DESIGN AND SIMULATION OF A CONTROLLABLE PITCH MARINE PROPELLER FOR ENHANCED MANEUVERABILITY AND EFFICIENCY

by

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ABSTRACT

This paper presents the design and simulation of a **4 -bladed controllable-pitch marine propeller** for relatively small to medium-sized vessels that enhances both maneuverability and efficiency in diverse maritime operational conditions, using the design basis of a small coastal twin screw passenger ferry. The design process utilized the wageningen B-series standard design chart (B4-70), using the optimum design line to carry out design analysis of the propeller, with detailed mathematical analysis/calculations to derive the propeller geometric parameters, followed by the development and modification of a 3D propeller model using SolidWorks. The hydrodynamic performance and behavior of the CPP were analyzed using Computational Fluid Dynamics (CFD) simulations across varying propeller pitch angles, enabling the determination of thrust and torque under different operational conditions. The results from parametric studies and optimization indicate that a decrease in the propeller blade tip pitch angle leads to improved efficiency, enhancing propulsion and fuel economy. The simulations also revealed that the maximum ahead thrust was achieved at a pitch angle of -30° from the design pitch, the maximum astern thrust at 60° from the design pitch, and approximately zero thrust at 20° from the design pitch.

KEYWORDS: Computational Fluid Dynamics, Controllable Pitch Propeller, Thrust, Torque, propeller pitch, blade area, expanded area.

1. INTRODUCTION

The pursuit of innovation in propulsion technologies is a fundamental aspect of the dynamic field of naval architecture and marine engineering. The effectiveness and maneuverability of marine propellers are critical as vessels navigate a variety of demanding maritime environments. Through a synthesis of design methodologies and advanced simulation tools, this paper aim to contribute to the ever-expanding knowledge base in marine propulsion and propeller design, pushing the boundaries of what is achievable in the dynamic realm of maritime technology.

Marine propulsion dates back to the advent of steam engines in the 19th century, (Carlton, 2012) which marked the shift from paddlewheels to propellers. Marine Propellers can be classified based on pitch as fixed and controllable pitch propellers. The blades in the fixed pitch propeller are permanently attached to the hub. In a Controlled Pitch type propeller, it is possible to alter the pitch by rotating the blade about its vertical (spindle) axis by means of mechanical and hydraulic arrangement consisting of an actuation system, a pitch control system and sensors (to monitor engine parameters and vessel conditions for optimal pitch adjustments). This helps in driving the propulsion machinery at constant load with no reversing mechanism required as the pitch can be altered to match the required operating condition. Thus the maneuverability improves and the engine efficiency also increases (Wankhede, 2020).

Conventional marine propellers, characterized by fixed-pitch designs, remain prevalent in contemporary ship design. However, these designs face challenges in optimizing efficiency across varying operating conditions (Faltinsen, 2010). The need for improved maneuverability, fuel efficiency, and reduced environmental impact has led to increased scrutiny of existing propeller technologies (Molland & Turnock, 2014). The controllable-pitch propeller's ability to adjust its blade angles addresses inherent limitations observed in fixed-pitch designs. This adaptability also plays a key role in improving maneuverability, allowing vessels to navigate challenging scenarios with greater precision and responsiveness.

Ongoing research focuses on advancing controllable-pitch propeller technologies. Computational Fluid Dynamics (CFD) simulations play a crucial role in understanding the hydrodynamic characteristics of these propellers (Molland & Turnock, 2014). Arifin et al., (2020) analysed the effect of changes in pitch ratio and number of blades on cavitation on

CPPs and concluded that the pressure ratio and percentage cavitated area on the propeller tends to increase at higher rotation and tends to increase on the higher pitch at the constant rotation. The Maritime Research Institute Netherlands (MARIN) performed open water propeller model tests to study the off- design performance of CPPs, resulting in the development of the Wageningen C and D series. Systematic measurements of the propeller thrust, torque and also the blade spindle torque were carried out for an entire range of operational conditions and pitch-settings of each propeller in the series. The series represent the most contemporary controllable pitch propeller design practice, both for open and ducted propellers, with balanced compromise between efficiency and comfort, while also observing practical and mechanical constraints (Dang et al., 2020). Ozturk et al., (2022) studied the effects of propeller pitch on ship propulsion and concluded that speed variations in ships with controllable pitch propellers are realized by tuning propeller pitch instead of by changing the revolution rate of the main engine. Adding that to understand and control CPPs, we need to know the potential consequences of propeller pitch variations on ship self-propulsion.

New designs and coatings were developed to minimize cavitation and underwater noise pollution, benefiting marine life and improving acoustic comfort for passengers and crew. However, there exists a need for further exploration and refinement to optimize controllable-pitch designs for specific vessel types and operational conditions.

1.1 DEFINITION OF TERMS RELATING TO CPP GEOMETRIC DESIGN

I. **Frame of Reference**: The global reference frame as defined by ITTC (1978) has the X-axis along the propeller shaft, with Y pointing starboard and Z downward. The propeller geometry defined by the local frame shares the X-axis but allows rotation of the y and z axes, with the rotation angle denoted by ϕ (Carlton, 2019).

II. **Blade Reference Line**: The "propeller reference axis" or "directrix" is the line normal to the shaft axis that defines the propeller blade. The "spindle axis", typically synonymous with the directrix, can sometimes be defined differently in special designs, lying normal to a shallow cone surface that shares the shaft axis but tapers aft. In such cases, the spindle axis is slightly inclined to the reference line (Carlton, 2019).

III. **Blade Tip and Root**: The blade tip is the furthest point on the blade from the hub. It is the outermost part of the propeller blade. The blade root is the part of the propeller blade that is attached to the hub (boss).

IV. **Pitch(P)**: This is the theoretical distance a propeller would move forward in a solid medium for each rotation, assuming no slip. Propeller blades are typically twisted to maintain a nearly constant pitch from root to tip. The pitch of a blade section can also be defined by the *pitch angle (θ)*, and altering this angle results in a corresponding change in both the propeller pitch and pitch ratio (Njaastad et al., 2022).

V. **Diameter (D):** The propeller diameter is the diameter of the circle traced by the blade tips, while the propeller radius (R) is half of this diameter, representing the distance from the center of the propeller hub to the tip of a blade.

VI. **Hub diameter (d)**: The propeller hub is the central part of the propeller where the blades are attached. The hub contains the mechanism for adjusting the pitch of the blades. The diameter of the hub is denoted by (d).

VII. **Blade Number (Z)**: This refers to the number of blades mounted on the propeller hub.

VIII. **Rake**: The angle of the propeller blade relative to a plane perpendicular to the propeller's axis, indicating how the blade leans forward or backward.

IX. **Skew**: This refers to the twist or angle of the propeller blade relative to its axis. The propeller skew angle (θ_{sp}) is the largest spanning angle between two lines from the propeller origin running through the various mid-chords of the radial blade sections (Njaastad et al., 2022).

X. **Propeller Disc Area (A_O)**: This is the area of the circle scribed by propeller blade tips.

XI. **Propeller Expanded Area (A_E):** This is the sum of areas of all the blades in an expanded blade outline outside the hub.

XII. **Thrust (T):** This is the force exerted by the propeller in the direction of its axis. It propels the ship either ahead or astern depending of its orientation.

XIII. Torque (Q): The propeller torque (Q) is the twisting torque applied to the propeller shaft. For the CPP, the blade spindle torque (Q_{BLADE}) is the torque acting about the vertical spindle axis of the blade as it rotates about this axis during the pitch change.

XIV. Advance Speed (V_A): The actual speed of the propeller through the water is known as the advance speed, V_A. This speed is less than the ship speed by the wake speed, V_W (Patterson & Ridley, 2014).

2. DESIGN METHODOLOGY/ MATHEMATICAL ANALYSIS

The propeller design basis refers to the delivered power (HP) to the propeller, the shaft rotational speed (propeller rpm), ship speed and wake fraction that are chosen to act as the design point for defining the propeller geometric features. Defining the design basis for the CPP design is extremely important in defining the design condition (design pitch) for the propeller.

With the basic design parameters for a small coastal twin screw passenger ferry (under the small - medium sized vessel category) defined by Carlton (2019) and the knowledge of the range of design basis for small to medium sized vessels, the specific design basis for the controllable pitch propeller design condition is defined.

Table 1: Basis for CPP design

DESIGN BASIS FOR THE CONTROLLABLE PITCH PROPELLER DESIGN	
Delivered Horsepower (P_D)	**1137 HP**
Ship Service Speed (V_S)	**16 knots**
Propeller RPM (N)	**300 RPM**
Wake Fraction (w)	**0.112**
Number of Blades (Z)	**4**

The CPP is designed to enhance efficiency and maneuverability by obtaining minimum power requirements, cavitation, noise, vibration and maximum efficiency conditions at an adequate revolution. Two methods are usually used in the propeller design:

I. The use of design diagrams (particularly the B_P - δ chart) obtained from systematic open water model test series data.

II. The development of the design based on circulation theory.

The design procedure was restricted to the use of design charts and series, the Wageningen B-series, certified by the Society of Naval Architecture and Marine Engineers (SNAME). The design uses the Wageningen B4- 70 (B_P - δ) chart to obtain the appropriate propeller geometry, design pitch, optimum efficiency and performance for the CPP design condition. Certain propeller chart characteristics such as propeller pitch (P), pitch ratio (P/D), speed of advance (V_A), propeller diameter (D), blade area ratio (A_E/A_O), number of blades (Z), blade outline, thickness and section profiles are taken into consideration, governed by the need to avoid cavitation. The assumed blade patterns are elliptical and airfoil in section at the root. The use of this propeller design chart (B_P - δ chart), alongside the knowledge of the design basis in table 1, makes it possible to explore the best combination of diameter, revolution per minute (rpm) and pitch ratio that gives the optimum efficiency.

Admiral Taylor derived a set of design coefficients termed B_P and δ; these coefficients are defined as follows:

$$B_P = \frac{{P_D}^{0.5} \times N}{{V_A}^{2.5}} \tag{1}$$

$$\delta = \frac{N \times D}{V_A} \tag{2}$$

Where

B_P is the power coefficient;

δ is the design coefficient;

P_D is the delivered horsepower in British or metric units depending on the diagram used;

N is the propeller rpm;

V_A is the speed of advance (knots);

D is the propeller diameter (ft).

The B_P - δ chart (design diagram) as shown in figure 1 comprises a plotting of B_P (abscissa), against pitch ratio (ordinate), with line of constant δ and superimposed open water efficiency. This diagram forms the basis of the design procedure. The power coefficient, B_P, is usually known from the engine and ship characteristics as defined in the equation above.

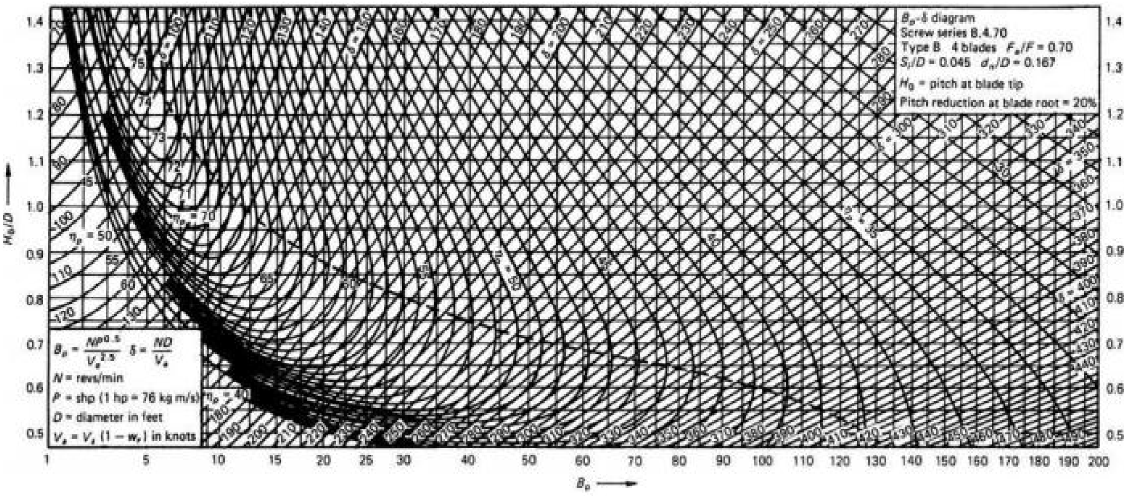


Fig. 1: B4 -70 B_P - δ diagram (courtesy: MARIN.)

In the figure above, an optimum propeller open water efficiency (η_o) line can be seen as being the locus of the points on the diagram, which has the highest efficiency for a given value of B_P. As a result, it is possible to use the chart to select values of δ and P/D to maximize the propeller open water efficiency (η_o) as define by the power coefficient for a given powering condition (Carlton, 2019).

Therefore, basic cpp geometry can be derived in terms of diameter D, since D = $\delta \cdot Va/N$, and P/D.

The design basis for the propeller design, shown in table 1 is reiterated below.

Propeller delivered horsepower, P_D = **1137 hp (847.86 kW)**

Propeller rotational speed, N = **300 rpm**

Ship speed, V_S = **16 knots**

Wake fraction, w = **0.112**

Number of Blades = **4**

Given the above parameters, the mean speed of advance, V_A, can then be determined by the equation,

$$V_A = V_S (1 - \omega) \quad (3)$$

Therefore,

$$V_A = 16 (1 - 0.112)$$

V_A = 14.21 knots (7.31 m/s)

Having gotten the value for the advance speed, the power coefficient, B_P, can be evaluated using taylor’s formula (equ 1).

$$B_P = \frac{1137^{0.5} \times 300}{14.21^{2.5}}$$

$$B_P = 13.29$$

From the Wageningen B4-70 series chart, with the B_p value obtained, using the optimum open water efficiency line, the value of the optimum design coefficient (δ_{opt}) is obtained and this is used to calculate the propeller optimum diameter, D_{opt} (equ 2) . The expanded blade area ratio (A_E/A_O) is also obtained from the chart.

Optimum design coefficient, $\delta_{opt} = 145.9$

Expanded blade area ratio, $A_E/A_O = 0.70$

Note: The value of the optimum design coefficient (δ_{opt}) can also be obtained from regression equations. One example of such equation based on the Wageningen B series, produced by Van Gunsteren (1972), is given below.

$$\delta = 100\left[\frac{{B_P}^3}{155.3+75.11{B_P}^{0.5}+36.76B_P}\right]^{0.2} \times \left[0.9365 + \frac{1.49}{Z} - \left(\frac{2.101}{Z} - 0.1478\right)^2 \times \frac{A_E}{A_0}\right]$$

From Taylor's design coefficient formula (equ 2), the equation for the optimum diameter is obtained;

$$D_{opt} = \frac{\delta_{opt} \times V_A}{N} \qquad (4)$$

The optimum diameter is then obtained from the above equation,

$$D_{opt} = \frac{145.9 \times 14.21}{300}$$

$$D_{opt} = 6.91\, ft \ (2.11m)$$

Having obtained the optimal diameter, the behind hull diameter (D_b) is calculated to define the diameter of the propeller when working under the influence of the ship rather than in open water. For an actual propeller working behind a ship, the diameter usually needs to be reduced from the optimum value obtained from standard series data. This is usually done by reducing the optimum diameter by 5% and 3% for single and twin screw vessels respectively (Carlton, 2019). Since, the design basis is based on the latter, the optimum diameter is reduced by 3% to obtain the behind hull diameter.

$$3\%\ of\ D_{opt} = 3\%\ of\ 6.91 = 0.2073\, ft$$

∴ Behind hull propeller diameter, $D_b = 6.91 - 0.2073 = 6.70\, ft\ (2.04m)$

Given that the values for the power coefficient and behind hull diameter have been determined, the mean pith ratio (design pitch), P/D, can be evaluated.

First, the behind hull value for the design coefficient (δ_b) has to be determined. From taylor's formula,

$$\delta_b = \frac{N \times D_b}{V_A} \qquad (5)$$

$$\therefore \quad \delta_b = \frac{300 \times 6.70}{14.21} = 141.5$$

With this value, alongside the B_P value, the equivalent pitch ratio and the propeller open water efficiency is obtained from the B4 - 70 chart.

The Equivalent Pitch Ratio = 1.025

Propeller open water efficiency , η_o = 0.67 (67%)

For the Wageningen B4 series, there is a 20% reduction of pitch towards the blade root (as indicated in the chart). Therefore the equivalent pitch ratio derived from the chart needs to be reduced by 1.5% to arrive at the mean pitch ratio (Carlton, 2019).

$$1.5\% \; of \; 1.025 = 0.015375$$

∴ Mean Pitch Ratio, P/D $= 1.025 - 0.015375 = 1.01$

Thus, the design pitch for the CPP is obtained from the mean pitch ratio.

Design Pitch, P $= 1.01 \times 6.70 = 6.767ft \; (2.06m)$

For the CPP design, the minimum hub diameter (d) is obtained from the ratio:

$$\frac{d}{D_b} = 0.24$$

$$\therefore \quad d = 0.24 \times 6.70 = 1.608ft \; (0.5m)$$

From, the design pitch, we evaluate the design pitch angle (θ) at blade tip and blade root,

$$\theta = (\frac{P}{2\pi r}) \qquad (6)$$

$$\theta_t = (\frac{2.06}{2\pi \times 1.02}) = 17.81°$$

$$\theta_r = (\frac{2.06}{2\pi \times 0.25}) = 52.67°$$

To obtain the propeller blade disc area (A_O) and the expanded area (A_E), the expanded area ratio (0.7) obtained from the chart is used.

Blade disc Area (A_O) = $\frac{\pi {D_b}^2}{4}$ (7)

$$\therefore \quad A_o = \frac{\pi \times 2.04^2}{4} = 3.27m^2$$

Blade expanded Area (A_E) = $0.70 \times 3.27 = 2.29m^2$

2.1 DETERMINATION OF CPP THRUST AND TORQUE AT DESIGN PITCH CONDITION

The Thrust (T) and Torque (Q) generated by the controllable pitch propeller at the design condition (based on the design pitch) are evaluated by the formulas;

Propeller Thrust (T) $= \frac{P_D \times \eta_O}{V_A}$ (8)

$$\therefore \quad Propeller\ Thrust\ (T) = \frac{847.86kW \times 0.67}{(14.21 \times 0.5144)m/s} = 77.71kN$$

Propeller Torque (Q) $= \frac{P_D}{2\pi \times n}$ (9)

$$\therefore \quad Propeller\ Torque\ (Q) = \frac{847.86kW}{2\pi \times (\frac{300}{60})} = 26.99\ kN.m$$

2.2 DETERMINATION OF OPEN WATER PERFORMANCE COEFFICIENT AT DESIGN PITCH CONDITION

The non-dimensional terms used to express the general performance characteristics for the propeller geometric configuration are as follows:

Thrust coefficient, $K_T = \frac{T}{\rho n^2 D^4}$ (10)

Torque coefficient, $K_Q = \frac{Q}{\rho n^2 D^5}$ (11)

Advance coefficient, $J = \frac{V_A}{nD}$ (12)

where ρ is the density of sea water (1025kg/m^3 approx.),

n is the propeller rotational speed (rev/sec).

Thus, the values for the thrust, torque and advance coefficients for the CPP at design condition can be calculated from the formulas given (equ 10 - 13).

$$K_T = \frac{77.71 \times 10^3}{1025 \times 5^2 \times 2.04^4} = 0.175$$

$$K_Q = \frac{26.99 \times 10^3}{1025 \times 5^2 \times 2.04^5} = 0.0298$$

$$J = \frac{14.21 \times 0.5144}{5 \times 2.04} = 0.72$$

Table 2: Summary of cpp design parameters (design condition)

S/N	PARAMETER	UNIT
1	Delivered horsepower (P_D)	1137hp
2	Ship Speed (V_S)	16 knots
3	Propeller RPM (N)	300 rpm
4	Wake fraction (w)	0.112
5	Number of Blades (Z)	4
6	Advance speed (V_A)	14.21 knots
7	Power Coefficient (B_P)	13.29
8	Optimum design coefficient (δ_{opt})	145.90
9	Behind hull design coefficient (δ_b)	141.45
10	Optimum diameter (D_{opt})	2.11m
11	Behind hull diameter (D_b)	2.04m
12	Expanded Area Ratio (EAR)	0.7
13	Blade Expanded Area (A_E)	2.29m^2
14	Blade Disc Area (A_O)	3.27m^2
15	Equivalent Pitch Ratio	1.025
16	Mean Pitch Ratio (P/D)	1.01
17	Propeller open water efficiency (η_o)	0.67
18	Propeller design pitch (P)	2.06m
19	Propeller hub diameter (d)	0.50m
20	Design pitch angle at blade tip (θ_t)	17.81°
21	Design pitch angle at blade root (θ_r)	52.67°
22	Blade thickness fraction (t_o/D)	0.045
23	Propeller Thrust at design pitch condition (T)	77.71kN
24	Propeller Torque at design pitch condition (Q)	26.99kN·m
25	Thrust coefficient at design condition (K_T)	0.175
26	Torque coefficient at design condition (K_Q)	0.0298
27	Advance coefficient at design condition (J)	0.72

To analyse the performance of the CPP at varying pitch conditions, simulations using Solidworks CFD are conducted. The simulations were performed for a range of pitch below and above the design pitch, as well as for varying loads.

2.3 PROPELLER MATERIAL

The material chosen for the CPP design is the Nickel-Aluminium Bronze (NAB). This material was chosen purely based on current industry standards. According to Carlton (2019), from the 1980s till the date, the nickel-aluminium bronze has gained an almost complete dominance over other propeller materials, accounting for 82% of the propellers classed by Lloyd's Register. Some desirable properties of NAB alloy includes; corrosion resistance, high strength, wear resistance, weldability and high resistance to cavitation erosion. The nickel- aluminium bronze alloys usually contains 9% - 9.5% aluminium with more than 4% nickel and iron contents each, this amount of nickel content is required to obtain the best corrosion resistance.

3. 3D MODELLING, SIMULATION AND RESULTS

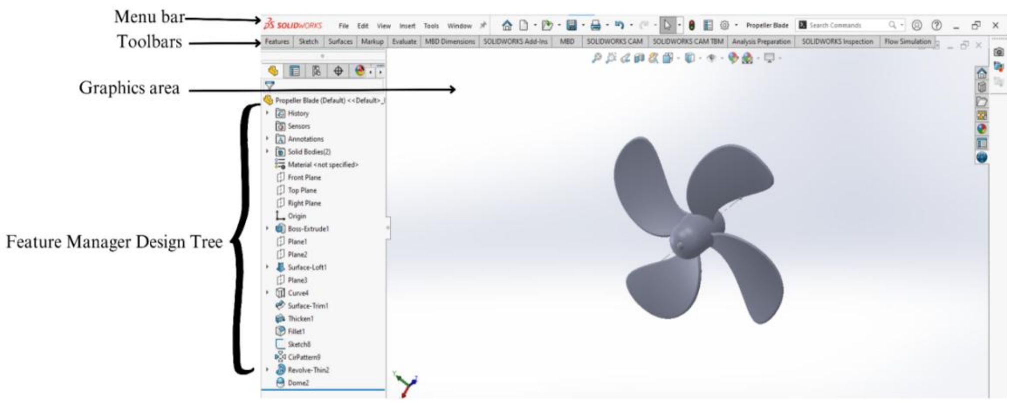


Fig. 2: SolidWorks User Interface

3.1 THE BLADE PITCH -CHANGE MECHANISM : 3D MODELLING

The Blade pitch - change mechanism used in the cpp design is a **push- pull rod mechanism** (a modification of an initial concept by Abdelrahman Yousry), designed to reduce the mechanical complexity and larger hub size associated with the conventional hub - piston mechanism with the aim of enhancing efficiency and reducing cavitation (associated with relatively larger hub sizes). The push - pull rod mechanism also reduces the risk of problems in service and environmental threats associated with the hub - piston mechanism. It is an inboard hydraulic actuation system (i.e the motion of the rod is actuated by an hydraulic system inside the ship).

The longitudinal motion of the push-pull rod is converted into the rotary pitch control motion of the propeller blades by the yoke, whose pins fit into a pin slot through to the propeller blades. The major parts of the blade pitch mechanism (the push-pull rod, the yoke, the yoke pin, the bearing and rings, and the pin-slot) which forms the hub assembly is modelled with

SolidWorks and shown below.

I. THE PUSH-PULL ROD AND YOKE ASSEMBLY

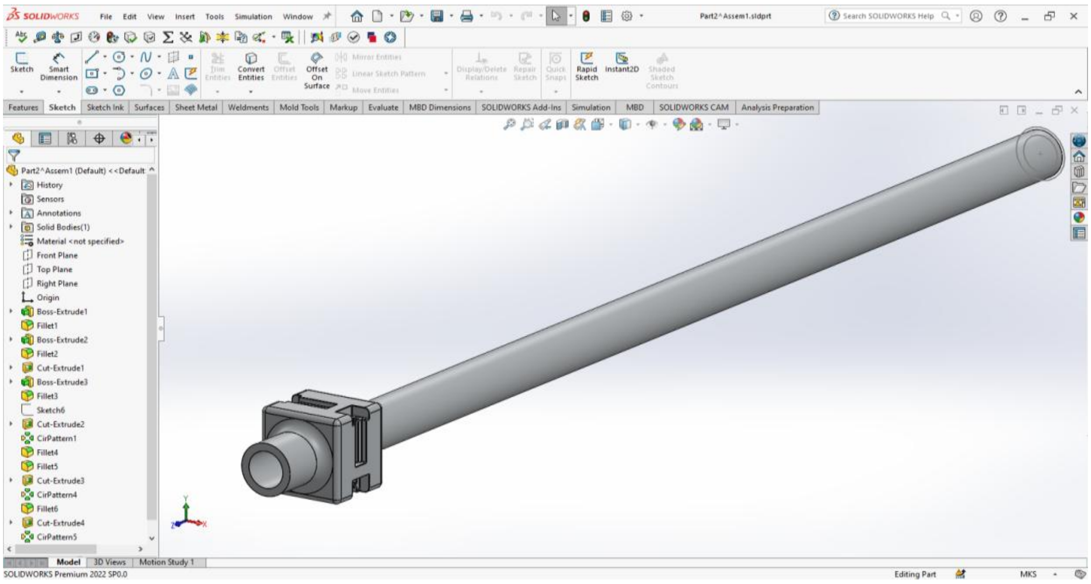


Fig. 3: 3D Representation of the push-pull rod and yoke assembly

II. THE YOKE PIN

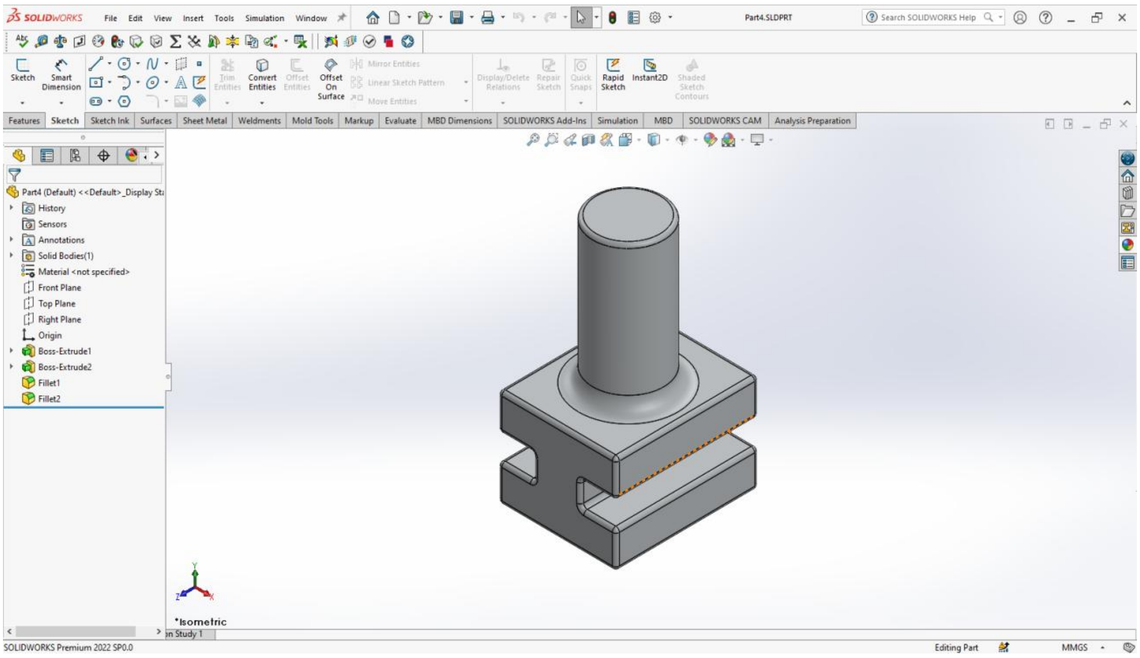


Fig. 4: 3D Representation of the yoke pin

III. THE PIN SLOT

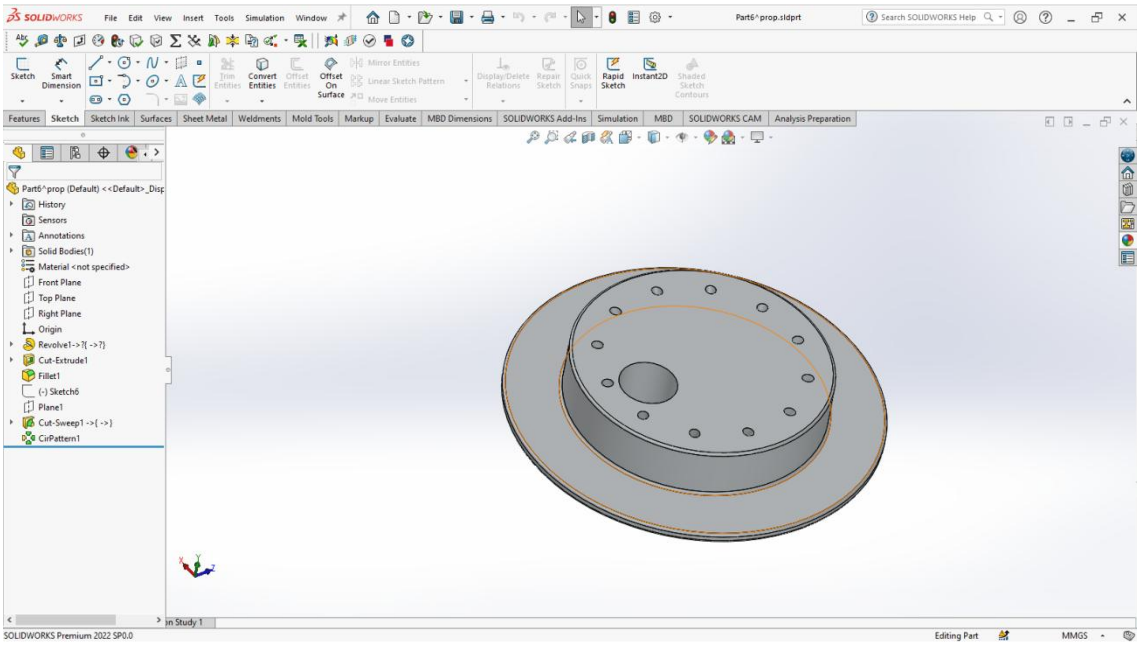


Fig. 5: 3D Representation of the Pin Slot

IV. THE BEARINGS/ RINGS

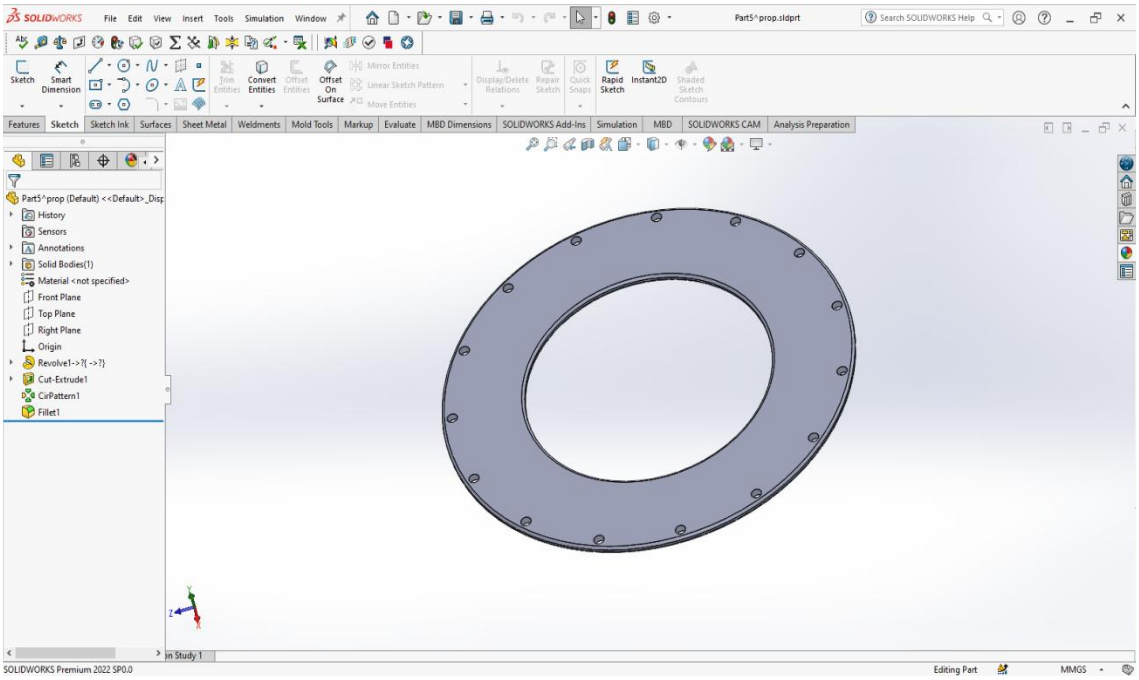


Fig. 6: 3D Representation of the Bearing/ Rings

V. THE CPP HUB ASSEMBLY

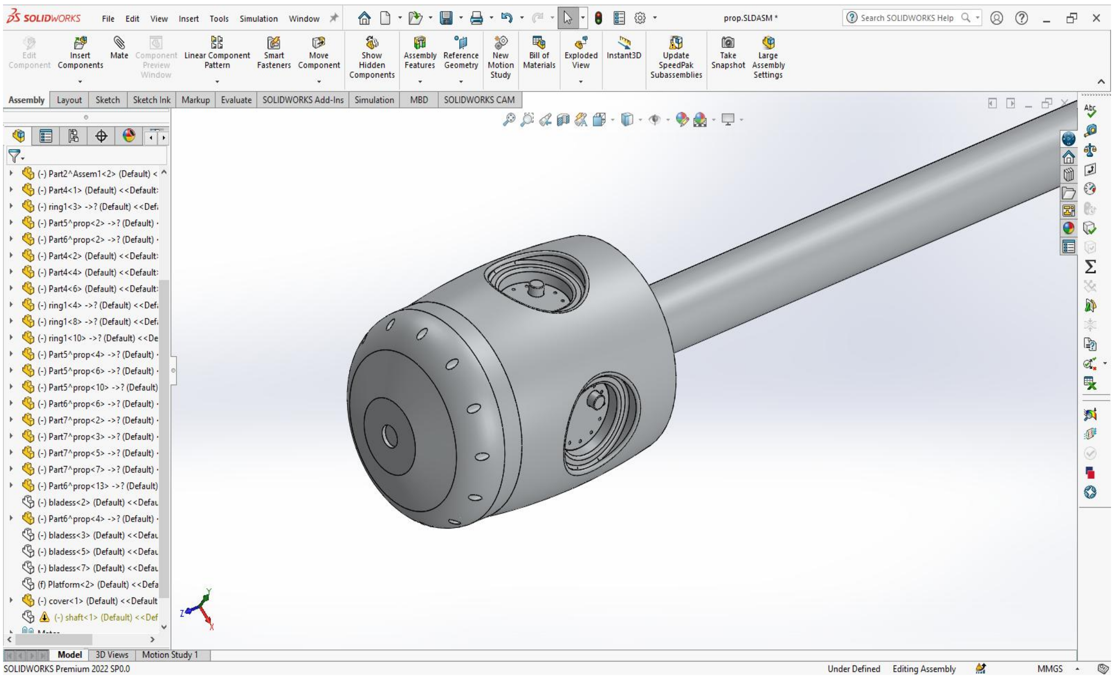


Fig. 7: 3D Representation of the Hub Assembly

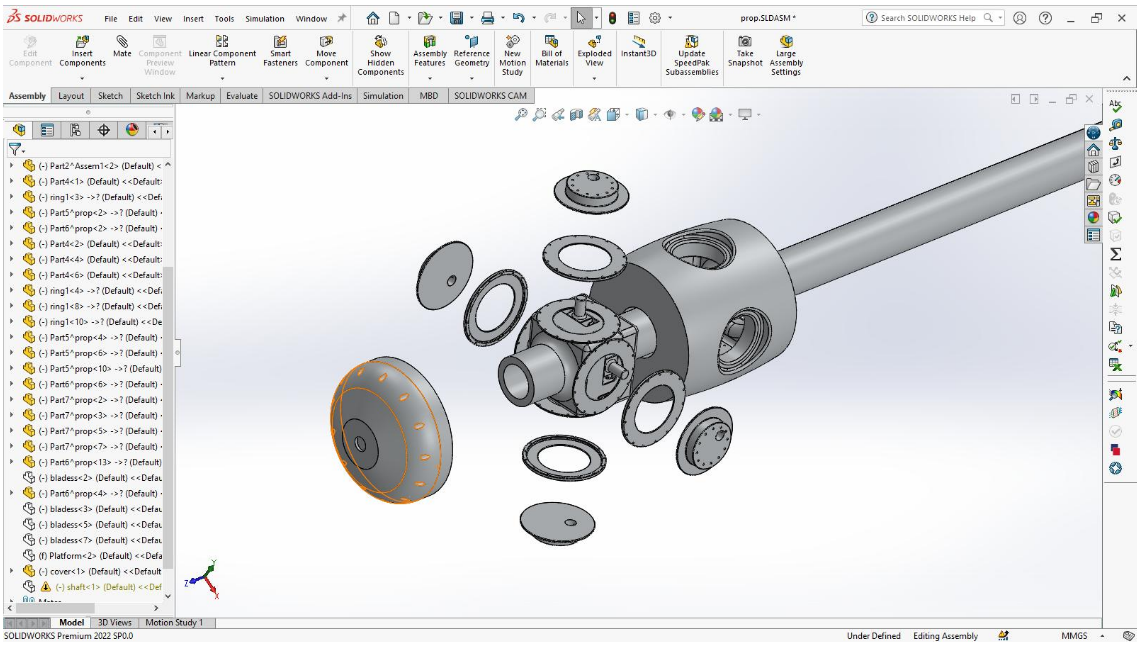


Fig. 8: Exploded View of the Hub Assembly

VI. THE CPP MODEL REPRESENTATION

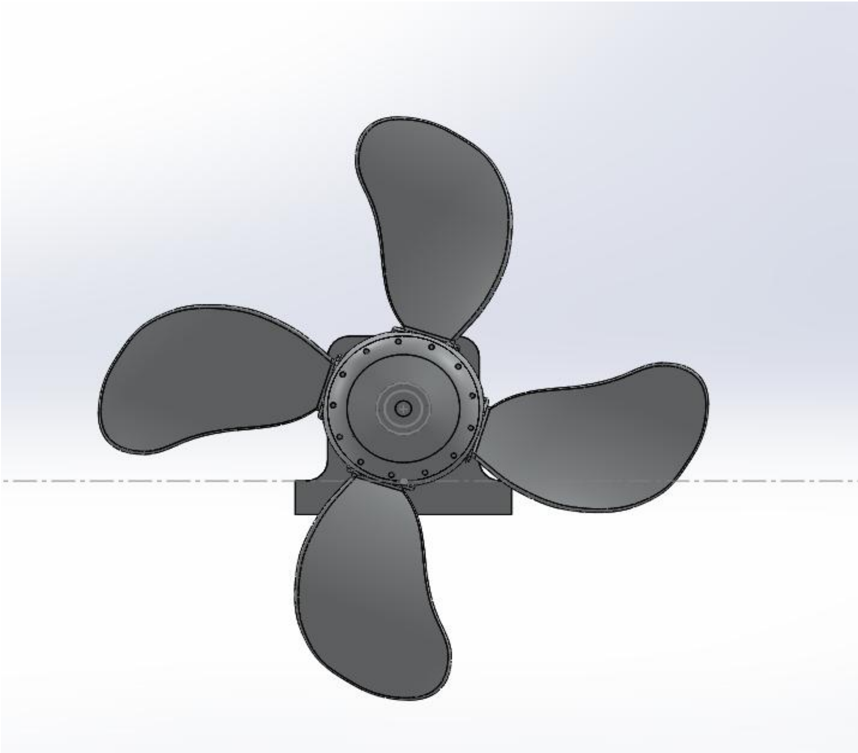


Fig. 9: The CPP Model

3.2 SIMULATION FOR CPP DESIGN OPTIMIZATION AND HYDRODYNAMIC BEHAVIOUR

Solidworks simulation software offers advanced design techniques like parametric analysis and optimization. These tools expedite the process of finding the best possible design solutions with improved accuracy, ultimately leading to superior product performance.

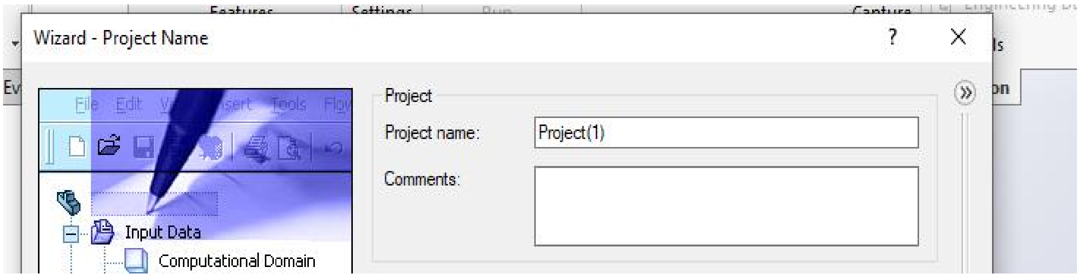
3.2.1 SETTING UP THE SIMULATION ENVIRONMENT

Simulation Objectives:

I. Blade optimization for efficiency.
II. Performance prediction at varying pitch conditions.

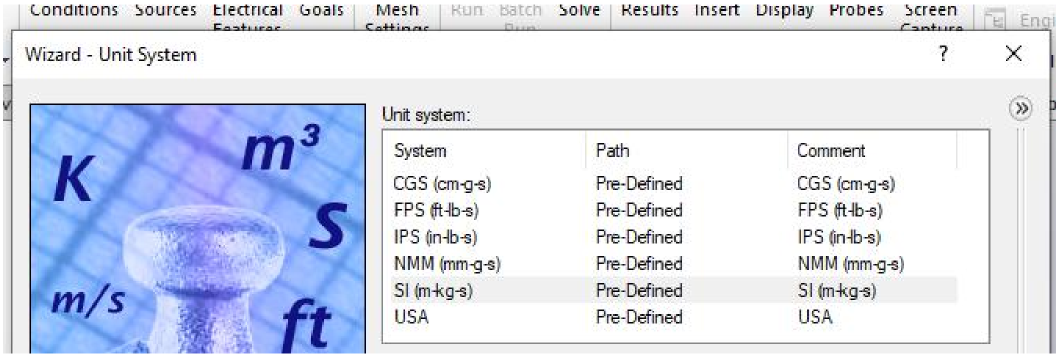
STEP 1: Initializing Project

I. Project name: Title of Project.
II. Configuration: Create configuration.



STEP 2: Defining the metric system

Metric System: SI unit (m-kg-s)



STEP 3: Defining the nature of simulation

Analysis type: External Analysis

Defining the Physical Environment

Fluid flow: true

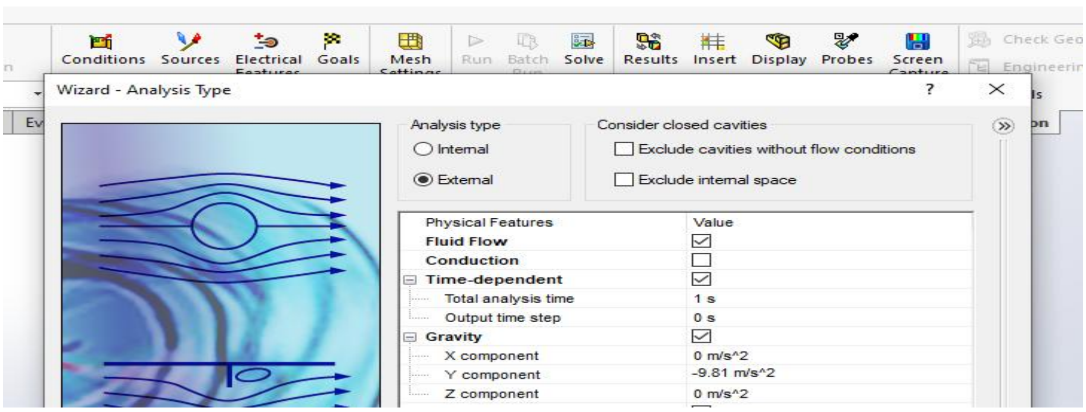
Time Dependent: true

Gravity:

x component - ($0ms^{-1}$)

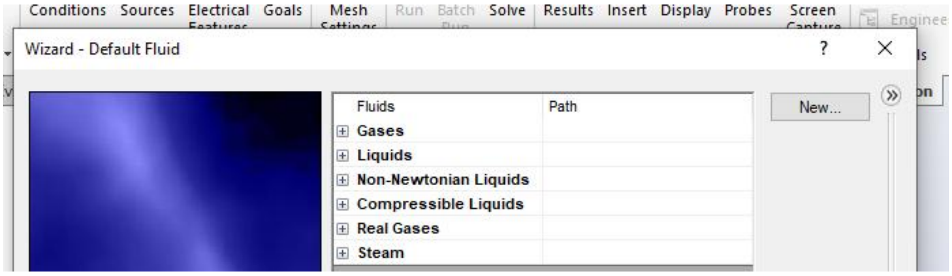
y component - ($-9.81ms^{-1}$)

z component - ($0ms^{-1}$)



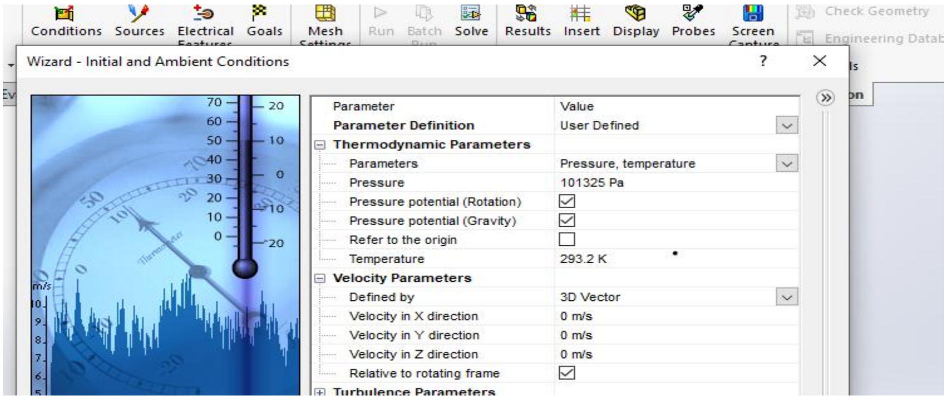
STEP 4: Defining the nature of the fluid

Fluid: Salt water (Density: 1025kgm^{3})



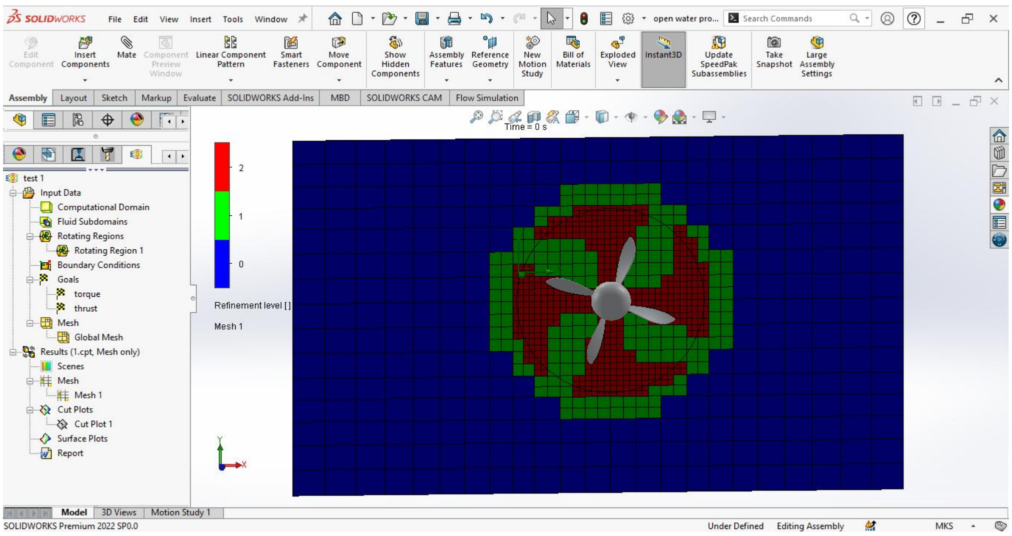
STEP 5: Defining Physical Parameters

Relative Rotating Frame: True



STEP 6: Generating Mesh and set up goals for the simulation.

Mesh Refinement size: 3

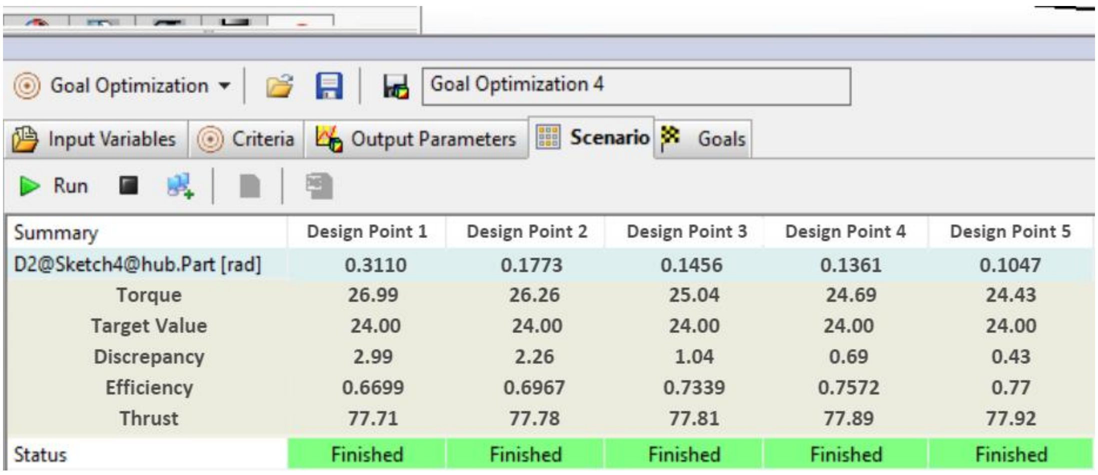


STEP 7: Run the simulation.

3.3 SIMULATION RESULTS DISCUSSION AND ANALYSIS

Our observation suggests that decreasing the tip angle of attack on a marine propeller can lead to interesting performance improvements. The study found that when the blade tip angle of attack was decreased, the torque experienced by the propeller shaft decreased and the efficiency increased. The decreased tip angle of attack might have reduced the strength of this vortex, leading to less wasted energy and ultimately, a more efficient use of engine power.

Instead of manually finding the most suitable angle pitch for the blade tip (6.0deg) for our needs, Parametric studies in solidworks and the Goal Optimization option was utilised. As a result the twist angle of the tip was varied automatically until the desired efficiency was achieved. By carefully tailoring the tip angle of attack, between reduced engine load and improved thrust, it led to a more efficient design.



Summary	Design Point 1	Design Point 2	Design Point 3	Design Point 4	Design Point 5
D2@Sketch4@hub.Part [rad]	0.3110	0.1773	0.1456	0.1361	0.1047
Torque	26.99	26.26	25.04	24.69	24.43
Target Value	24.00	24.00	24.00	24.00	24.00
Discrepancy	2.99	2.26	1.04	0.69	0.43
Efficiency	0.6699	0.6967	0.7339	0.7572	0.77
Thrust	77.71	77.78	77.81	77.89	77.92
Status	Finished	Finished	Finished	Finished	Finished

Fig. 10: Solidworks Goal Optimisation for cpp design optimization

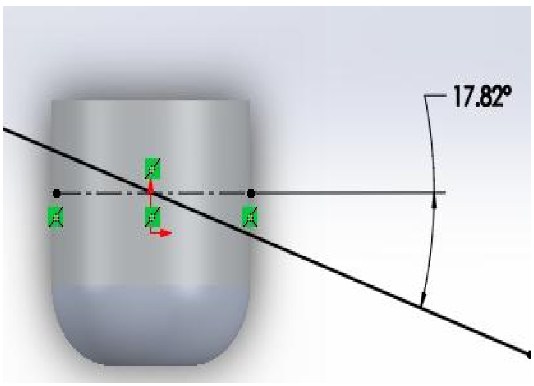


Fig. 11: Initial Blade Tip Pitch Angle

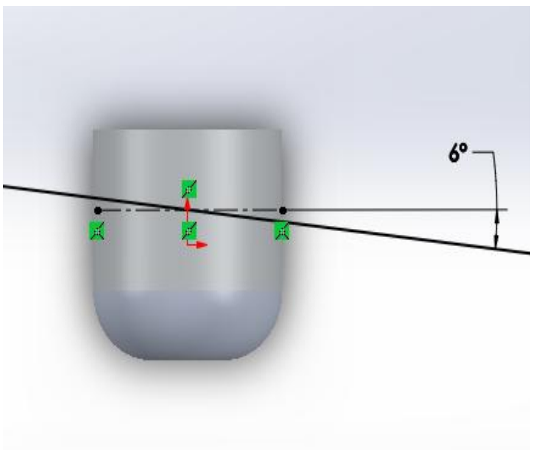


Fig. 12: Final Blade Tip Pitch Angle

Table 3: Simulation Result at Design Pitch

Parameters	Initial Design	Optimized Design
V_A (m/s)	7.31	7.6
J	0.72	0.73
T (kN)	77.71	77.92
Q (kN·m)	26.99	24.43
K_T	0.175	0.18
K_Q	0.030	0.027
η_o	0.67	0.77

3.4 ANALYSIS OF CPP PERFORMANCE AT VARYING PITCH CONDITIONS

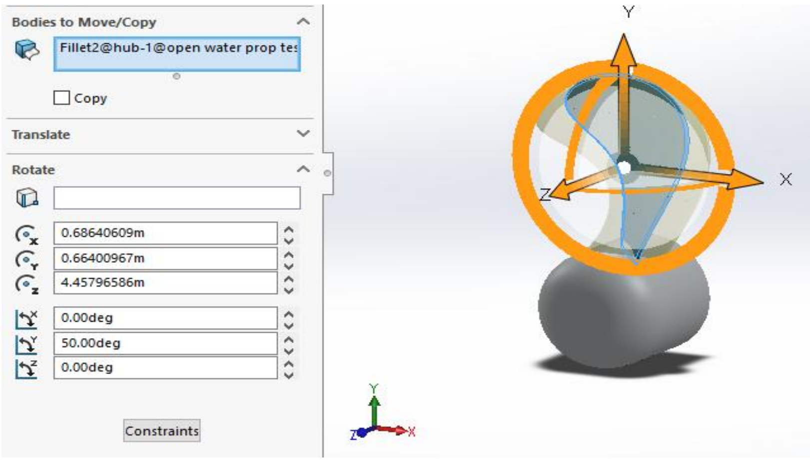


Fig. 13: Change in blade pitch angle

The adjustable pitch angle of the controllable pitch propellers (CPP) significantly impacts propulsion. As illustrated in Figure 13, a positive pitch angle is achieved by rotating the blade clockwise from the design pitch around the y-axis, while a negative angle results from counter-clockwise rotation from the design pitch.

This adjustment in pitch angle influences the magnitude and direction of thrust and torque generated by the propeller. At specific pitch settings, thrust and torque can become minimal, allowing the vessel to maintain its position despite a constant engine speed, this is illustrated in figure 15. Furthermore, adjusting the pitch angle can even reverse the direction of the thrust force, enabling the ship to move in reverse (astern) as seen in figure 16.

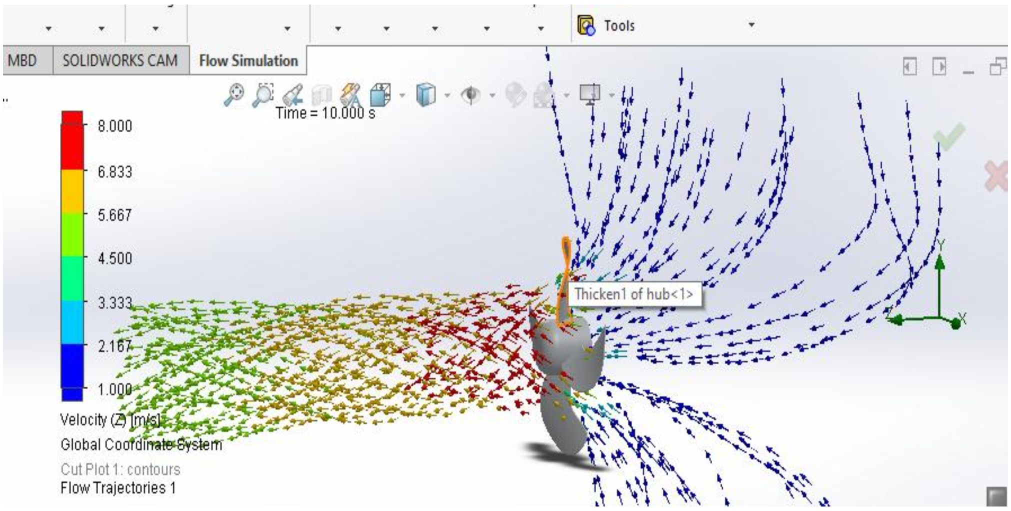


Fig. 14: Propeller - water interaction at positive thrust Condition (ahead motion)

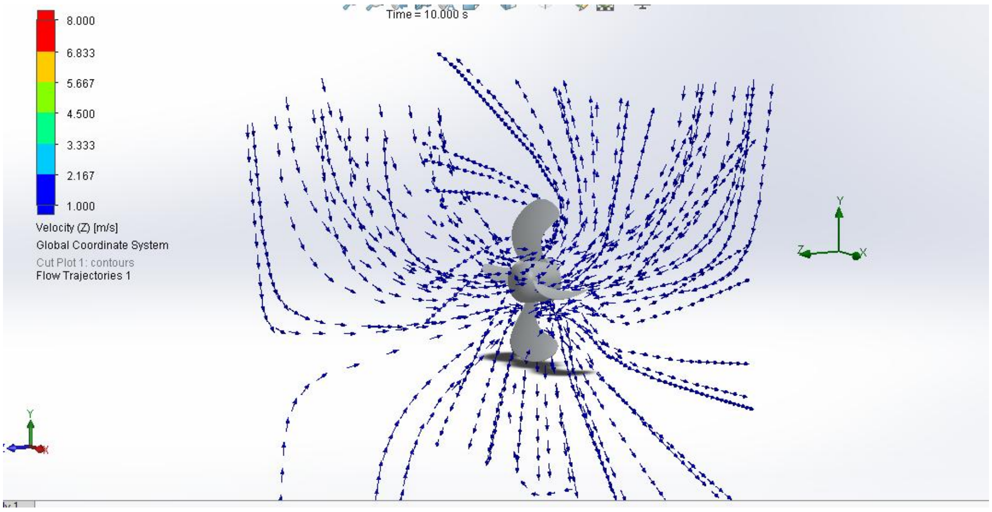


Fig. 15: Propeller - water interaction under approximate zero thrust Condition

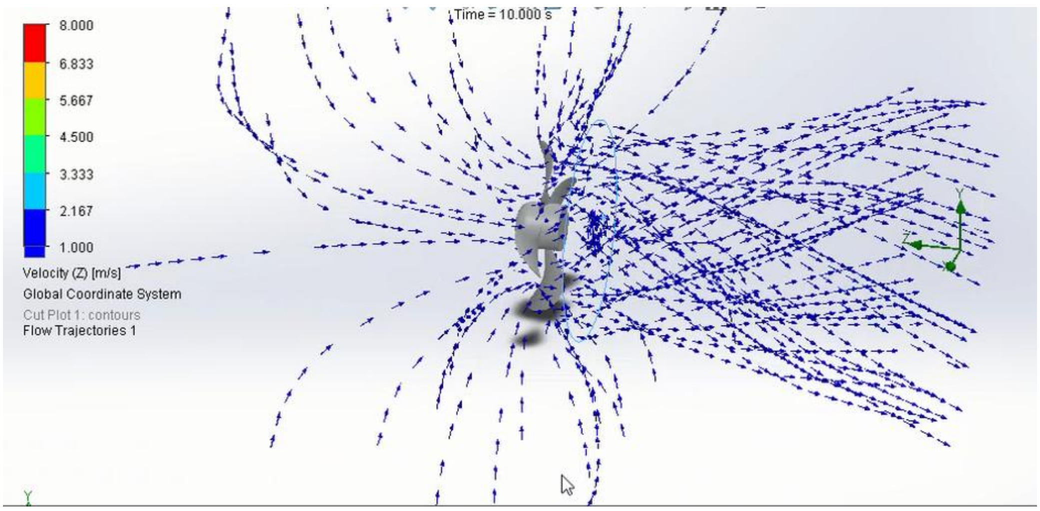


Fig. 16: Propeller - water interaction at negative thrust Condition (astern motion)

Propeller mechanics rely on Newton's third law of motion. As the propeller rotates, its blades push water rearward. This reaction force, acting in the forward direction, propels the ship. This force is referred to as Thrust (T). When the water is pushed forward the thrust force acts backwards thereby reversing the direction of the ship. A Positive thrust moves the vessel forward and a negative thrust moves it backward.

Table 4: Simulation results for positive change in pitch angle

Pitch angle (β)	10°	20°	30°	40°	50°	60°
T (kN)	34.318	-0.818	-12.095	-39.015	-61.627	-87.465
Q (kN·m)	8.153	3.228	7.276	19.880	39.656	55.786

Table 5: Simulation Results for negative change in pitch angle

Pitch angle (β)	-10°	-20°	-30°	-40°	-50°	-60°
T (kN)	83.094	89.018	109.708	101.682	91.510	36.509
Q (kN·m)	39.971	65.349	99.448	135.359	218.930	217.041

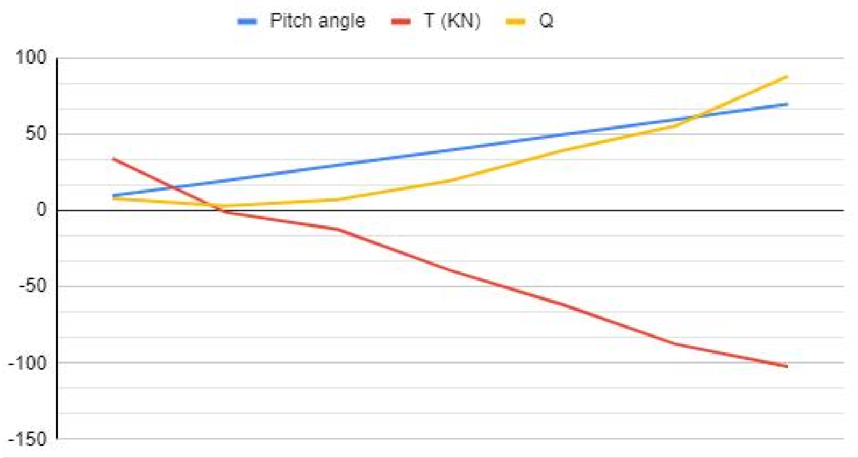


Fig.17: Graph showing trend for thrust and torque for positive increase in pitch angle

Fig. 18: Graph showing trend for thrust and torque for negative increase in pitch angle

From the simulation, the behaviour of the controllable pitch propeller has been analyzed. It has been observed that the magnitude of the thrust varies as the blade is rotated clockwise or counter clockwise from the design pitch position. The maximum ahead thrust was found at a pitch angle at -30° from the design pitch. While approximate zero thrust was found at a pitch angle of 20° from the design pitch.

3.5 THE 3D MODEL OF THE FINAL DESIGN FOR THE CONTROLLABLE PITCH PROPELLER

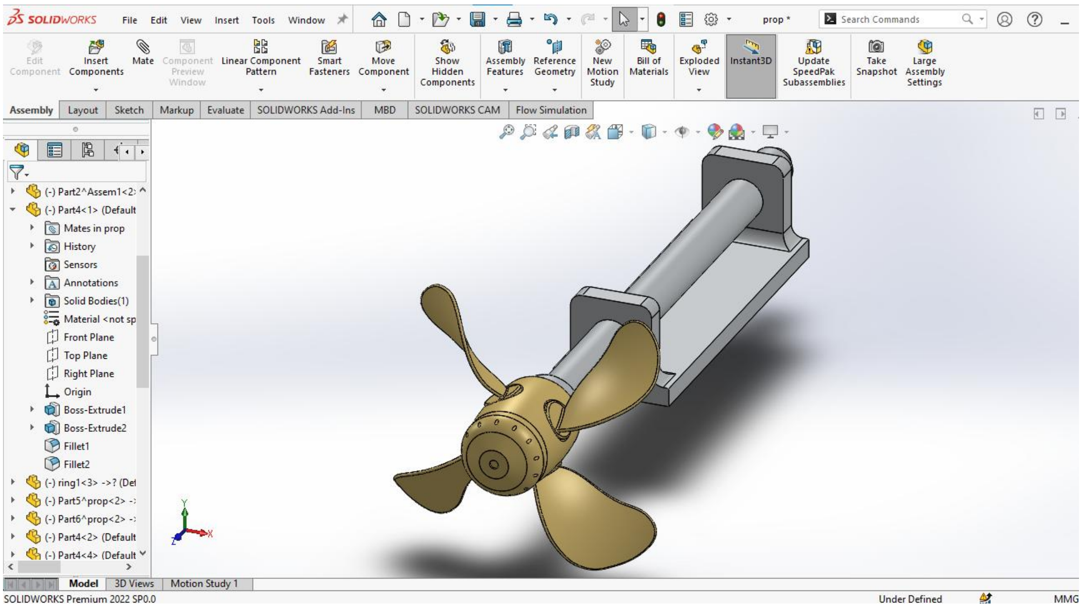


Fig. 19: 3D view of the Controllable Pitch Propeller design model

4. CONCLUSION

The design and simulation of a 4-bladed controllable-pitch marine propeller for small to medium-sized vessels, for enhancing maneuverability and efficiency in different maritime operational conditions was carried out.

One of the key findings from the simulations was the identification of an optimal pitch angle range for the propeller blades. By analyzing the flow patterns and forces acting on the blades at different pitch angles, the pitch angle that maximized thrust while minimizing drag was determined. This optimization resulted in a propeller design that achieved a higher level of efficiency compared to the initial design.

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