed to determine the best geometries of the modified propeller to yield the optimized strength and performance in flow analysis.

A. Propeller Design Model

The geometry data of the reference model, *INSEAN E779A* was referred from [6] and is shown in Table 1. Figure 1 show the 3D propeller solid model in SolidWorks. The geometries of the original model were altered for analysis in the subsequent steps.

Table 1. Properties of Propeller

Styles	Uses
Model	INSEAN E779A
Number of Blade	3
Twist Angle	50°
Blade Thickness	2.5mm
Angle between Lead and Hub propeller	71.39°
Blade Diameter	227.27mm
Propeller Rotational Speed	2000rpm
Model	INSEAN E779A
Material	Steel Alloy
Number of Blade	3

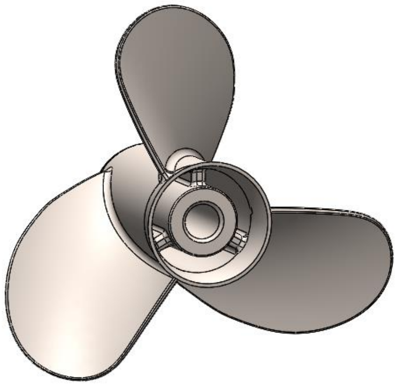

Figure 1. 3-D View of Propeller

B. Convergence Test

For simulation analysis, determining a suitable mesh size in simulating the propeller is important to create accurate result. According to FEA theory, the FE models with fine mesh yields highly accurate results but may take longer computing time. In order to analyze the best mesh size, convergence mesh testing being carry out. Figure 2 shows the results of maximum Von Misses Stress (MPa) vs Element Size (mm). Based on the data, after element size of 5 mm, the result started to converge as the percentage difference is lower than 5%. Figure 3 shows the propeller with fine mesh generation. Figure 4 shows Maximum von Misses Stress Result for element mesh size of 5mm.

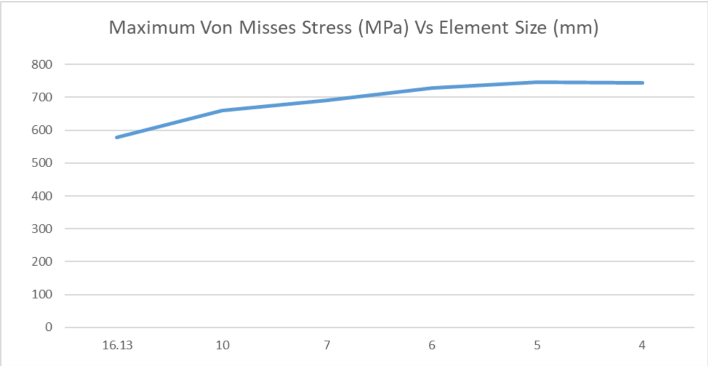

Figure 2. Graph of Maximum Von Misses Stress (MPa) Vs Element Size (mm)

Figure 3. Propeller with Fine Mesh Size

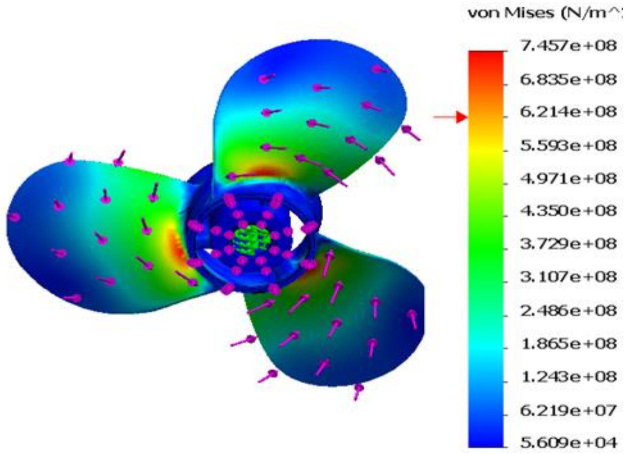

Figure 4 Maximum Von Misses Stress Result for element mesh size 5mm

C. FEA Analysis Setup

Finite element analysis (FEA) was applied on the propeller using SolidWorks Simulation software to obtain stress that focus on area specifically with large stress Fixture was applied to the center of propeller which is known as shaft. Then, an external load of 2000N was applied onto the hub and blade propeller. The first step of the setup was to sketch the circle around the propeller and extruded without merging, enclosing the entire propeller. Then, a rotating domain was applied on the newly created extruded cylinder with the rotational speed of 2000rpm. Finally, the surfaces in contact with the fluid were selected which resulted into 54 faces on the propeller as shown in Figure 4. The same setup was applied onto all proposed propeller models for the analysis of velocity and pressure trajectory flow. The details that were used in generating simulation flow are shown in Table 2.

Figure 4. Selected Faces of Propeller

Table 2. Parameters for Flow Simulation

Parameters	Setting
Type	Fluid
Material	Water
Fluid Velocity	0m/s
Analysis Type	External
Flow Type	Turbulent & Laminar
Domain Type	Rotating (2000rpm)
Fluid Temperature	293.2K
Reference Pressure	101.325K

D. Boundary Condition

Boundary conditions shows how a system, for example fluid interacts with its surrounding known as environment. Boundary conditions is required in every fluid simulation to define the inlets and outlets of a model and is shown in Figure 5 and Table 3.

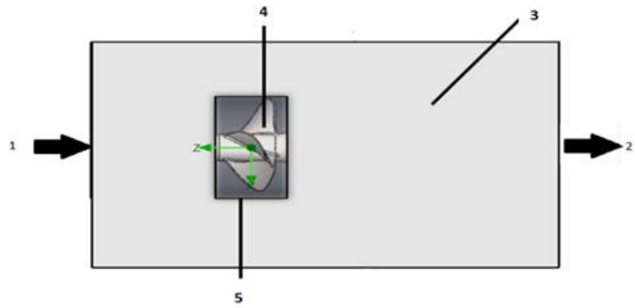

Figure 5. Selected Faces of Propeller

Table 3. Label for Boundary Condition

Number	Boundary Condition
1	Inlet
2	Outlet
3	Side (Stationary Domain)
4	Propeller
5	Rotating Domain

4. Verification

Verification test was done on the propeller to compare the proposed models in this paper with the referred work done by [6]. The mesh size used in generating the experiment is 6mm. Table 4 shows that the percentage difference is below 15% which within acceptable ranges.

Table 4. Result for Accuracy Test

Design	Result Obtained by Reference Work [6]	Result Obtained in this study	Percentage Difference
Von Misses Stress	699.492Mpa	745.7Mpa	6.1966%
Deflection	6.835mm	6.945mm	1.5839%
Velocity Trajectory	31.423m/s	31.305m/s	1.9741%

5. Geometry Redesign On Propeller Model

Several tests were done on the proposed models of the modified propeller with geometries changes to identify the best design. Blade's twist angle, thickness, and angle between leading edge and hub of propeller were targeted for modification and analyzed to measure the strength and efficiency to prevent any trade-off in either performance criterion. From this analysis, the optimum design would be selected.

Figure 6 shows the diagram where two planes which each represents top and bottom of their plane at the corner of the blade. They are known as leading edge and trailing edge which shown at Figure 7. Every propeller has a twist at the length of the blade to allow the entire blade in creating uniform thrust and greater angle of attack at the tip of the blade. In this test, propeller twist is known as the rotation of two plane perpendicular to the helix axis.

Blade twist is where the chord line changes from the blade root to the tip. The twisting blade in certain angle will allow the air to meet across the length of blade to generate thrust to the plane. If it is at the same angle, the propeller will generate highest thrust and lowest drag. Besides, when the propeller rotates, the tip is found to moves in faster speed comparing to its hub. Hence, the blades are twisted in order to increase the propeller's efficient. However, if the propeller is over twisted, the propeller's strength might decrease due to thin profile in the propeller blade.

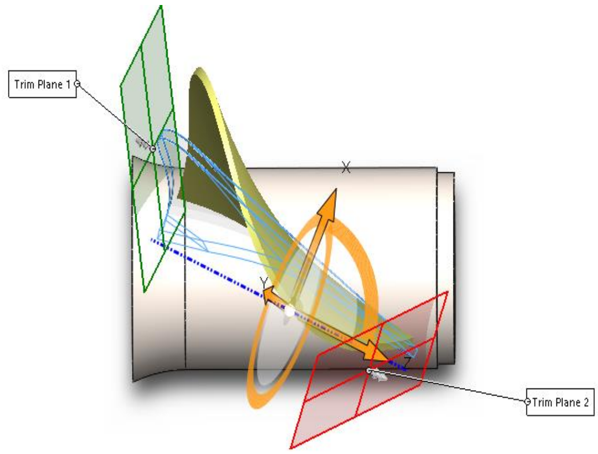

Figure 6: Twist Angle of the Propeller Blade

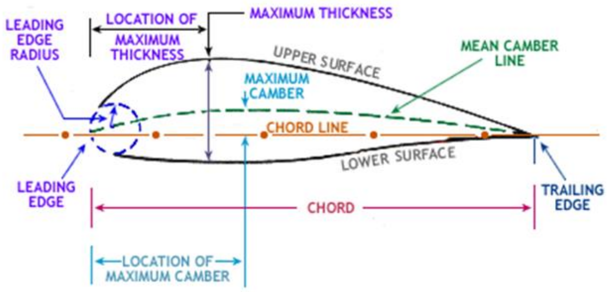

Figure 7: Details of Propeller Blade [9]

Propeller-blade outline plays major role in the effectiveness of propeller in fluid simulation as the angle of attack will be affected. This can be done by altering the angle between leading edge and hub. Leading edge functions in leading fluid into the flow when forward thrust is provided by piercing the water surface. A defect in leading edge will cause significant loss in aerodynamic and flow characteristics of the propeller. Angle between leading edge to propeller hub were tested with 60°, 71.3°, 90°, 110° and 130°. As the angle increases, the blade's profile will appear to be narrower in shape [10]. Figure 8 shows the Sketched Diagram of Angle from the Leading Edge to the Propeller Hub.

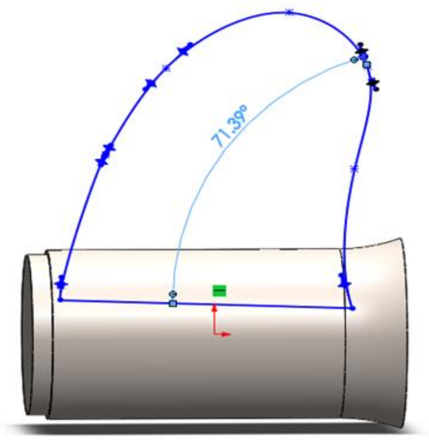

Figure 8: Sketched Diagram of Angle from the Leading Edge to the Propeller Hub.

The thickness of propeller affects strength and propeller speed in flow. So, in this analysis, the proposed propeller designed in different thickness were simulated in both FEA and CFD. The part that the propeller blade connects to the propeller's hub are found to be the weakest point exposed to breakage. By thickening the propeller can solve the problem but a good propeller should have thin profile as it provides lower displacement which would lead to higher speed due to higher thrust force. Figure 9 show the sketched diagram would be extruded with the thickness of the propeller blade. A thicker propeller blade will have stronger strength but at the same time will yield lower the efficiency of propeller.

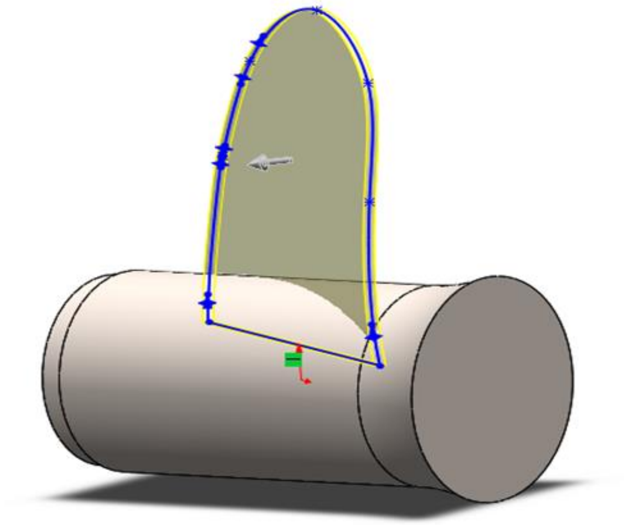

Figure 9: Extruded Thickness on Propeller Blade

6. Result And Discussion

The original design of the propeller was modified with different twist angles of the propeller blade to identify the best angle to provide better strength and efficiency in fluid flow. The twist angle of the original propeller was 50°. Case 1 shows the propeller tested by different twist angle i.e. 20, 30, and 40 degrees. As tabulated in Table 5, the result shows that when the propeller twist angle decreases after 40°, the pressure trajectory increases significantly. The higher-pressure trajectory will cause the ship to produce higher torque which would reduce the propeller speed due to resistive force. Hence, design A1 and B1 were rejected-although they have lower Von Misses Stress. By comparing the designs, C1 and D1, design C1 was selected as it produces higher trust force in the flow analysis. Figure 10 shows the Pressure Trajectory Result for Design C1.

Table 5. Result for Case 1 (Twist Angle)

Parameters	**Design A1**	**Design B1**	**Design C1**	**Design D1**
Twist Angle	20	30	40	50

Von Misses Stress, MPa	667.5	734.7	764.4	745.7
Deformation, mm	3.834	4.950	6.014	6.945
Strain, $x10^{-3}$	2.262	2.376	2.126	2.265
Factor of Safety	0.9172	0.8060	0.8445	0.832
Pressure Trajectory, Pa	437224.18	403612.76	274017.89	271497.50
Velocity Trajectory, m/s	31.428	31.398	31.359	31.305
Average Thrust, N	2090.123	2041.986	2694.823	2526.233

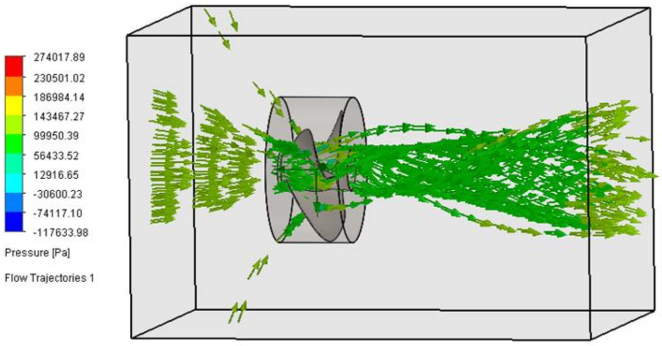

Figure 10: Pressure Trajectory Result for Design C1

The enhanced design version, C1 was brought to Case 2 for further test and improvement. Different angles of leading edge to propeller hub i.e. 60, 90, 110, and 130 degrees were tested. Table 6 shows that design A2 with 60° has the highest maximum Von Misses stress; but it has the least performance in flow analysis. Hence, design A2 was rejected. It was observed that with the increase of leading edge angle, the velocity trajectory also increases before it starts to decrease after 110°. Design D2 was chosen as the optimum design by considering it has the highest velocity trajectory and was proceeding to further analyzed in Case 3.

Table 6. Result for Case 2

(Angle from Leading Edge to Hub)

Parameter	**A2**	**B2**	**C2**	**D2**	**E2**
Blade Angle	60°	71.39°	90°	110°	130°
Von Misses Stress, MPa	753.5	764.4	776.1	767.7	778.1
Deformation, mm	5.987	6.014	6.079	6.170	6.276
Strain, x10-3	2.355	2.126	2.231	2.481	2.376
Factor of Safety	0.8234	0.8445	0.7995	0.8082	0.7974
Pressure Trajectory, Pa	318183.80	274017.89	280243.51	277531.16	277531.16
Velocity Trajectory, m/s	31.262	31.359	31.598	31.675	31.609
Average Thrust, N	1796.68	2694.823	2701.96	2843.69	2754.11

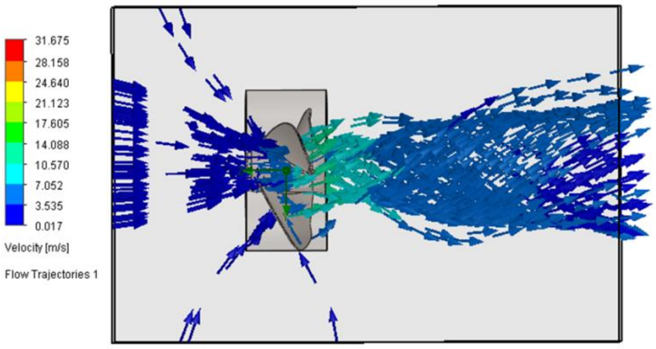

Figure 11: Velocity Trajectory Result for Design D2

Case 1 and Case 2 successfully increased the thrust force of the modified propeller but minimum improvement in static strength was observed. Previous studies showed that maximum stress is always located at the area where the blade connects to the hub. Improvement could be made by increasing the thickness of the propeller but a thick propeller will lower down its performance. Case 3 was then tested with different thickness of propeller blade i.e. 2.5mm, 3.0mm and 3.5mm. Table 7 shows that as the thickness of the propeller blade increases, maximum Von Misses Stress of the propeller increases. The maximum stress reduces greatly with each increment of 0.5mm on the thickness. Design C3 shows good results on maximum Von Misses Stress but it has the lowest value in velocity trajectory and thrust force. Design B3 with lower maximum stress was selected with minor decrease in thrust force as a trade-off.

Table 7. Result for Case 3 (Thickness).

Parameters	**Design A3**	**Design B3**	**Design C3**
Thickness, mm	2.5	3.0	3.5
Von Misses Stress, MPa	767.7	530.6	319.7
Deformation, mm	6.170	3.655	2.462
Strain, x10-3	2.481	1.516	1.137
Factor of Safety	0.8082	1.169	1.584
Pressure Trajectory, Pa	277531.16	286896.16	278960.97
Velocity Trajectory, m/s	31.675	31.679	31.091
Average Thrust,N	2843.69	2781.659	1788.88

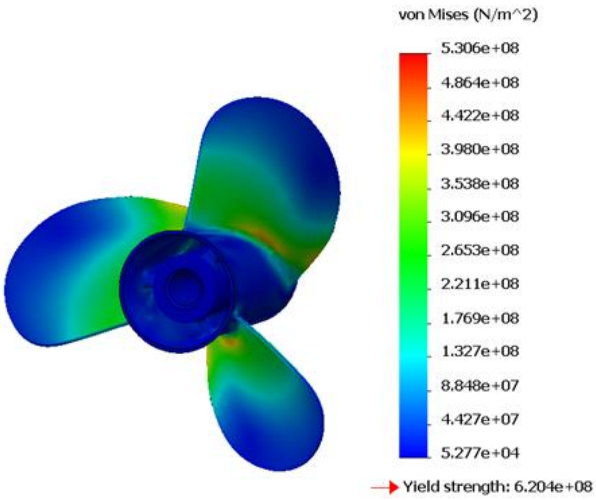

Figure 12: Maximum Stress Result for Design B3

7. Conclusion

After completing all the tests, several changes for improvement were made on the geometries of the original propeller, *INSEAN E779A* model. The twist angle was changed from 50° to 40°; angle between the leading edge to the hub was changed from 71.39° to 110°; blade thickness was changed from 2.5mm to 3.0 mm. Maximum Von Misses Stress was improved as much as 37.96%, from 669.492Mpa to 530.6MPa. Trust force was improved by 3.12%, from 2694.823N to 2781.659N.

The changes of geometries in a propeller with the aim to yield greater strength and efficiency in fluid flow was conducted in this paper. Simulation results show that the modified propeller has lower deformation, higher maximum Von Misses Stress and strain while the safety factor has been improved greatly. The efficiency of the modified propeller also improved as the velocity trajectory was higher compared to the original model which would boost the thrust force generated by the propeller.

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