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

PRESENTED BY

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SUBMITTED TO

THE MARINE ENGINEERING DEPARTMENT,
FACULTY OF ENGINEERING,
UNIVERSITY OF BENIN

IN PARTIAL FULFILLMENT OF THE REQUIREDMENT FOR THE AWARD OF A BACHELOR'S DEGREE IN MARINE ENGINEERING

APRIL 2024

CERTIFICATION

This is to certify that this project work was carried out by EDEKOVWERE OGHENEFEJIRO DAVID (ENG1805235), ONYEAGHALA FAVOUR NZUBECHI (ENG1805277), IBHAFIDON EHIMARE RICHARD (ENG1805245) and EHIGIATOR WISDOM EFOSA (ENG1805239) of the Department of Marine Engineering, University of Benin, Benin City, Edo State, Nigeria, under the supervision of Professor Godfrey O. Ariavie.

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DEDICATION

We dedicate this project to God almighty, for His guidance and blessings throughout this endeavor. We also dedicate this project to our families and friends for their unwavering support and encouragement throughout this journey. Their love and belief in us have been our constant motivation. And lastly, to all the researchers and engineers whose groundbreaking work has paved the way for advancements in marine propulsion.

ACKNOWLEDGEMENT

First and foremost, we want to express my heartfelt gratitude to the Almighty God for His guidance, blessings, and strength throughout this project. Without His grace, none of this would have been possible.

We would like to extent our deepest appreciation to our project supervisor, Professor Godfrey O. Ariavie, for his exceptional guidance, support, and mentorship. His insights and encouragement have been invaluable to our project. His contributions continue to inspire and guide us in our pursuit of knowledge and innovation.

We also extend our thanks to our lecturers, Engr. W. Jaja, Dr. A. Orogun, Engr. M. Osikhueme, Dr. P. Ekhator, Dr. O. Ighodaro, Dr. H. Egware, and others to name a few, for their valuable input and guidance.

Additionally, we extend our thanks to the following individuals for their contributions and support.

The Family of Mr. and Mrs. Leo Edekovwere, Eseoghene Edekovwere, Destiny Erhimefe, Oghenefejiro Erhimefe, Avunu Wisdom and Usiagu Victor, for their invaluable support and sacrifices toward the successful completion of the project.

The Family of Mr. and Mrs. Desmond Onyeaghala, for their immense contribution and support.

The Family of Mr. And Mrs. Ehigiator, Emmanuel Ehigiator, for their encouragement and contributions.

The Family of Mr. and Mrs. Ibhafidon, for their invaluable support and contribution to the success of this project.

Lastly, we would like to acknowledge the University of Benin for providing us with the resources and environment conducive to learning and innovation.

ABSTRACT

The project is focused on designing and simulating a controllable-pitch marine propeller for small to medium sized vessel such as fishing trawlers, passenger ferries, tugs and yacht, recognizing the pivotal role such technology plays in optimizing vessel performance. By addressing limitations in conventional fixed-pitch propellers, the project has been able to contribute to the evolution of marine propulsion systems, pushing the boundaries of efficiency and adaptability.

The project methodology involved a comprehensive literature review on marine propulsion and propeller design principles, followed by the formulation of a mathematical analysis for the controllable-pitch propeller design. SolidWorks 3D modeling software is utilized to create a detailed propeller design, which is then subjected to Computational Fluid Dynamics (CFD) simulations to analyze hydrodynamic performance. An iterative optimization process refines the design based on simulation outcomes, aiming for enhanced efficiency and performance.

Through parametric studies and optimization, the project successfully demonstrates the efficiency gains achievable by adjusting the blade tip pitch angle. The controllable-pitch propeller's ability to adapt to varying operational conditions is highlighted, showcasing its potential for improved fuel efficiency and maneuverability. The project contributes to the ongoing advancements in marine propulsion technology, offering insights into the design and simulation of controllable-pitch propellers for small to medium-sized vessels.

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ABBREVIATIONS

2D - Two Dimensional

3D - Three Dimensional

BAR - Blades Area Ratio

CAD - Computer Aided Design

CFD - Computational Fluid Dynamics

CPP - Controllable Pitch Propeller

DES - Detached Eddy Simulations

DNS - Direct Numerical Simulations

EAR - Expanded Area Ratio

FPP - Fixed Pitch Propeller

HP - Horsepower

ITTC - International Towing Tank Conference

JIP - Joint Industry Project

KCA - Kings College Admiralty

LES - Larger Eddy Simulation

MARIN - Marine Resesearch Institute Netherlands

RANS - Reynolds- Averaged Navier Stokes

RPM - Revolutions per Minutes

SNAME - Society of Naval Architects and Marine Engineers

CHAPTER 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. This project embarks on a journey to design and simulate a controllable-pitch marine propeller, driven by the recognition of the pivotal role such advancements play in optimizing vessel performance. With a focus on enhancing both efficiency and maneuverability, this endeavor seeks to address current limitations in conventional propeller designs, bringing forth a more adaptive and responsive solution. Through a synthesis of design methodologies and advanced simulation tools, we aim to contribute to the ever-expanding knowledge base in marine propulsion, pushing the boundaries of what is achievable in the dynamic realm of maritime technology. This introduction lays the groundwork for an exploration into the design intricacies and simulation intricacies that will unfold in the subsequent chapters, with the ultimate goal of steering marine propulsion towards new horizons.

1.1 BACKGROUND OF STUDY

The history of marine propulsion dates back to the advent of steam engines in the 19th century, which marked a transformative period in naval architecture (Carlton, 2012). The shift from paddlewheels to propellers in the late 1800s marked a significant milestone in marine propulsion, providing vessels with a more efficient means of thrust generation (Molland & Turnock, 2014). A propeller is a fan like structure which is used to propel the ship by using the power generated and transmitted by the main engine of the ship. The transmitted power is converted from rotational motion to generate a thrust which imparts momentum to the water, resulting in a force that acts on the ship and pushes it forward (ahead) or backwards (Eckstein, 2016).

A ship propels on the basis of Bernoulli's principle and Newton's third law. A pressure difference is created on the forward and aft side of the propeller blade and water is accelerated behind the blades. The thrust from the propeller is transmitted to move the ship through a transmission system which consists of a rotational motion generated by the main engine crankshaft, intermediate shaft and its bearings, stern tube shaft and its bearing and finally by the propeller itself. A ship can be fitted with one, two and rarely three propellers depending upon the speed and manoeuvring requirements of the vessel (Wankhede, 2020).

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. 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).

Conventional propellers, with fixed-pitch configurations, encounter limitations in scenarios with varying vessel speeds and loading conditions (Carlton, 2012). The fixed pitch often results in suboptimal performance, leading to increased fuel consumption and reduced overall efficiency (Molland & Turnock, 2014).

Controllable-pitch marine propellers represent a pivotal advancement in marine propulsion technology, offering dynamic control over blade angles during operation. Unlike conventional fixed-pitch designs, the controllable-pitch propeller allows the adjustment of blade angles, providing ship operators with unparalleled flexibility in optimizing thrust under varying conditions (Carlton, 2012). The mechanism involves altering the pitch of the propeller blades, enabling vessels to adapt to different operational requirements, such as changes in speed, load, or environmental conditions (Faltinsen, 2010). This adaptability is particularly crucial in dynamic maritime environments, where vessels often encounter varying hydrodynamic forces.

The controllable-pitch propeller's ability to adjust its blade angles addresses inherent limitations observed in fixed-pitch designs. It promises increased efficiency by enabling vessels to maintain optimal performance across a spectrum of operating conditions, a critical factor in the pursuit of enhanced fuel efficiency and reduced environmental impact (Molland & Turnock, 2014). This adaptability also plays a key role in improving maneuverability, allowing vessels to navigate challenging scenarios with greater precision and responsiveness.

Furthermore, controllable-pitch technology extends its relevance beyond the maritime sector. The aviation industry has adopted similar mechanisms for aircraft propellers, showcasing the versatility and effectiveness of this design paradigm in optimizing performance. As this project delves into the design and simulation of a controllable-pitch marine propeller, it seeks to unlock the full potential of this technology, pushing the boundaries of efficiency, maneuverability, and adaptability in maritime propulsion systems.

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). However, there exists a need for further exploration and refinement to optimize controllable-pitch designs for specific vessel types and operational conditions.

1.2 MOTIVATION

This project is motivated by the imperative to address the limitations of conventional marine propellers and capitalize on the adaptability offered by controllable-pitch designs. The goal is to contribute to the ongoing advancements in marine propulsion technology, aligning with the evolving demands for increased efficiency, maneuverability, and sustainability in maritime operations.

1.3 STATEMENT OF PROBLEM

The current landscape of marine propulsion faces persistent challenges in optimizing the efficiency and maneuverability of vessels, particularly concerning conventional fixed-pitch marine propellers. Fixed-pitch designs, while widely used, exhibit limitations in adapting to varying operational conditions, resulting in suboptimal performance in terms of fuel efficiency and maneuvering capabilities. The fixed pitch, being static, fails to account for the dynamic nature of maritime environments where vessels often encounter diverse operating conditions, including changes in speed, load, and environmental factors. This lack of adaptability contributes to increased fuel consumption, reduced overall efficiency, and compromises the ability of vessels to navigate with precision, especially in dynamic scenarios such as harbor maneuvers or when transiting through congested waterways.

Prevalent controllable pitch propeller designs are mechanically complex and they have a relatively larger hub compared with the fixed pitch propellers because the hub has to have space for a hydraulically activated mechanism for blade pitch (angle) control. Due to the relatively large hub, cavitation can be induced and the efficiency is reduced. They also involve a higher risk of problems in service and can pose environmental threats (such as oil leakage into the ocean).

Existing solutions, while addressing certain aspects of these challenges, fall short of providing a comprehensive and adaptive solution for vessels operating in diverse maritime environments. The need for a more dynamic and responsive marine propeller design becomes evident to overcome the limitations of fixed-pitch propellers. This research identifies a critical gap in the current state of marine propulsion technology, emphasizing the necessity for a controllable-pitch marine propeller capable of dynamically adjusting blade angles during operation. The problem at hand is twofold: optimizing the propeller's performance to ensure maximum efficiency under varying operational conditions and enhancing the maneuverability of vessels in dynamic maritime environments. Addressing these challenges requires a breakthrough in both design and simulation techniques to propel marine propulsion technology towards greater adaptability and efficiency.

This project seeks to address the identified problem by designing and simulating a controllable-pitch marine propeller, contributing to the evolution of marine propulsion systems for enhanced maneuverability and efficiency.

1.4 AIMS AND OBJECTIVES

The aim of this project is to design and simulate 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.

This objectives of the project are as follows:

1. Analyze existing literature on marine propulsion, propeller design, and controllable-pitch technologies.

2. Study design theories, series, charts and formulate mathematical analysis for the design of the Controllable Pitch Propeller.

3. Employ the SolidWorks 3D modeling software to create a detailed design of the controllable-pitch propeller.

4. Perform CFD simulations (with the aid of the SolidWorks software simulation software) to analyze fluid dynamics around the controllable-pitch propeller, optimize blade design and predict performance at different pitch angles.

5. Refine the propeller design based on simulation results for enhanced efficiency and performance.

1.5 SIGNIFICANCE OF STUDY

The significance of the project lies in its potential to positively impact marine propulsion. Introducing a controllable-pitch design addresses limitations in fixed-pitch propellers, aiming to enhance efficiency, reduce fuel consumption, and improve operational adaptability and maneuverability. This project aligns with the maritime industry's need for sustainable and efficient transportation, offering economic benefits while minimizing environmental impact.

1.6 PROJECT SCOPE AND LIMITATIONS

The scope of this project encompasses the design and simulation of a controllable-pitch marine propeller with a focus on enhancing maneuverability and efficiency in diverse maritime operational conditions. The project will involve an extensive literature review on marine propulsion, propeller design principles, and controllable-pitch technologies. The design phase will utilize SolidWorks 3D modeling software to create a detailed representation of the controllable-pitch propeller, considering factors such as blade shape, hub configuration, and overall geometry. Computational Fluid Dynamics (CFD) simulations, performed using SolidWorks flow, will analyze the fluid dynamics around the propeller under varying operational conditions. The optimization process will be iterative, refining the design based on simulation results to achieve enhanced propeller performance.

The project is confined by several limitations that shape its boundaries. Firstly, there will be no physical prototyping, as the project's emphasis is placed on design and simulation rather than construction and testing of an actual propeller prototype. Material properties for the propeller components will be assumed based on industry standards, as actual material testing is beyond the project's scope. The CFD simulations, essential for understanding fluid dynamics, will involve simplifications and assumptions due to computational constraints. While the simulations will consider a range of operational conditions, real-world complexities such as cavitation effects, underwater turbulence, and interactions with vessel components may not be fully captured. Furthermore, the study will primarily focus on small to medium-sized vessels that require a high degree of maneuverability (such as yachts, tugs, passenger ferries, fishing vessels, etc), and generalizing findings to larger vessels with distinct operational requirements may be limited. The design analysis will mainly focus on the propeller open water performance. Lastly, the project lays emphasis on the CPP geometry and effect of pitch change, excluding detailed analysis on the behaviour of the pitch change mechanism. Acknowledging these limitations is essential for a nuanced interpretation of the project's outcomes and implications.

1.7 METHODOLOGY

The project methodology involves a systematic approach to designing and simulating a controllable-pitch marine propeller (CPP) for enhanced maneuverability and efficiency. The initial phase comprises an in-depth literature review to understand existing knowledge and challenges in marine propulsion, followed by an evaluation of conventional fixed-pitch propellers to identify areas for improvement. A mathematical analysis capturing the geometry and dynamic behavior of the CPP will be formulated, leading to the utilization of SolidWorks 3D modeling software for detailed propeller design. Computational Fluid Dynamics (CFD) using SolidWorks will analyse propeller hydrodynamics performance.. An iterative optimization process will refine the design based on simulation outcomes.

CHAPTER 2

LITERATURE REVIEW

The exploration of marine propulsion technologies has long been a focal point in maritime engineering, with the efficiency and maneuverability of vessels standing as pivotal factors in their operational success. This literature review aims to dissect the intricacies of controllable pitch propellers, shedding light on their historical development, working principle, research/findings and inherent limitations. By establishing a solid foundation in the existing body of knowledge, we can discern the driving forces behind the continual quest for innovative propulsion systems within the maritime industry. Efficiency, maneuverability, and environmental considerations emerge as paramount concerns, propelling the need for advancements in propulsion technologies. This review sets the stage for a deeper exploration into the realm of controllable-pitch marine propellers, seeking to address the shortcomings identified in conventional fixed-pitch designs.

2.1 THE CONTROLLABLE PITCH PROPELLER: HISTORICAL DATA AND RECENT STUDIES/ DEVELOPMENT

The controllable-pitch propeller (CPP) system, also known as a variable-pitch propeller system, is a type of marine propeller system that allows for the adjustment of the blade pitch angle of a propeller while the vessel is in operation. In contrast to fixed-pitch propellers, where the blade angle is fixed and cannot be changed, variable-pitch propellers offer the ability to dynamically alter the pitch of the blades. Unlike fixed pitch propellers whose only operational variable is rotational speed, the controllable pitch propeller provides an extra degree of freedom in its ability to change blade pitch.

The mechanical propulsion of ships became a reality during the first part of the nineteenth century when reciprocating steam engines were first used for the purpose of driving paddle wheels. During this period, the screw propeller was developed from a strange helical structure into a useful unit which was more effective and much more compact than the voluminous paddle wheels (Van Manen, 1958).

Even at that early stage, thoughts were already turning to the possibility of reversible blades -which brought the concept of the controllable pitch propeller . In 1844, a patent was granted to Bennet Woodcroft for the invention of an external mechanism to reverse propeller blades. About one century ago another Englishman named Bevis designed a mechanism completely contained inside the propeller hub**.** The first practical applications of the reversible propeller, however, were found in the early part of the present century, together with the introduction of the diesel engine. The reason for this is easy to understand: direct reversing of a diesel engine was much more of a problem than reversing a steam engine. It is a remarkable fact that the diesel engine was first introduced for seagoing vessels in combination with a reversible propeller, only later being applied to drive a solid fixed pitch propeller. In 1908, a 160 Horse-Power (HP) Werkspoor-type reversible propeller was installed in a Dutch schooner, named 'San Antonio'. The equipment was intended for supplying auxiliary power to sailing craft and remained in service for twenty eight years. Two years later, in 1910, directly reversible diesel engines were installed in what were known at that time as diesel-propelled steamers. The `Vulcanus' and the `Selandia' are unforgettable names in this respect. The reversible propeller retained its popularity for a short period, but after 1920, the system of mechanical adjustment became inadequate for the steadily increasing power being installed on ocean-going ships, and the application of these propellers remained confined to small craft (Wind, 1971).

Hydraulic power was first introduced in 1934 as a means of providing the required adjusting forces, thus giving the controllable pitch propeller a new and unrestricted field of application. Kamewa, a Finnish company, emerged as a major player, introducing its innovative design featuring a single hydraulic piston actuating each blade (Strandell, 1940). For a long time the controllable pitch propeller was restricted to applications below 10,000 HP, but between 1940 - 1950, there has been a sudden increase in this respect. Propellers of 25,000 HP and more have already been put into service between 1950 and 2000. By the 1960s, CPPs were becoming increasingly reliable and efficient, finding their way onto larger cargo ships and tankers. Figure 2.1 illustrates how the power absorbed per propeller has increased for both solid (fixed pitch) and controllable pitch propellers from 1800 - 2000.

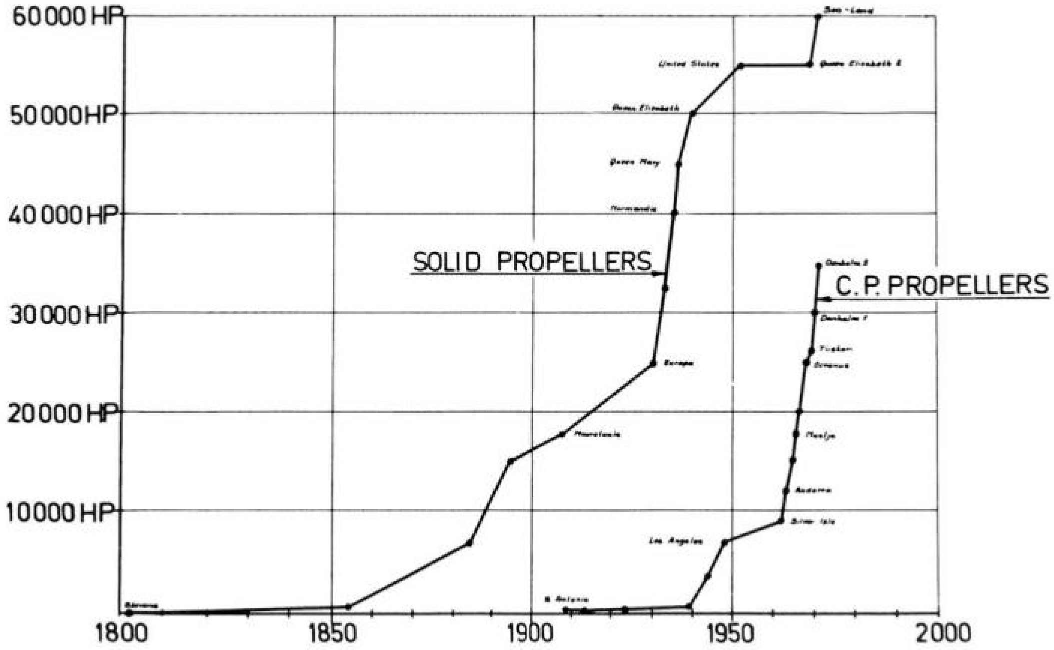


Figure 2.1: Power increase per propeller for solid and controllable pitch propellers of passenger- and merchant ships (wind, 1971).

Since the mid-1950s, the controllable pitch propeller has grown in popularity from representing a small proportion of the propellers produced to its current position of having a very substantial market share. This growth is illustrated by Figure 2.2 which shows the proportion of controllable pitch propeller systems when compared to the total number of propulsion systems classed with Lloyd’s Register during the period 1960 to 2004, taken at five-year intervals, whilst Table 2.1 shows the relative distribution of controllable pitch propellers within certain classes of ship type during this period. From the table it is seen that the controllable pitch propeller is most favoured in the passenger ships and ferries, general cargo vessels, tugs, offshore vessels and fishing trawlers (mainly because of their maneuverability requirements), noting of course that this relates to vessels with installed powers of greater than 2000 bhp (Carlton, 2012).

Currently, the controllable pitch propeller has about a 35% market share when compared to fixed pitch propulsion systems and tends to be most popular in the ferry, general cargo, tug and trawling markets (Carlton, 2019).

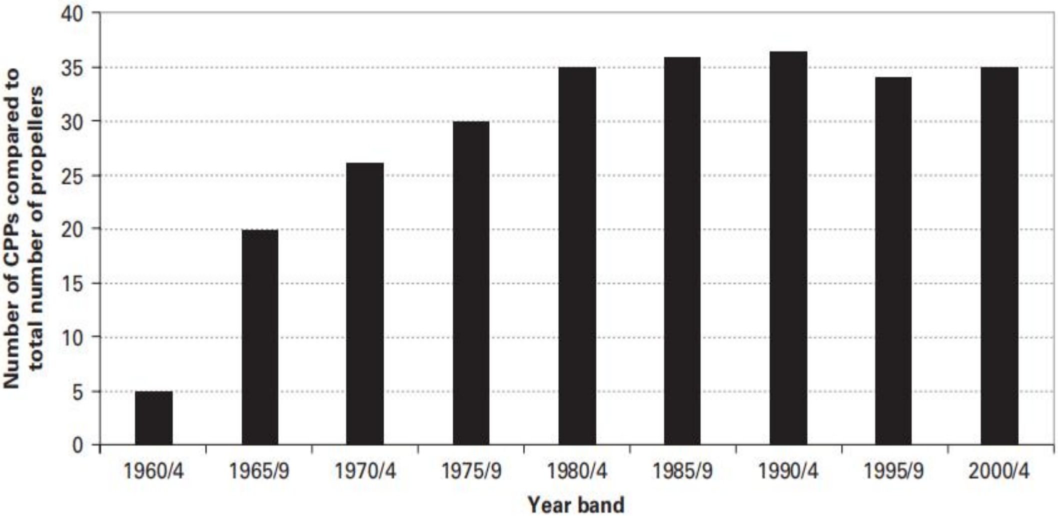
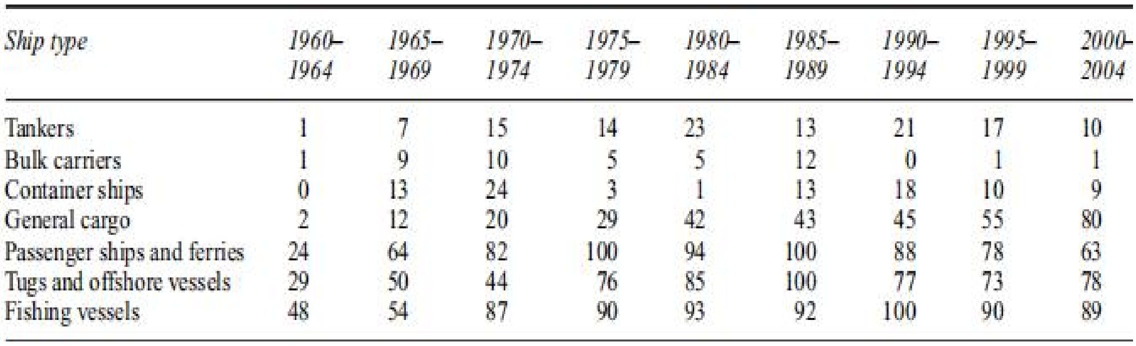


Figure 2.2: Market Share of controllable pitch propellers from 1960 - 2004 (Carlton, 2019)

Table 2.1: Percentage relative distribution of controllable pitch propellers to the total number of propellers by ship type classed with Lloyd's Register and having installed powers greater than 2000 bhp (Carlton, 2019)



Ship type	*1960–1964*	*1965–1969*	*1970–1974*	*1975–1979*	*1980–1984*	*1985–1989*	*1990–1994*	*1995–1999*	*2000–2004*
Tankers	1	7	15	14	23	13	21	17	10
Bulk carriers	1	9	10	5	5	12	0	1	1
Container ships	0	13	24	3	1	13	18	10	9
General cargo	2	12	20	29	42	43	45	55	80
Passenger ships and ferries	24	64	82	100	94	100	88	78	63
Tugs and offshore vessels	29	50	44	76	85	100	77	73	78
Fishing vessels	48	54	87	90	93	92	100	90	89

The controllable-pitch propeller market is experiencing significant growth due to the increasing demand for fuel-efficient and technologically advanced propellers in the maritime industry. The market is driven by factors such as rising maritime trade activities, growing shipbuilding industry, and the need for reducing carbon emissions. The future outlook for the controllable-pitch propeller market is promising, with a strong emphasis on research and development to improve propeller design and efficiency. Additionally, the increasing adoption of automation and electric propulsion systems is likely to further boost market growth. Factors like stringent environmental regulations and the need for energy conservation are expected to drive the market in the foreseeable future.

The period between 2005 and 2023 witnessed significant advancements in marine controllable pitch propellers (CPPs), driven by the quest for increased efficiency, maneuverability, and sustainability. Some key developments includes:

1. Enhanced Automation and Integration:

I. CPPs became increasingly integrated with advanced ship control systems and autopilots. This enabled automatic blade pitch adjustments based on real-time data like speed, load, and environmental conditions, optimizing performance and reducing pilot workload.

II. Sensor data from CPPs and other systems were utilized to develop predictive maintenance algorithms. These algorithms could anticipate potential issues before they occurred, minimizing downtime and maintenance costs (Wang et al., 2019).

2. Focus on Sustainable Performance:

I. Research efforts focused on creating optimized blade profiles for specific applications, including high-speed vessels, fuel-efficient cargo ships, and those operating in challenging environments like ice or debris. These blades aimed to improve efficiency and reduce emissions. (Carlton, 2019).

II. Traditional hydraulic systems were challenged by electric and hybrid actuation methods. These alternatives promised quieter operation, reduced maintenance requirements, and increased energy efficiency, especially when paired with renewable energy sources like on-board solar panels. (Geertsma et al., 2017)

3. Material and Manufacturing Advancements:

I. The use of advanced materials like composite blades and lighter alloys gained traction. These materials offered improved strength, reduced weight, and enhanced corrosion resistance, further contributing to efficiency and durability.

II. 3D printing technology began to be explored for the production of CPP components. This technology enabled more complex and customized designs, optimizing performance for specific vessel needs..

2.1.1 RECENT STUDIES AND ADDITIONAL AREAS OF INNOVATION

A recent study on the analysis of the effect of changes in pitch ratio and number of blades on cavitation on CPPs (Arifin et al, 2020) concluded that the pressure ratio on the propeller tends to increase at higher rotation and tends to increase on the higher pitch at the constant rotation. The cavitation area that occurred on the propeller is influenced by the following variables i.e. the rotation (rpm), diameter propeller (cm), and propeller pitch ratio. This article suggested possible solutions in reducing cavitation by controlling propeller parameters under different conditions.

The Maritime Research Institute Netherlands (MARIN) performed open water propeller model tests to study the off- design performance of CPPs, which led to the development of two new propeller series (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. Compared to the ideal efficiency, the C-series propellers show good efficiency values (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. To understand and control CPPs, we need to know the potential consequences of propeller pitch variations on ship self-propulsion. The pitch ratio, corresponding to the maximum open-water propeller efficiency value, differed depending on ship speed. This indicates that an optimum propeller pitch must be identified to increase efficiency.

New designs and coatings were developed to minimize cavitation and underwater noise pollution, benefiting marine life and improving acoustic comfort for passengers and crew.

There have also been advancements in control systems and blade design aimed to further improve maneuverability, particularly for vessels operating in crowded or challenging environments.

2.2 KEY COMPONENTS AND PARTS OF THE CONTROLLABLE PITCH PROPELLER SYSTEM

1. Blade Pitch Control Mechanism:

Variable-pitch propellers (CPPs) have a mechanism for adjusting the pitch angle of each blade. This can be achieved through hydraulic, electro-mechanical, or electro-hydraulic systems depending on the design of the variable-pitch propeller.

2. Hub and Blade Construction:

Blades are the primary components that generate thrust. They are attached to the hub and can be individually adjusted in pitch.

The propeller hub is designed to accommodate the movement of each blade. The hub of the controllable pitch propeller, in addition to providing a housing for the blade actuation mechanism, must also be sufficiently strong to withstand the propulsive forces supplied to and transmitted from the propeller blades.

In general, therefore, controllable pitch propellers tend to have larger hub diameters than those for equivalent fixed pitch propellers. Typically, the controllable pitch propeller hub has a diameter in the range 0.24–0.32D: in contrast, fixed pitch propeller boss diameters are generally within the range 0.16–0.25D (Carlton, 2019).

3. Actuation System:

Actuators are devices that convert energy into motion. In the context of controllable-pitch propellers, actuators are used to move and control the pitch of the blades. These can be hydraulic cylinders, servos, or other mechanisms that respond to control inputs.

4. Pitch Control System:

The pitch control system, often integrated into the vessel's propulsion control system, allows the operator to adjust the pitch of the propeller blades based on operational requirements.

5. **Control Console:**

The control console is the interface through which the operator adjusts the pitch of the propeller blades. It includes levers, switches, or electronic controls to manipulate the pitch control system.

6. **Power Source:**

The power source provides the energy needed to operate the pitch control system and actuators. This can be hydraulic power, electrical power, or a combination depending on the system's design.

7. **Sensors:**

Sensors are used to monitor various parameters such as engine speed, load, and vessel conditions. This information can be fed back into the control system to optimize pitch adjustments.

2.3 PITCH CONTROL MECHANISM

Controllable pitch propellers (CPPs) utilize various pitch control mechanisms, and three common types stand out in marine propulsion systems. Hydraulic systems rely on pressurized hydraulic fluid to drive pistons or cylinders within the propeller hub, ensuring precise blade angle adjustments with high power density and reliability but introducing complexity and maintenance concerns. Electric-mechanical systems employ motors to drive gears or screws, offering simplicity and lower maintenance requirements, yet may exhibit limited power density and potential susceptibility to electrical faults. Electro-hydraulic systems combine electric motors and hydraulic pumps, offering a balanced solution with high power density, precise control, and reduced risk of leaks, albeit with increased complexity and maintenance requirements. Each type presents a unique set of advantages and challenges, allowing vessel operators to choose the most suitable CPP configuration based on specific performance and operational needs.

2.3.1 OVERVIEW OF THE HYDRAULIC PITCH CONTROL MECHANISM

The hydraulic pitch actuating mechanism, designs can be broadly grouped into two principal types; those with inboard and those with outboard hydraulic actuation (Carlton, 2012). Figure 2.3 shows these principal types in schematic form.

CPPs are generally actuated by hydraulic oil power systems due to their high power–volume ratio (Geway et al, 1979). Usually,the simplest hydraulic–mechanical actuator is used: the piston in a cylinder (Martelli et al., 2013).

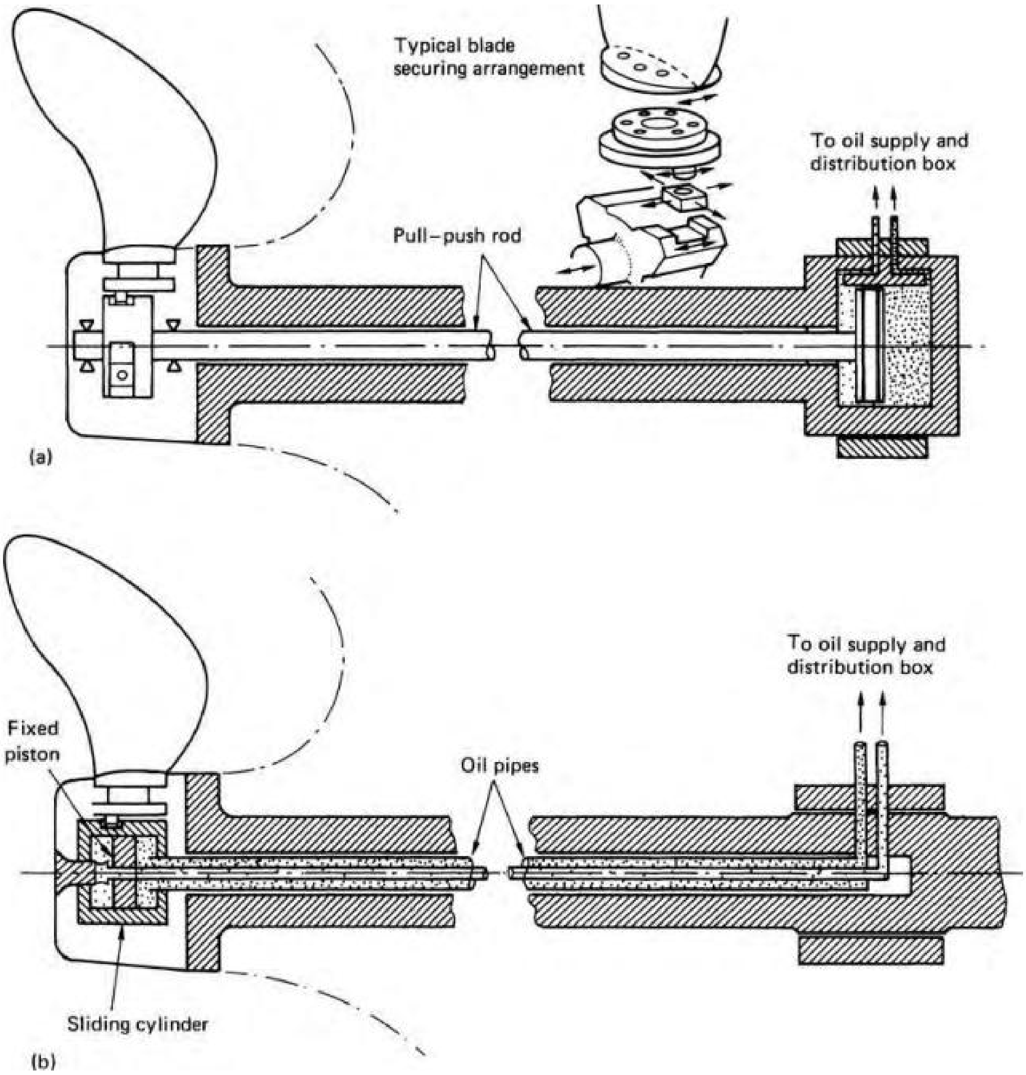


Figure 2.3: Controllable pitch propeller schematic operating systems: (a) Inboard hydraulic actuation system and (b) hub-piston system (Carlton, 2019)

The main elements of a CPP hydraulic system are the following: a tank, pumps, filters, valves, pipelines, oil distribution (OD) box, double-effect cylinder, cooler and sensors. The oil flows from the tank to the OD box in a normal pipe inside the engine room. The OD box is a directional valve located on the shaft from which the oil flows through a twin pipe inside the shafting to the propeller hub piston.

Inside the CPP hub, a double-effect hydraulic cylinder is actuated by the oil pressure in a longitudinal direction (stroke) (see Figure 2.4). Two actuating chambers are needed in order to move the blade in both positive and negative pitch angles. The pitch can be measured with the feedback pipe, a potentiometer attached to the inner transmission line.

For a more accurate pitch measurement, the sensors can be positioned inside the hub. The chosen pitch angle is achieved by the proportional pitch controller that compares the actual pitch set-point with the real pitch and manipulates the oil valve (Martelli, 2014).

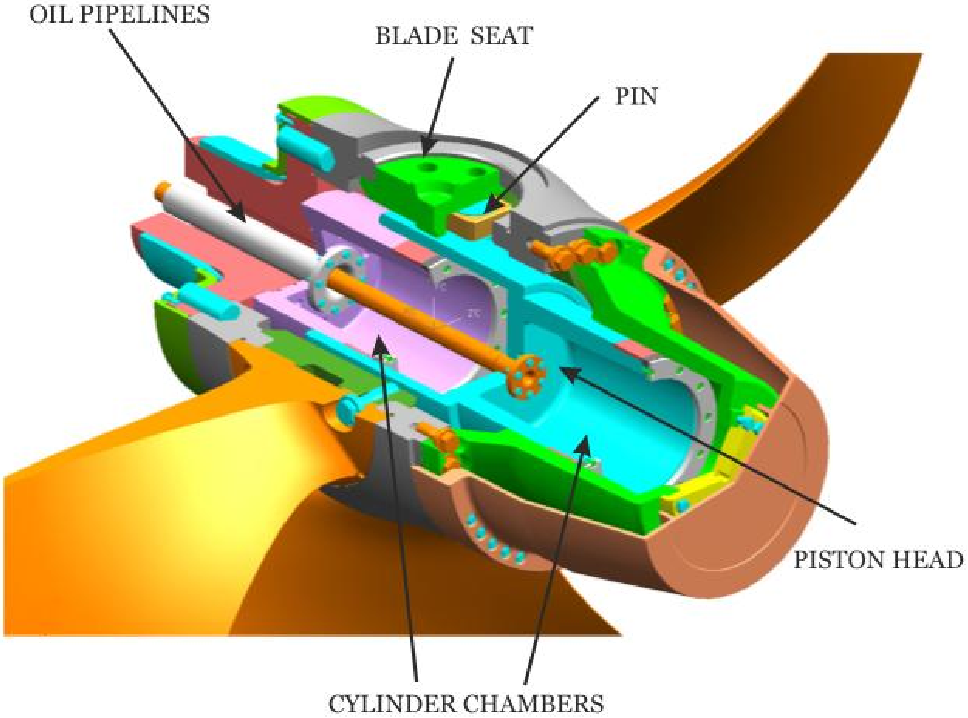


Figure 2.4: Main elements inside a CPP hub (Martelli et al, 2013).

The piston is connected to the blades (generally four or five) by a pin. Different types of connecting mechanisms exist to convert the piston stroke into a blade angular rotation.

Martelli et al., (2013) considered the pin–slot mechanism (see Figure 2.5). On the right of the figure, the rotation of the blade carrier driven by the piston inside the CPP hub is shown, while on the left the pin–slot kinematic is shown. For the pin–slot mechanism, the relationship between the hydraulic force generated inside the hub (piston force) and the spindle torque is the following:

$$Q_{hyd} = \frac{F_{hyd} \cdot e_{yp}}{cos^2(\varphi)} \tag{2.1}$$

Where Q_{hyd} (N·m) is the hydraulic torque, F_{hyd} (N) is the hydraulic force, e_{yp}(m) is the eccentricity of the yoke pin and φ (rad) is the pitch angle.

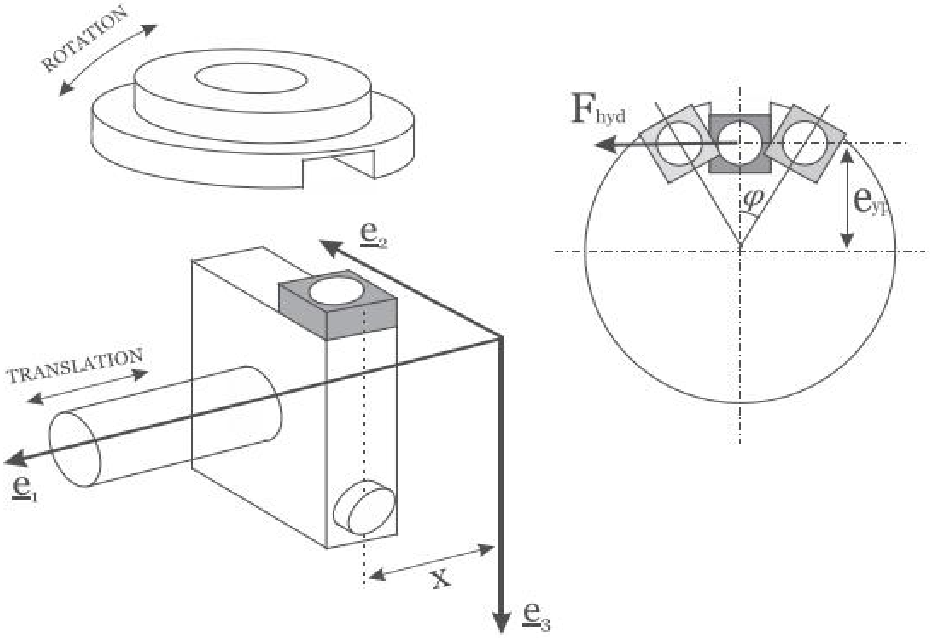


Figure 2.5: Pin-slot Mechanism (Martelli et al, 2013)

The relationship between the linear movement (piston stroke) and the pitch angle (blade angular position) is expressed as

$$x_{pist} = x_{MAX\_AH} - tan(\varphi_{MAX\_AH} - \varphi)e_{yp} \tag{2.2}$$

Where x_{pist} (m) is the instantaneous linear position (stroke), x_{MAX_AH} (m) is the maximum stroke ahead and φ_{MAX_AH} (rad) is the maximum pitch ahead. All the variables appearing on the right-hand side of equation (2.2) are derived from the corresponding mechanism drawing represented in Figure 2.6.

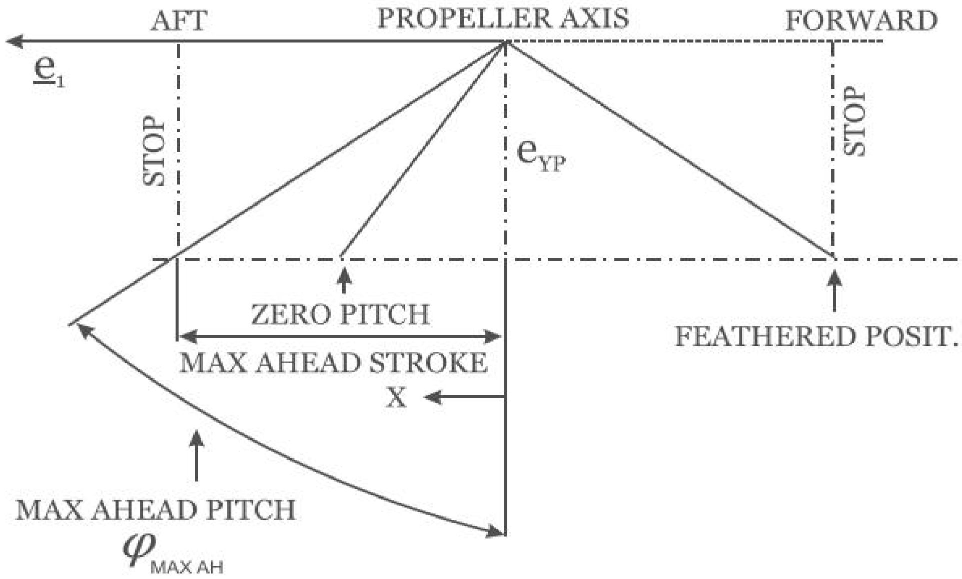


Figure 2.6: Relationship between linear and angular positions (Martelli et al, 2013)

With the aid of the pitch control mechanism, which can be operated from both, the engine room and bridge, controllable pitch propellers can be used to run the ship in forward and astern direction both, without the requirement to change the direction of rotation of the engine. This is simply achieved by changing the pitch angle or the blade's angle of attack.

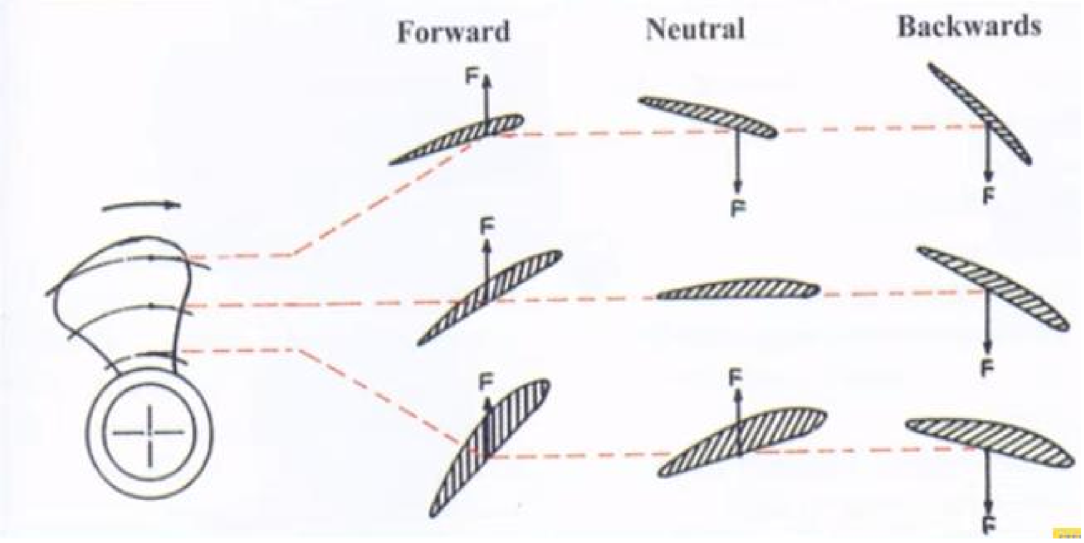


Figure 2.7: Blade sections shown in various pitch orientations (brighthubengineering, 2022)

Figure 2.7 shows the cross section of blades. We will assume that the ship is moving in the ahead direction and the arrows shows the direction of the forces generated that pushes the ship forward. When the blade is at zero position, the propulsive forces acting on both the sides are equal in magnitude, but opposite in direction. Even though the net propulsive force is zero, the propeller absorbs a large amount of energy to convert it to wake turbulence. If the ship is to reverse, the blades are moved even further, this will result in a propulsive thrust in the forward direction, facilitating the ship to reverse (brighthubengineering, 2022).

The two major downsides of the CPP is its relatively larger hub (which can cause cavitation and reduce efficiency), and the mechanical complexity of the prevalent hydraulic system, which involves a higher risks of problems in service and can pose environment treats during operation (such as oil leakage into the ocean) and limits transmission power. The CPP is also relatively expensive, up to 3-4 times as expensive as a corresponding fixed pitch propeller (Wankhede, 2020).

2.4 THE DESIGN AND ANALYSIS LOOP

The phases of the propeller design process can be summarized as shown in Figure 2.8 and 2.9. From the figures, it is seen that the creation of the artifact commences with the definition of the problem, and this implies that a sufficient and unambiguous specification for the propulsion problem has been produced.

This design specification must include the complete definition of the inputs and required outputs, including any permissible deviations from these definitions, as well as any constraints that may be placed on the design. Following the design definition phase, the process moves to the synthesis phase where the basic propeller design is formulated using the various capabilities that are at the designer’s disposal. To provide a notionally optimal solution, the synthesis phase cannot exist in isolation and must be conducted with the analysis and optimization phases in an interactive loop. This iterative approach is needed to refine the design to that required: that is, a design that complies with the original specification and has an optimal property about it. However, the design loop must be flexible enough should an unresolvable conflict arise with the original definition of the design problem, to allow for an appeal to be made to change the definition of the design problem. In some cases, it is also likely that this appeal process may lead to the identification of areas for longer-term research to enhance future design solutions (Carlton, 2019).

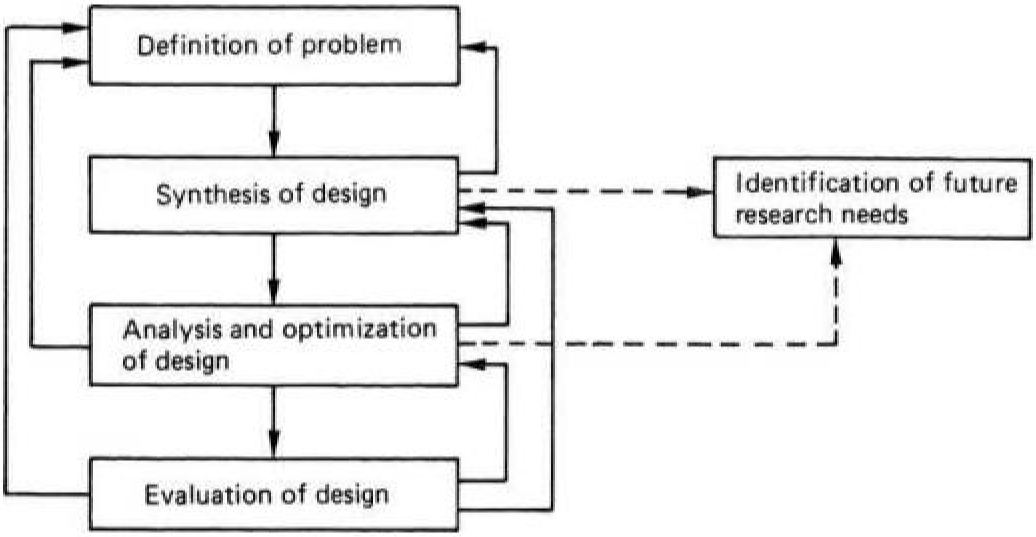


Figure 2.8: Phases of Engineering Design (Carlton 2019)

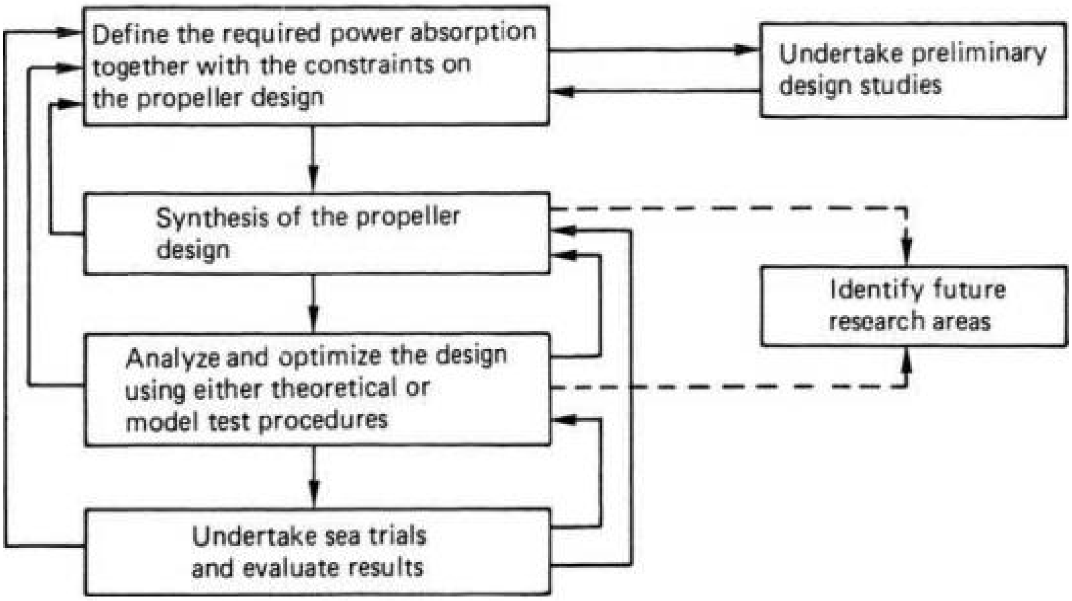


Figure 2.9: Phases of Propeller Design (Carlton 2019)

Propeller parameters such as, shaft RPM (rotational speed), direction of rotation, propeller diameter, pitch- diameter ratio, blade area ratio, section form, cavitation, skew, hub form, duct form, propeller tip cavitation, etc show be taken into consideration in the design process of the controllable pitch propeller (Carlton, 2019).

2.5 STANDARD PROPELLER MODEL TEST SERIES DATA

Over time, different organizations around the world have carried out tests on propeller models to develop several propeller standard series. The major aim in carrying out these systematic propeller test is to generate a database that serve as a reference book to enable designers comprehend the factors and variables which influence propeller performance and, in special cases, the inception and nature of cavitation on the propeller blades under different operating conditions. The second purpose for carrying out these tests is to provide design diagrams, or charts, which will assists in selecting the most appropriate principal dimensions of actual propellers for full - size ship applications (carlton, 2019) .

The most commonly used propeller series by designers and analysts includes:

I. **The Wageningen B-Screw Series** : This is a very extensive and widely used propeller series. The series was presented in a set of papers presented by van Lammeren (1936) and Troost (1938, 1940, 1951). It can also be referred to as the "Troost Series" (Carlton, 2019).

II. **The Wageningen C & D series** : These are two new propeller series, developed by The Maritime Research Institute Netherlands (MARIN) in association with a Joint Industry Project (JIP). The C and D series relates to the controllable pitch propellers where C series focuses on non-ducted CPPs and the D series is centered on ducted CPPs (Carlton, 2019). The principal aim of developing the new CPP series is to assists shipbuilding and offshore industries in comprehending the off - design performance of the CPPs , for which systematic data was lacking (Dang et al., 2020).

III. **The Japanese AU- Series**: This series is a complementary series to the Wageningen B -series, although not as popular. The series reported by Yazaki (1962) consists of propellers having blade area ratio (BAR) in the range of 0.40 - 0.758, and a range of blade numbers from four (4) to seven (7).

iv. **Gawn Series**: This propeller series comprises of 37 three-bladed propellers covering a range of pitch ratios from 0.4 - 2.0 and blade area ratios from 0.2 to 1.1. The results of these series were presented by Gawn (1952). The propellers of this series each had a diameter of 503mm . Each of the propellers has a uniform face pitch, segmental blade sections, constant blade thickness ratio (0.060) and a hub diameter of 0.2D. The developed blade outline was of elliptical form.

v. **KCA Series**: This is a complementary series to the Gawn series. The KCA series comprises of 30 three- bladed, 406mm models, embracing a range of pitch ratios from 0.6 to 2.0 and blade area ratios from 0.5 to 1.1. The KCA series is also known as the Gawn Burrill series (Gawn and Burrill 1957).

vi. **Lindgren Series (Ma- Series)**: Lindgren (1961), tested a series of three- and five-bladed propellers with a range of pitch ratios from 1.00 to 1.45 and developed area ratios from 0.75 to 1.20. The propellers are all constant pitch with modified elliptical blade forms and sections of circular back profiles (Carlton, 2019).

vii. **Newton - Radar Series**: This series comprises a limited set of 12 three- bladed propellers intended for high-speed craft propulsion. This series was designed for pitch ratios in the range of 1.0 - 2.0 and blade area ratios from about 0.5 to 1.0 (Newton, 1961).

2.6 CPP HYDRODYNAMICS AND COMPUTATIONAL FLUID DYNAMICS

The optimization of hydrodynamic performance and efficiency of propellers is one of the basic considerations in the present day. During the years, the efficiency of marine propellers has been investigated by means of various theoretical and experimental methods. The theoretical analysis of hydrodynamic performance and design of marine propellers started and developed from the 19th century (Shamsi, 2003). Rankine proposed the first practical theory of propellers in 1865. He developed a momentum theory also called the actuator disc theory (Shamsi, 2003). The blade element theory was developed by William Froude in 1878, this theory is based on the two dimensional flow around each blade redial cross-section (Carlton, 2012). The basis of modern theories in recent years are usually aerodynamics and many scientists such as Lancaster, Kutta, Joukowski, Manc and Prandtl developed theories in this field of study. In 1927, Ludwig Prandtl and Albert Betz employed the Kutta-Joukowski circulation theorem for analysis of marine propellers. The work of Prandtl and Betz led Lerbs to develop the propeller circulation theory or lifting line theory in 1952. In this theory, the blades of the propeller are replaced by a system of bound vortices along the blades and helical trailing vortices in the slipstream (Breslin & Andersen, 1994).

The geometry of marine propellers is very complex compared to turbine blades and fans because they have variable section profiles, pitch angles and chord length. Therefore the flow around the ship propeller is so complex. All two-dimensional approaches used to model the flow around a propeller blade (like lifting-line theories) introduce considerable errors that must be corrected afterwards. These days, the more complicated three-dimensional propeller theories are employed for propeller design. They include the lifting-surface methods (vortex-lattice methods); where blade thickness is not considered, the boundary element methods (panel methods); where the blade thickness is considered. Boundary element methods are based on the approach developed by Hess and Smith (1967). In these methods, the surfaces of propeller blades and hub are discretized by a number of small quadrilateral panels having constant source and doublet distribution (Bertram, 2000).

Hydrodynamics and computational fluid dynamics play pivotal roles in the intricate design of marine controllable-pitch propellers (CPPs), where challenges like cavitation, flow separation, and varying fluid conditions profoundly impact performance. Cavitation, characterized by the formation and collapse of vapor bubbles around propeller blades, poses a substantial risk to efficiency and durability. This phenomenon necessitates intricate hydrodynamic design modifications, such as optimizing blade shapes to mitigate risks and improve overall propeller efficiency. Additionally, managing flow separation, the detachment of fluid from propeller surfaces, is crucial in reducing drag and maintaining optimal performance. Hydrofoil design enhancements and camber optimization represent key strategies to minimize flow separation effects. Addressing the impact of varying fluid conditions, such as water temperature and vessel speed, is equally critical for consistent CPP performance (Blazek, 2001). Computational fluid dynamics (CFD) simulations, utilizing methodologies like Reynolds-Averaged Navier-Stokes (RANS), Large Eddy Simulation (LES), Detached Eddy Simulations (DES) and Direct Numerical Simulations (DNS), prove instrumental in predicting and mitigating these hydrodynamic challenges (Carlton, 2012). Furthermore, modelling and simulation softwares such as SolidWorks and Ansys provides a versatile platform for researchers to customize simulations, allowing for a nuanced understanding of fluid dynamics in CPPs. This integration of advanced modeling and simulation techniques enables engineers to optimize CPP designs, ensuring efficiency and reliability across diverse operational conditions.

CHAPTER 3

DESIGN METHODOLOGY/THEORY AND MATHEMATICAL ANALYSIS

The design and simulation of a controllable pitch marine propeller for enhanced maneuverability and efficiency require a comprehensive understanding of the fundamental theory, design methodologies, and mathematical analysis. This chapter focuses on explaining the key concepts and principles that form the basis of the design process, as well as the analytical/design tools and techniques used to define the propeller geometry and evaluate the controllable pitch propeller performance both in its design pitch and off -design conditions.

The chapter begins with a discussion on the definition of terms relating to the CPP design, aiming to provide a common understanding of the terminology used throughout the chapter. This is followed by the the theoretical analysis of CPP action, which explains the principles governing the operation of the controllable pitch propeller and how pitch adjustment impacts thrust and efficiency.

Subsequently, the propeller design basis is outlined, providing the fundamental design point and requirements that guide the design process. This includes all initial parameters that acts as the basis for the design of the principal propeller geometric features. The selection criteria for propeller material is also discussed, considering factors such as strength, corrosion resistance, and weight.

The design and components of the hub mechanism, which allow for the adjustment of the propeller blade pitch, are also described in detail. Following this is the design approach and method used to develop the CPP design (based on the design pitch), as well as the mathematical analysis and calculations employed to evaluate the performance of the propeller (at the design pitch).

Furthermore, the chapter explores the analysis of the CPP off-design conditions, discussing how the propeller design performs under varying speeds or loads, and its impact on efficiency and maneuverability. Finally, cavitation considerations in design are addressed, emphasizing the importance of mitigating cavitation through design choices to ensure the propeller's performance and longevity.

In general, this chapter provides a comprehensive overview of the design methodology, theory, and mathematical analysis and calculations employed in the development of the controllable pitch marine propeller, laying the groundwork for the following chapter on CAD modelling, simulation and performance evaluation.

3.1 DEFINITION OF TERMS RELATING TO CPP DESIGN

The definitions of terms relating to the design of the controllable pitch propeller are essential for understanding the design methodology and mathematical analysis presented later in the chapter. This term include the following:

I. **Frame of Reference**: The global frame of reference presented by the 10th International Towing Tank Conference (ITTC) , 1978, is shown in figure 3.1, is a right- handed, rectangular Cartesian system. The X- axis coincides with the shaft axis and positive forward, the Y-axis is positive to starboard and the Z-axis is positive in the vertically downward direction. The propeller geometry is defined by a local reference frame (x, y, z) having a common axis such that OX and Ox are coincident, but allowing the mutually perpendicular axes Oy and Oz to rotate relative to the OY and OZ fixed global frame as shown in Figure 3.2. The angular displacement of Oz from OZ is denoted by ϕ (Carlton, 2019).

II. **Blade Reference Line**: The line normal to the shaft axis which defines the propeller blade is called the “propeller reference axis” or the “directrix”. The term “spindle axis”, about which the CPP blade spindle torque is defined is often synonymous with the directrix. However, in cases of special designs, the “spindle axis” has been defined to lie normally to the surface of a shallow cone, which has a common axis with the shaft axis and tapers towards the aft direction. For such cases, the spindle axis is inclined to the reference line by a few degrees (Carlton, 2019).

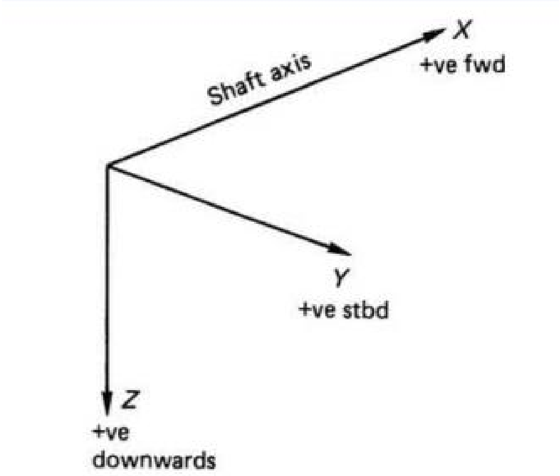


Figure 3.1: Global reference frame

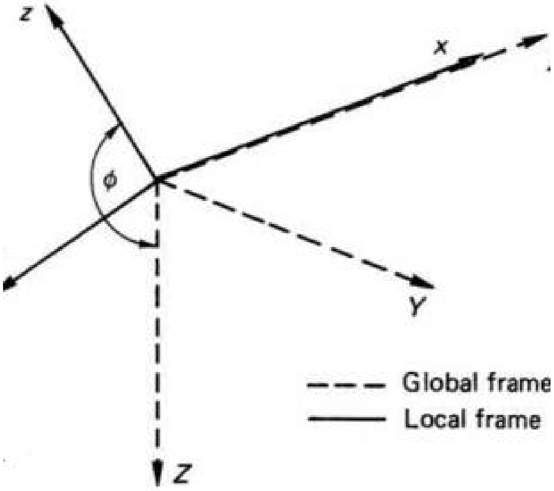


Figure 3.2: Local reference frame

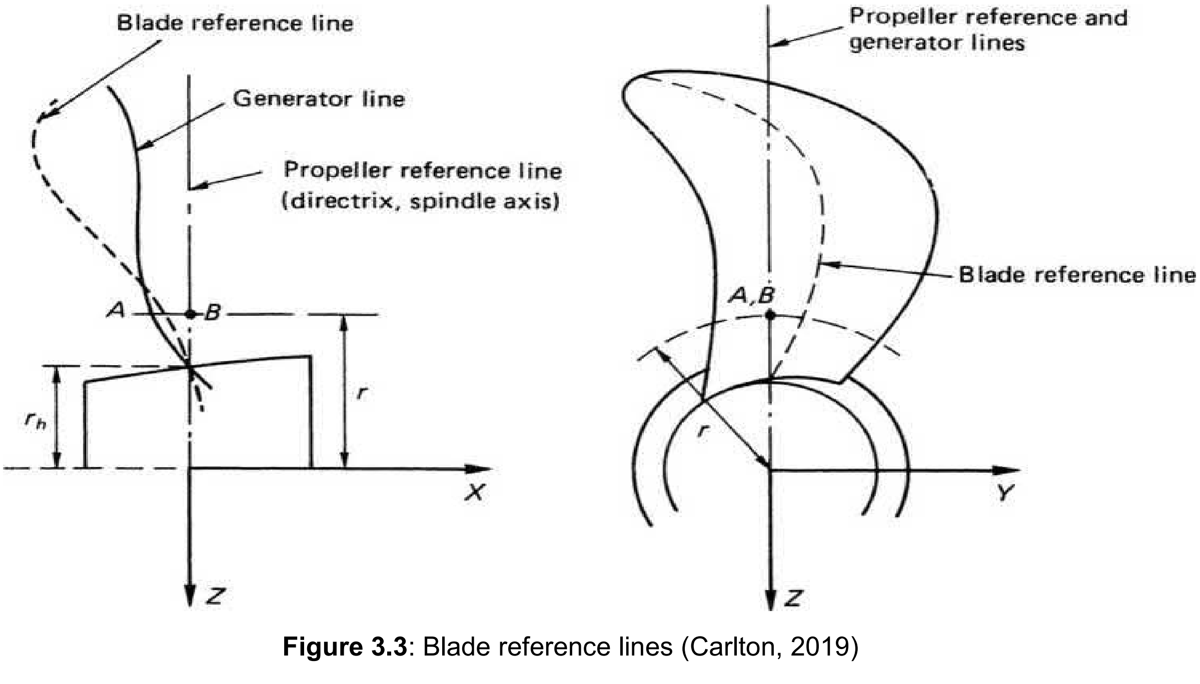


Figure 3.3: Blade reference lines (Carlton, 2019)

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). It is the base of the blade where it meets the hub. The blade root is the thickest and strongest part of the blade to withstand forces and stresses during operation.

IV. Pitch(P): The propeller pitch is the theoretical distance (P) a propeller will move forward in a solid medium for each rotation, not allowing for slip. The distance is illustrated in Figure 3.4. Generally, the propeller blades are twisted to achieve almost constant pitch of the blades from root to tip (Njaastad et al., 2022). The pitch of a blade section can also be defined as an angle known as the **pitch angle (θ).** A change in the pitch angle results in a corresponding change in the propeller pitch and pitch ratio.

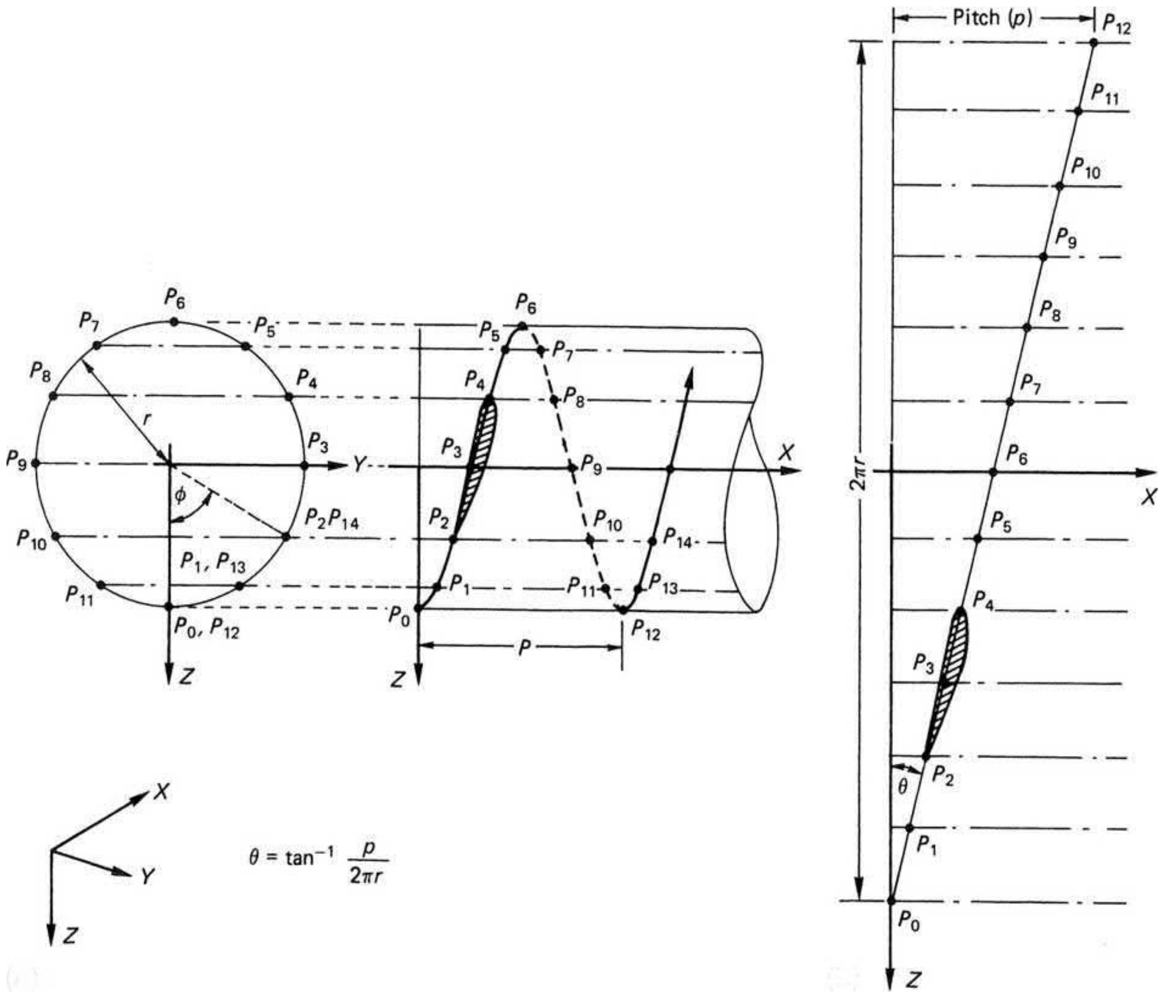


Figure 3.4: Propeller pitch (Carlton, 2019)

V. Diameter (D): The propeller diameter is the diameter of the imaginary circle scribed by the blade tips of the propeller. The propeller radius (R) is simply the radius of this circle.

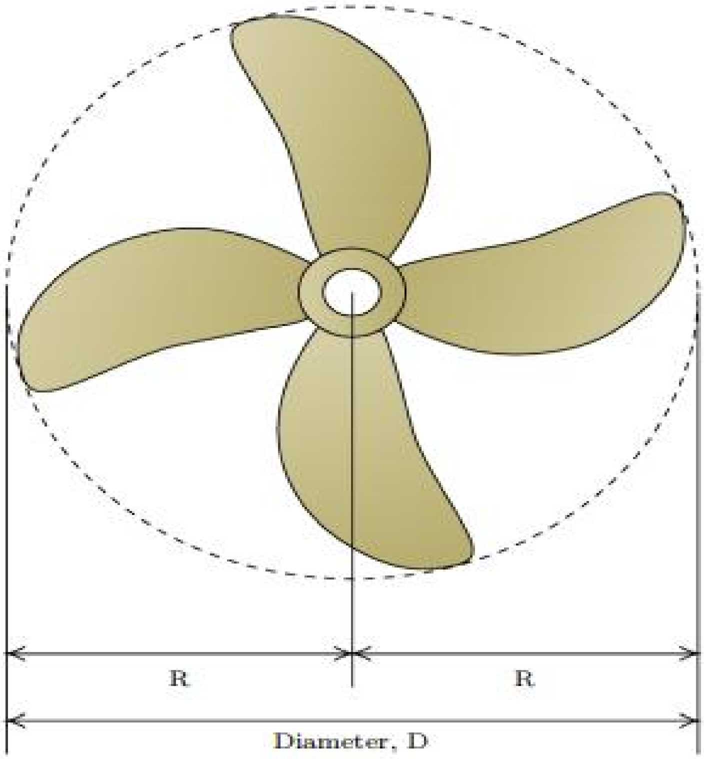


Figure 3.5: Propeller Diameter and Radius (Carlton 2019)

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. The number of blades is a crucial design parameter that affects the performance of the propeller.

VIII. **Rake**: Rake refers to the angle of the propeller blade relative to a plane perpendicular to the propeller's axis. It is the angle at which 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. Skew can help reduce vibration and noise, improve efficiency, and provide smoother operation (Njaastad et al., 2022).

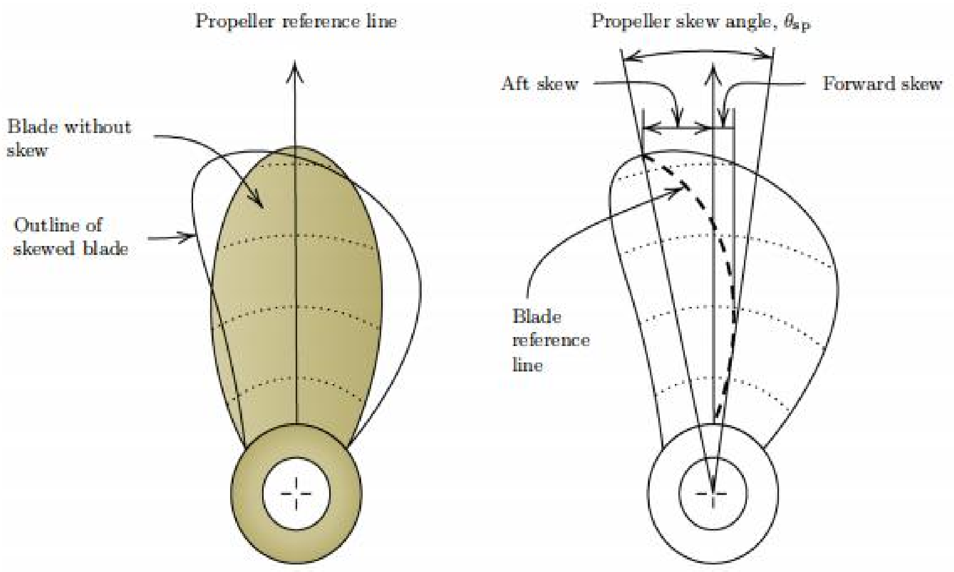


Figure 3.6: Propeller Skew (Njaastad et al., 2022)

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 is simply the force that 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).

3.2 THEORETICAL ANALYSIS OF CPP ACTION

The propeller momentum theory, also known as the actuator disk theory, is a simple theory of propeller action based on the axial motion of water passing through the propeller, used to analyze the performance of a propeller. It treats the propeller as a disk that acts as an actuator in the flow field, accelerating the fluid passing through it to generate thrust. The theory is based on the conservation of momentum principle, which states that the change in momentum of the fluid per unit time passing through the propeller is equal to the propeller thrust. By applying this principle, the theory allows for the calculation of thrust, power, and efficiency of the propeller based on parameters such as blade geometry, rotational speed, and fluid properties.

The theoretical analysis of Controllable Pitch Propeller (CPP) action is fundamental to understanding the dynamics of these propellers and their operational efficiency. CPPs are defined by their ability to change the pitch of their blades while in motion, which significantly impacts their performance in various operating conditions.

The adjustment of blade pitch in CPPs allows the propeller to optimize its performance by varying the amount of thrust generated. Increasing the pitch (angle of attack), causes an increase in the lift (thrust) but also raising drag. On the other hand, decreasing the pitch reduces both (lift) thrust and drag. This adaptability enables CPPs to adjust their thrust levels to match the vessel's speed, load, and environmental conditions, ensuring optimal performance (Woud & Stapersma, 2003).

Efficiency is an important consideration in propeller design, and CPPs excel in this regard. The ability to adjust pitch enables CPPs to operate at their most efficient point across a range of conditions. By aligning the pitch with the vessel's requirements, CPPs can minimize fuel consumption and enhance overall performance, making them a preferred choice for vessels seeking to balance power and efficiency (Carlton, 2019).

One of the exceptional characteristics of CPPs is their superior maneuverability. By independently adjusting the pitch of each blade, CPPs can provide thrust in varying directions, leading to accurate control over the vessel's movement and speed. This level of control is particularly important in tight maneuvering situations, such as docking, harbour maneuvers or navigating through narrow waterways, where accuracy and responsiveness are paramount.

3.3 THE PROPELLER DESIGN BASIS

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.

From research, the range of the design basis for small to medium sized vessels (which the project focuses) is shown the table 3.1.

Delivered Horsepower (P_D)	**500 - 15,000 HP**
Ship Speed (V_S)	**5 - 25 Knots**
Propeller RPM (N)	**100 - 300 RPM**
Wake Fraction (w)	**0.08 - 0.12**

Table 3.1: Range of design basis for small to medium size vessels

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.

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**

Table 3.2: Basis for CPP design

3.4 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.

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.

3.4. 1 DESIRABLE PROPERTIES OF THE NICKEL- ALUMINIUM BRONZE (NAB) ALLOY

Some of the desirable properties of NAB alloy include:

I. **Corrosion Resistance**: NAB alloy exhibits high resistance to general corrosion, especially in marine environments where it is exposed to seawater and other corrosive elements.

II. **High Strength**: NAB alloy has a high strength to weight ratio, making it suitable for applications where a strong and durable material is required. It can withstand high loads and stresses.

III. **Wear Resistance**: The alloy has good wear resistance, making it suitable for use in components that experience friction and wear, such as bearings and bushings. This property helps extend the lifespan of components and reduces maintenance requirements.

IV. **Weldability**: NAB alloy is weldable, allowing for the fabrication of complex components and structures. It has good repair characteristics including freedom from successive cracking.

V. NAB also has high resistance to cavitation erosion, corrosion fatigue resistance in sea water and a high resistance to crevice corrosion and impingement attack.

3.5 THE BLADE PITCH - CHANGE MECHANISM: DESIGN AND COMPONENTS

The blade pitch-change mechanism is a mechanism located in the propeller hub (boss) that facilitates the change of blade pitch angle (angle of attack). This mechanism, controlled from the bridge through an hydraulic actuation, is responsible for adjusting the angle of the propeller blades to control the thrust and efficiency of the propeller.

The Blade pitch - change mechanism used in this cpp design is a **push- pull rod mechanism,** designed to reduce the mechanical complexity and larger hub size associated with the conventional hub - piston mechanism (discussed in Chapter 2) 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).

This major components of this mechanism, situated inside the propeller hub, includes: the push-pull rod, the yoke, the yoke pin, the bearing and rings, and the pin-slot.

I. **Push-Pull Rod:** The push-pull rod is a mechanism for adjusting the pitch of the propeller blades. It connects to the yoke and allows for manual or automated adjustment of blade pitch.

II. **Yoke:** The yoke is a part of the push pull rod that connects the blades to the hub. It provides support and allows the blades to pivot for pitch adjustment.

III. **Yoke Pin:** The yoke pin secures the blade to the yoke and allows for rotation. It ensures the blades are correctly positioned and allows for pitch changes.

IV. **Pin Slot:** The pin slot is a feature in the hub where the yoke pin fits. It provides a precise location for the pin, ensuring the proper alignment and functioning of the propeller blades.

V. **Bearings and Rings:** Bearings and rings are components that support the rotation of the propeller blades within the propeller hub assembly. They reduce friction and wear, ensuring smooth operation.

In summary, 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 design model (showing all the components) is visually represented in chapter 4.

3.6 PROPELLER GEOMETRY DESIGN APPROACH

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 (lifting line, lifting surface, vertex lattice and boundary element method,

This project work covers the first design method only.

The design procedure was restricted to the use of design charts and series, the Wageningen B and C 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 use of this propeller design chart (B_P - δ chart), alongside the knowledge of the design basis in table 3.2, 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:

$$B_P = \frac{P_D^{0.5} \times N}{V_A^{2.5}} \tag{3.1}$$

$$\delta = \frac{N \times D}{V_A} \tag{3.2}$$

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 3.7 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.

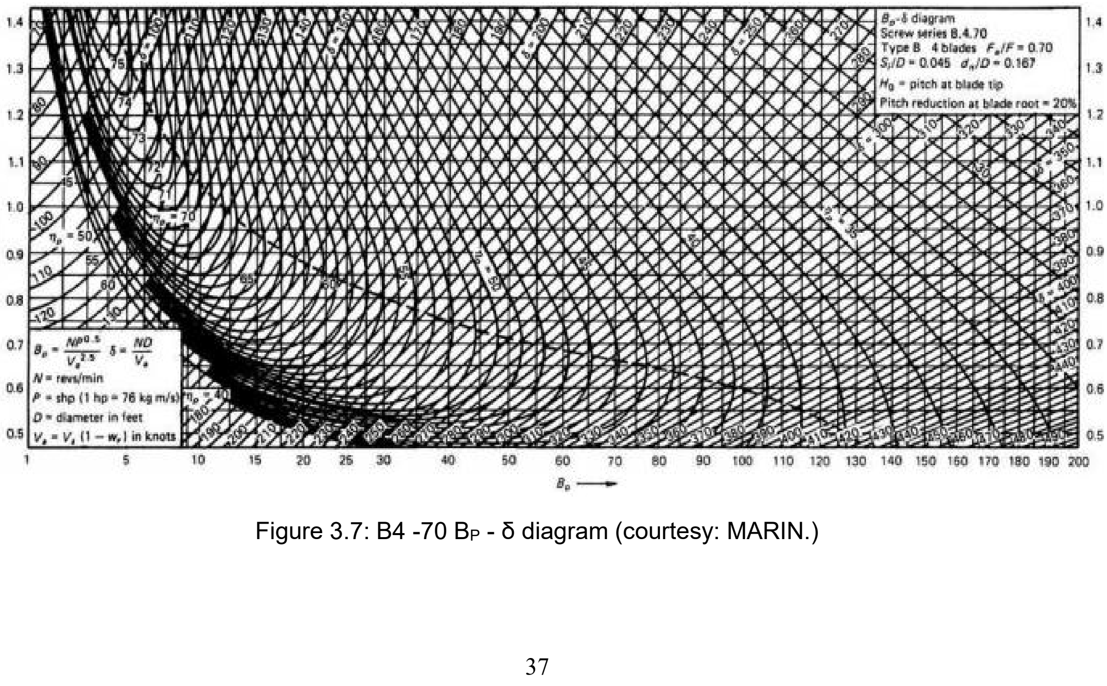


Figure 3.7: B4 -70 B_P - δ diagram (courtesy: MARIN.)

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 = *δ· Va/N*, and P/D.

3.7 MATHEMATICAL CALCULATIONS AND ANALYSIS (BASED ON THE PROPELLER DESIGN PITCH)

The design basis, derived from a small twin screw passenger ferry as shown in table 3.2 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,

$$V_A = V_S\,(1 - \omega) \qquad (3.3)$$

Therefore,

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

$$V_A = 14.21 \text{ knots } (7.31 \text{ m/s})$$

Having gotten the value for the advance speed, the power coefficient, B_P, can be evaluated using taylor's formula (equ 3.1).

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

$$B_P = 13.29$$

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}) according to equation 3.2. The expanded blade area ratio (A_E/A_O) is also obtained from the chart.

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

$$\text{Expanded blade area ratio, } A_E/A_O = 0.70$$

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.

$$\delta = 100\left[\frac{B_P{}^3}{155.3+75.11B_P{}^{0.5}+36.76B_P}\right]^{0.2} \times \left[0.9365+\frac{1.49}{Z}-\left(\frac{2.101}{Z}-0.1478\right)^2 \times \frac{A_E}{A_0}\right] \quad (3.4)$$

From Taylor's design coefficient formula (equ 3.2), the equation for the optimum diameter is obtained;

$$D_{opt} = \frac{\delta_{opt} \times V_A}{N} \quad (3.5)$$

The optimum diameter is then obtained from the above equation,

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

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

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.

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

∴ 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 (equ 3.2),

$$\delta_b = \frac{N \times D_b}{V_A} \tag{3.6}$$

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

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 , $\eta_o = 0.67$ (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).

$$1.5\% \text{ of } 1.025 = 0.015375$$

$$\therefore \quad \text{Mean Pitch Ratio, P/D} = 1.025 - 0.015375 = 1.01$$

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

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

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

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

$$\therefore \quad d = 0.24 \times 6.70 = 1.608\text{ft} \ (0.5\text{m})$$

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

$$\theta = \tan^{-1}\left(\frac{P}{2\pi r}\right) \tag{3.7}$$

$$\theta_t = \tan^{-1}\left(\frac{2.06}{2\pi \times 1.02}\right) = 17.81°$$

$$\theta_r = \tan^{-1}\left(\frac{2.06}{2\pi \times 0.25}\right) = 52.67°$$

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.

$$\text{Blade disc Area } (A_O) = \frac{\pi {D_b}^2}{4} \tag{3.8}$$

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

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

3.7.1 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;

$$\text{Propeller Thrust (T)} = \frac{P_D \times \eta_O}{V_A} \qquad (3.9)$$

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

$$\text{Propeller Torque (Q)} = \frac{P_D}{2\pi \times n} \qquad (3.10)$$

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

3.7.2 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:

$$\text{Thrust coefficient, } K_T = \frac{T}{\rho n^2 D^4} \qquad (3.11)$$

$$\text{Torque coefficient, } K_Q = \frac{Q}{\rho n^2 D^5} \qquad (3.12)$$

$$\text{Advance coefficient, } J = \frac{V_A}{nD} \qquad (3.13)$$

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 3.11 - 3.13).

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

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

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

3.7.3 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°
22	Design pitch angle at blade tip (θ_r)	52.67°
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

Table 3.3: Design and peformance parameters

3.8 THE CPP PERFORMANCE AT VARYING PITCH CONDITIONS

Off-design conditions refer to situations where the CPP operating parameters deviate from the design parameters. This could include changes in ship speed, varying load, or operating condition such as shallow water or high waves. The controllable pitch propeller is identical to the fixed pitch propeller in its design pitch condition. In its off-design conditions, a further set of parameter arises: these are the blade spindle torques and the hydrodynamic pitch angles. When operating in its off -design conditions, special analysis is required to determine the blades spindle torque and magnitude of the actuation forces required.

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

3.9 CAVITATION CONSIDERATION IN THE PROPELLER DESIGN

Cavitation is the formation and subsequent collapse of vapor bubbles in a liquid when the local pressure drops below the vapor pressure of the liquid. This phenomenon can cause damage to the propeller. The focus of design should be to accept that cavitation will occur but to minimize its effects, both in terms of the erosive and pressure effects (Carlton, 2019).

In the design of the Controllable Pitch Propeller (CPP), two main considerations were made to reduce the potential for cavitation. Firstly, a low rotational speed (RPM) for the propeller was chosen. This decision was based on the understanding that cavitation is more likely to occur at higher speeds, where the pressure difference between the front and back of the blade is more significant. By selecting a lower RPM, the propeller operates within a speed range where cavitation is less likely to occur, reducing the risk of damage to the blades and improving overall efficiency (Carlton, 2019).

Secondly, the hub of the propeller was designed with a minimum diameter. This design choice helps to minimize the formation of cavitation bubbles by reducing the pressure difference between the leading and trailing edges of the blades. A smaller hub diameter also helps to reduce the overall size and weight of the propeller, which can have additional benefits for the performance of the vessel.

By carefully considering these factors in the design of the CPP, we minimize the risk of cavitation and ensure optimal performance and durability of the propeller in various operating conditions.

CHAPTER 4

3-DIMENSIONAL MODELLING, SIMULATION AND RESULTS

This chapter explores the modeling of the controllable pitch propeller (CPP) and a simulation of its hydrodynamic behaviour using SolidWorks, a 3-dimensional computer-aided design (CAD) program. 3D modeling has become a fundamental tool across all engineering disciplines. It revolutionized the design process by allowing engineers to create digital representations of objects, offering significant advantages over traditional 2-dimensional drafting.

3D modeling is the process of creating a digital representation of a physical object in three dimensions using specialized software. 3D models are made within computer-based 3D modeling software. During the 3D modeling process, you can determine an object's size, shape, and texture. The process works with points, lines, and polygons to create the 3D shapes within the software.

4.1 SELECTION OF MODELING TECHNIQUE: 3D MODELLING FOR ENHANCED SIMULATION CAPABILITIES

3D and 2D modeling all have their use cases and applications in the Engineering design process, 3D modeling technique was utilised in the propeller design process for a number of reasons which will be seen shortly.

The choice between 3D and 2D modeling depends on the complexity of the project and the specific needs of the design process. While 2D models offer a faster and simpler method for creating initial layouts and conveying technical details, particularly for uncomplicated objects, their inherent limitations become apparent when dealing with intricate designs. 3D models provide a significant advantage by offering a realistic and interactive representation of an object. This ability to view the design from any angle and manipulate it virtually empowers engineers to gain a deeper understanding of complex geometries and their interactions. This enhanced visualization proves to be crucial in the early stages of design, allowing engineers to identify and address potential issues before they translate into costly physical prototypes.

Beyond improved visualization, 3D modeling unlocks a new level of design flexibility. The ease with which 3D models can be modified facilitates rapid design iterations. Engineers can explore various design options virtually, make adjustments on the fly, and optimize the design for better performance. Furthermore, 3D models can be integrated with simulation software, enabling virtual testing under various conditions. This eliminates the need for numerous physical prototypes, saving time and resources during the development process.

It's important to acknowledge that 2D modeling retains its value in specific situations. For simpler objects where a clear communication of dimensions and technical details is paramount, 2D drawings excel in their efficiency and ease of use. Additionally, 2D models often serve as the foundation for initial design layouts, providing a starting point for further development in 3D modeling software.

The decision between 3D and 2D modeling hinges on the project's specific requirements. When dealing with intricate designs that demand superior visualization, rapid iteration, and virtual testing capabilities, 3D modeling reigns supreme. However, 2D drawings remain a valuable tool for simpler objects, initial layouts, and situations where clear communication of technical details is the primary focus.

4.1.1 BENEFITS OF 3D MODELLING

I. **Enhanced Visualization**: 3D models provide a superior visual representation of designs, fostering improved communication between engineers and non-technical collaborators.

II. **Efficient Design and Prototyping:** The advent of 3D printers has revolutionized 3D CAD modeling, offering greater precision and accuracy compared to traditional fabrication methods.

4.2 3D MODELING WITH SOLIDWORKS

SolidWorks is a powerful 3D computer-aided design (CAD) software used for creating digital models of physical objects. Here's a quick rundown of its 3D modeling capabilities:

I. **Solid Modeling:** SolidWorks allows you to create solid 3D models, meaning the software understands the interior volume and properties of your design. This enables features like mass calculations and interference detection.
II. **Parametric Design:** Dimensions and relationships between features can be defined with parameters, allowing for easy and efficient design changes. Update one parameter, and the entire model adjusts accordingly.
III. **Feature-Based Modeling:** Complex models are built by adding or removing features like extrudes, cuts, and holes. This intuitive approach makes it easy to visualize the creation process.
IV. **Assembly Modeling:** Individual parts can be linked together to create assemblies, simulating real-world product interactions. Motion analysis tools can even be used to study how assemblies move.
V. **Sheet Metal Design:** SolidWorks offers specialized tools for designing sheet metal parts, including features for bends, flanges, and sheet metal forming techniques.

4.2.1 3D BUILDING 3D MODELS IN SOLIDWORKS: AN INTERFACE REVIEW

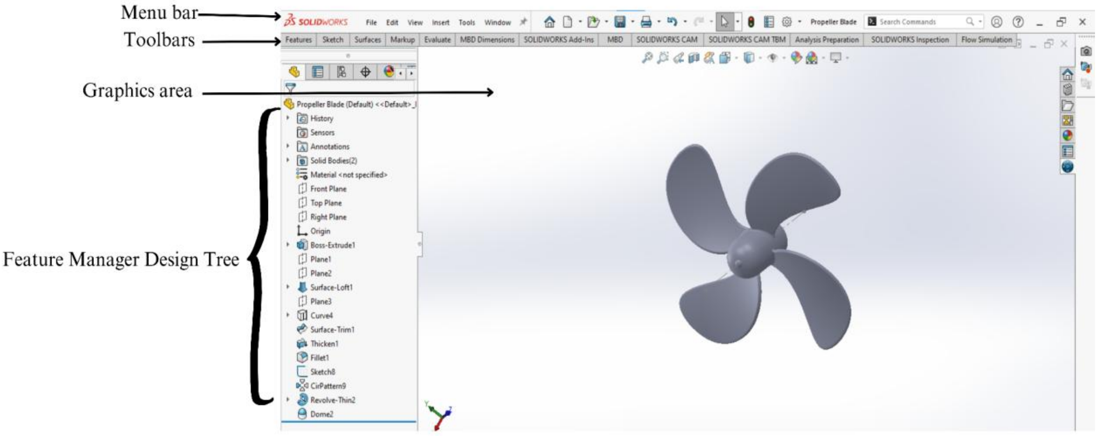


Figure 4.1: SolidWorks User Interface

SolidWorks offers a user-friendly interface specifically designed to streamline the 3D modeling process. The Menu Bar acts as a command center, providing access to various functionalities categorized into menus like File, Edit, and View. These menus can be further customized for user preference. For frequently used tools, Toolbars offer quick access to sketching, modeling, and assembly functions. The Command Manager dynamically adapts to the current task, displaying relevant tools for creating and modifying your 3D model. Once you've built your design, the Property Manager allows you to fine-tune details like dimensions, materials, and appearances without navigating through complex menus. The Feature Manager Design Tree presents a hierarchical view of your model, allowing you to easily select and modify specific components. Finally, the Status Bar keeps you informed about the current state of the software and provides helpful feedback during your design session.

In essence, these elements work together to create an intuitive and efficient environment for creating and manipulating 3D models in SolidWorks.

4.3 THE BLADE PITCH-CHANGE MECHANISM : 3D MODELLING

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 discussed in chapter 3 was modelled with SolidWorks. The 3D models of these parts are shown in the figures below.

I. THE PUSH-PULL ROD AND YOKE ASSEMBLY

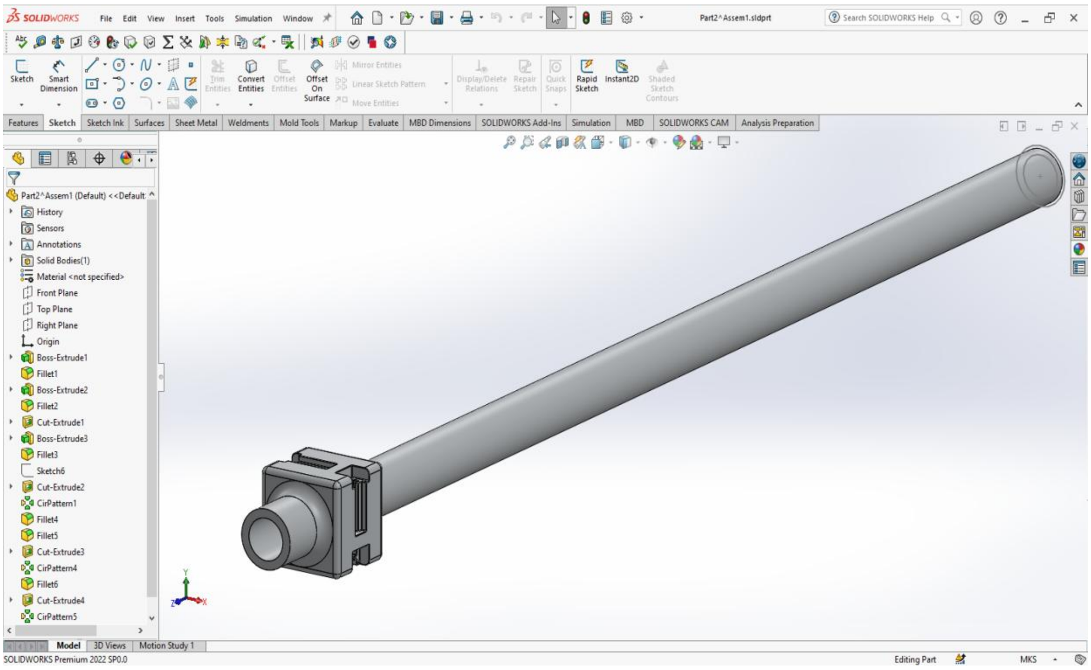


Figure 4.2: 3D Representation of the push-pull rod and yoke assembly

II. THE YOKE PIN

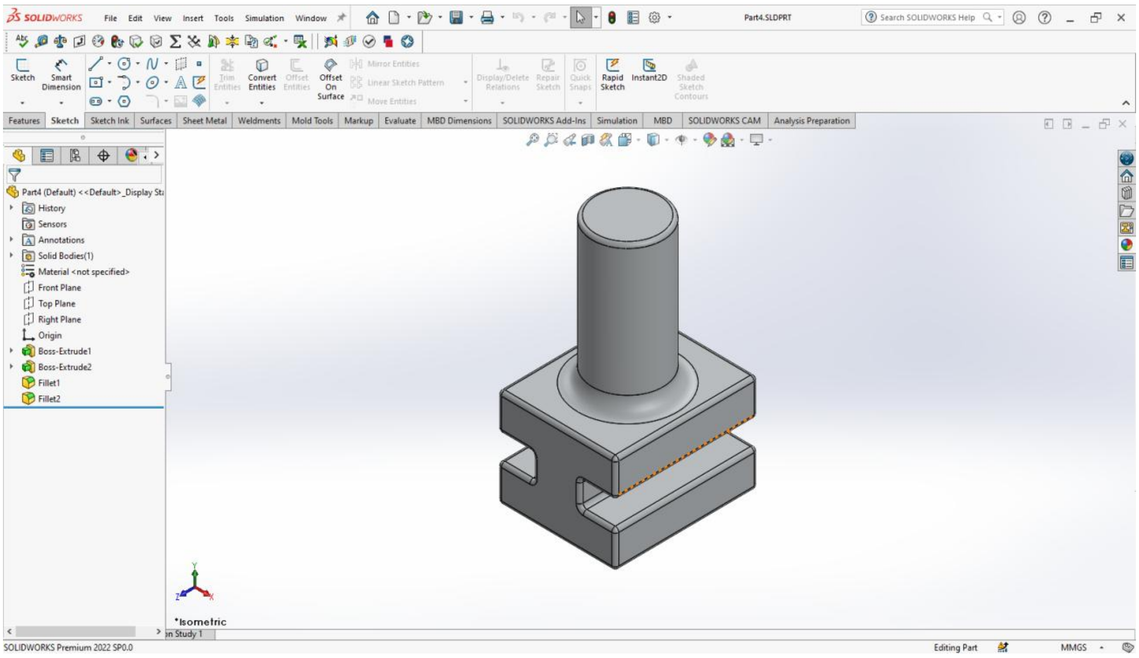


Figure 4.3: 3D Representation of the yoke pin

III. THE PIN SLOT

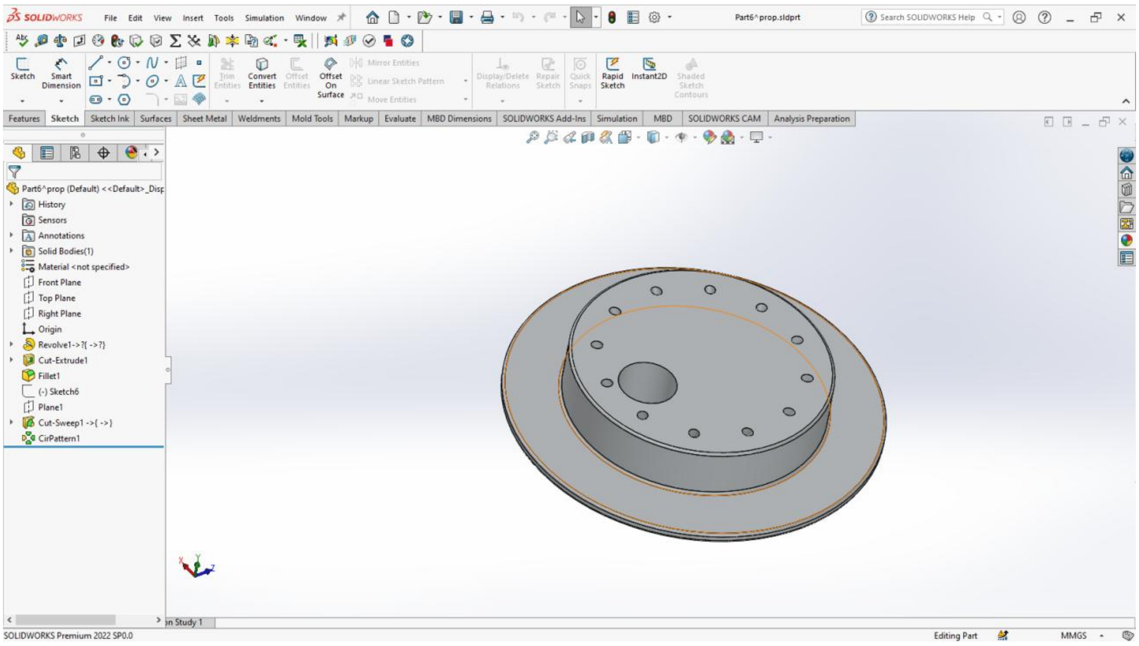


Figure 4.4: 3D Representation of the Pin Slot

IV. THE BEARINGS/ RINGS

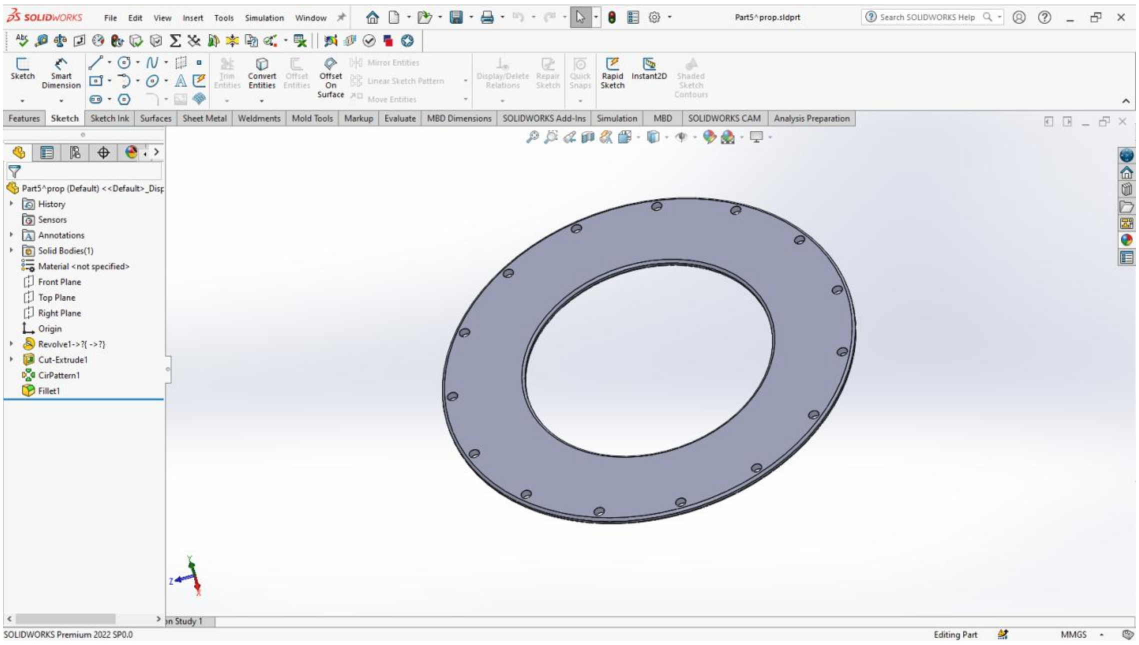


Figure 4.5: 3D Representation of the Bearing/ Rings

V. THE CPP HUB ASSEMBLY

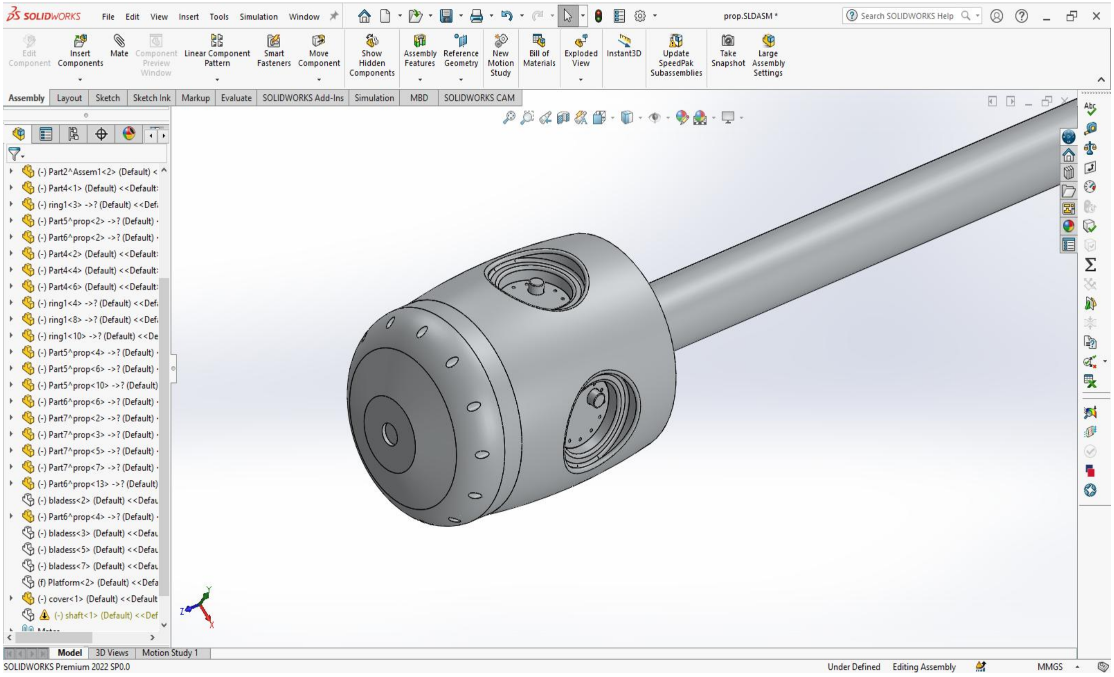


Figure 4.6: 3D Representation of the Hub Assembly

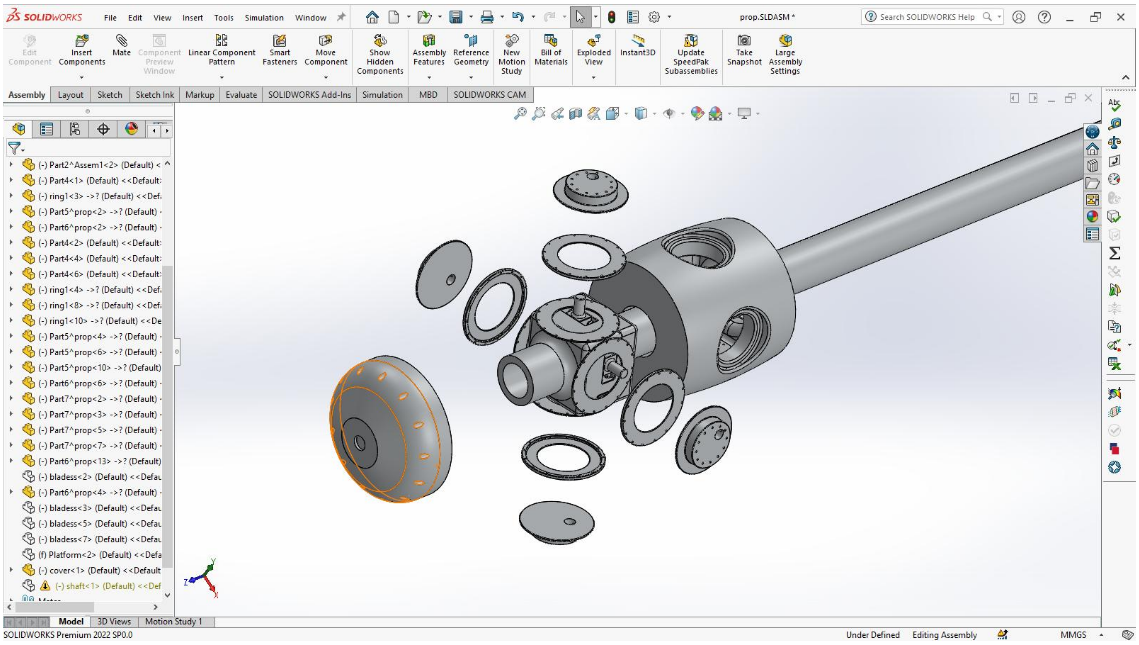


Figure 4.7: Exploded View of the Hub Assembly

THE CPP MODEL REPRESENTATION

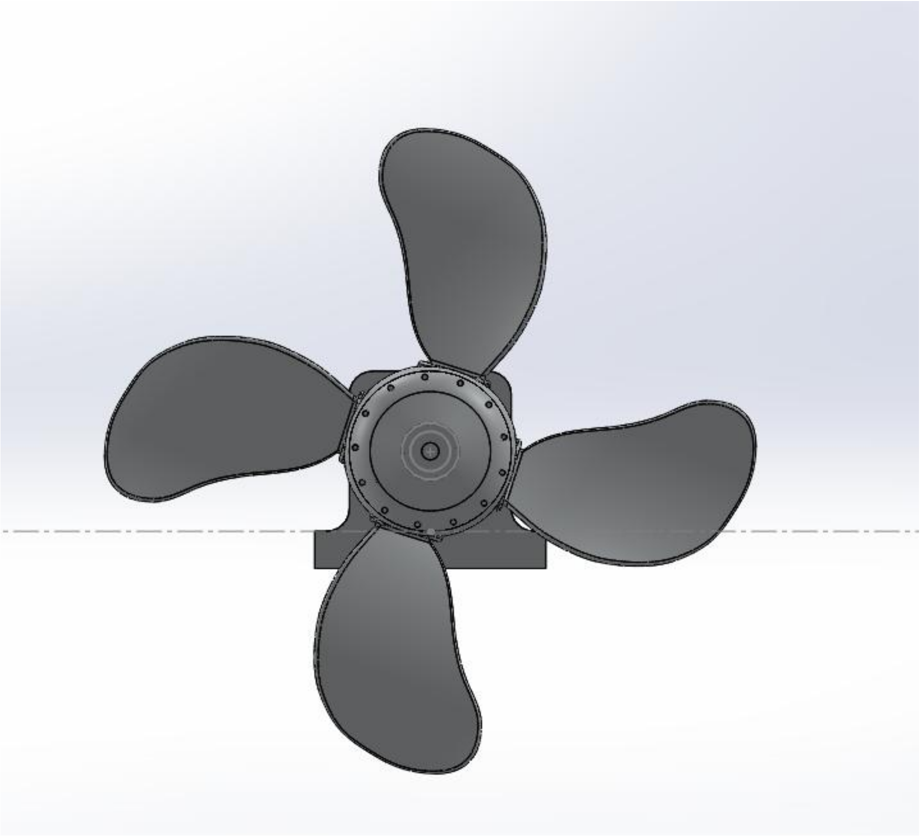


Figure 4.8: The CPP Model

4.4 SIMULATION FOR DESIGN OPTIMIZATION AND RISK MITIGATION

With Computer aided simulation, engineers can predict how a product will behave under various conditions, including physical stresses and even chemical reactions. This virtual testing allows for design optimization throughout the process, significantly reducing development time and financial resources associated with building and testing numerous physical prototypes. Beyond just saving time and money, simulation software empowers engineers in other crucial ways. It allows for early-stage optimization of designs by identifying potential issues before they become problems in physical prototypes. This proactive approach mitigates risks associated with physical testing, which can be expensive and time-consuming to fix later in the development cycle. Furthermore, simulation software offers advanced design techniques like parametric analysis and topology optimization. These tools expedite the process of finding the best possible design solutions with improved accuracy, ultimately leading to superior product performance.

Computational fluid dynamics methods are numerical techniques used to approximate the solutions to differential equations, usually partial differential equations. Real world problems involving fluid flow and structural analysis can be modeled into partial differential equations as a result CFD methods are employed to solve it. The finite volume method is specifically designed to handle fluid applications and is more efficient for most CFD applications.

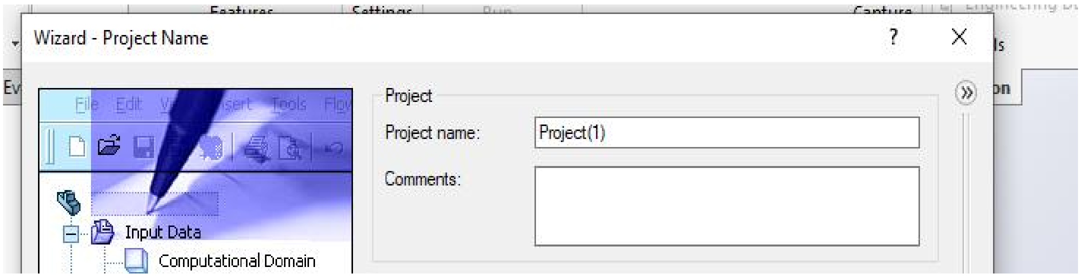
4.4.1 SETTING UP THE SIMULATION ENVIRONMENT

Simulation Objectives:

I. Blade optimization for efficiency.
II. Performance prediction at off design conditions.

STEP 1: Initializing Project

- Project name: Title of Project.
- Configuration: Create configuration.


Wizard - Project Name

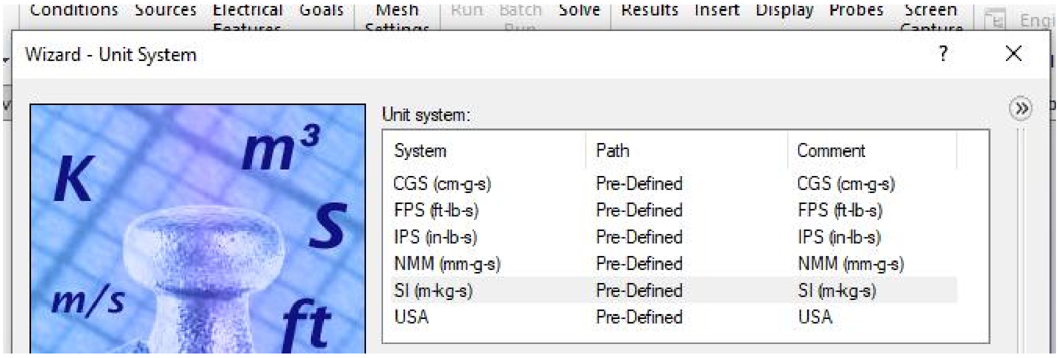
Project

Project name: Project(1)

Comments:

STEP 2: Defining the metric system

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

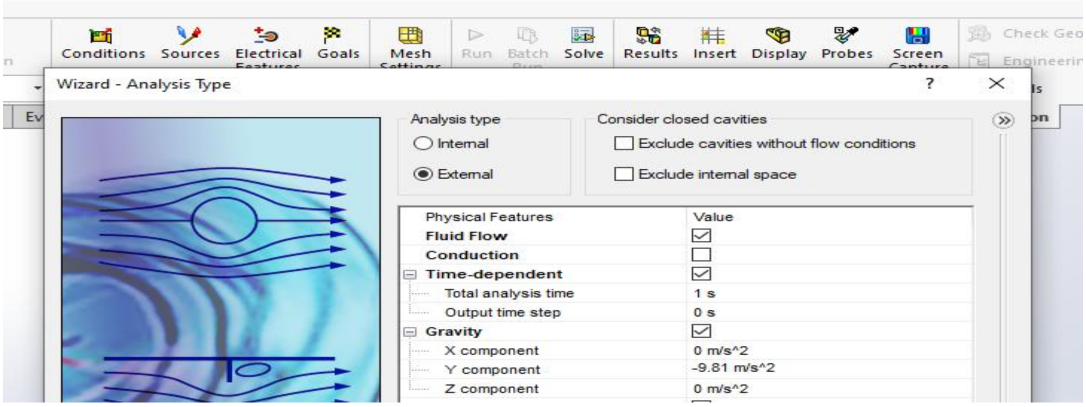

Wizard - Unit System

Unit system:

System	Path	Comment
CGS (cm-g-s)	Pre-Defined	CGS (cm-g-s)
FPS (ft-lb-s)	Pre-Defined	FPS (ft-lb-s)
IPS (in-lb-s)	Pre-Defined	IPS (in-lb-s)
NMM (mm-g-s)	Pre-Defined	NMM (mm-g-s)
SI (m-kg-s)	Pre-Defined	SI (m-kg-s)
USA	Pre-Defined	USA

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 ($0ms^{-1}$)


Wizard - Analysis Type

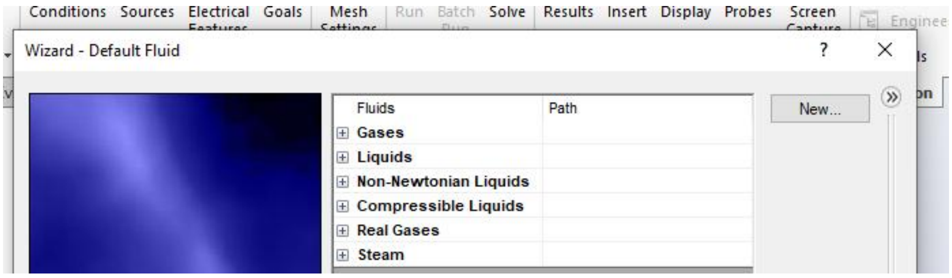
Analysis type
○ Internal
● External

Consider closed cavities
☐ Exclude cavities without flow conditions
☐ Exclude internal space

Physical Features	Value
Fluid Flow	☑
Conduction	☐
Time-dependent	☑
Total analysis time	1 s
Output time step	0 s
Gravity	☑
X component	0 m/s^2
Y component	-9.81 m/s^2
Z component	0 m/s^2

STEP 4: Defining the nature of the fluid

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

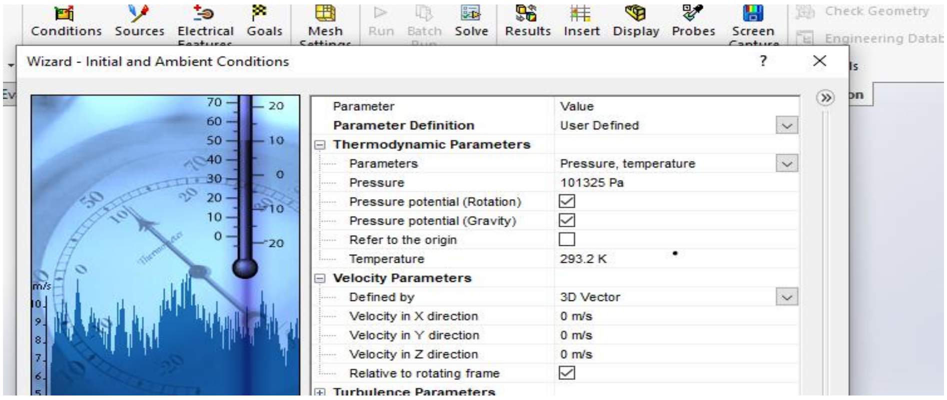


Wizard - Default Fluid

Fluids	Path
Gases	
Liquids	
Non-Newtonian Liquids	
Compressible Liquids	
Real Gases	
Steam	

STEP 5: Defining Physical Parameters

Relative Rotating Frame: True

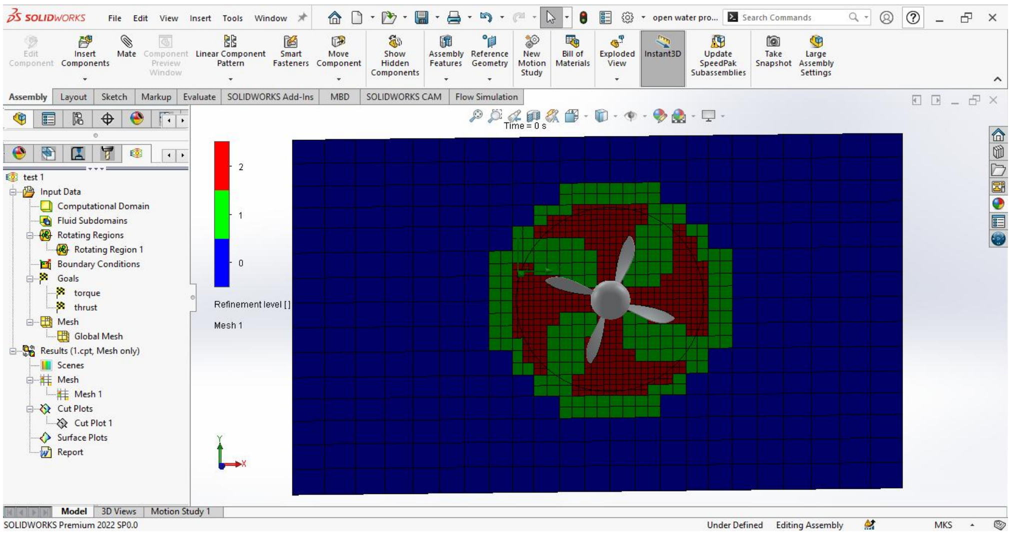


Wizard - Initial and Ambient Conditions

Parameter	Value
Parameter Definition	User Defined
Thermodynamic Parameters	
Parameters	Pressure, temperature
Pressure	101325 Pa
Pressure potential (Rotation)	☑
Pressure potential (Gravity)	☑
Refer to the origin	☐
Temperature	293.2 K
Velocity Parameters	
Defined by	3D Vector
Velocity in X direction	0 m/s
Velocity in Y direction	0 m/s
Velocity in Z direction	0 m/s
Relative to rotating frame	☑
Turbulence Parameters	

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

Mesh Refinement size: 3



STEP 7: Run the simulation.

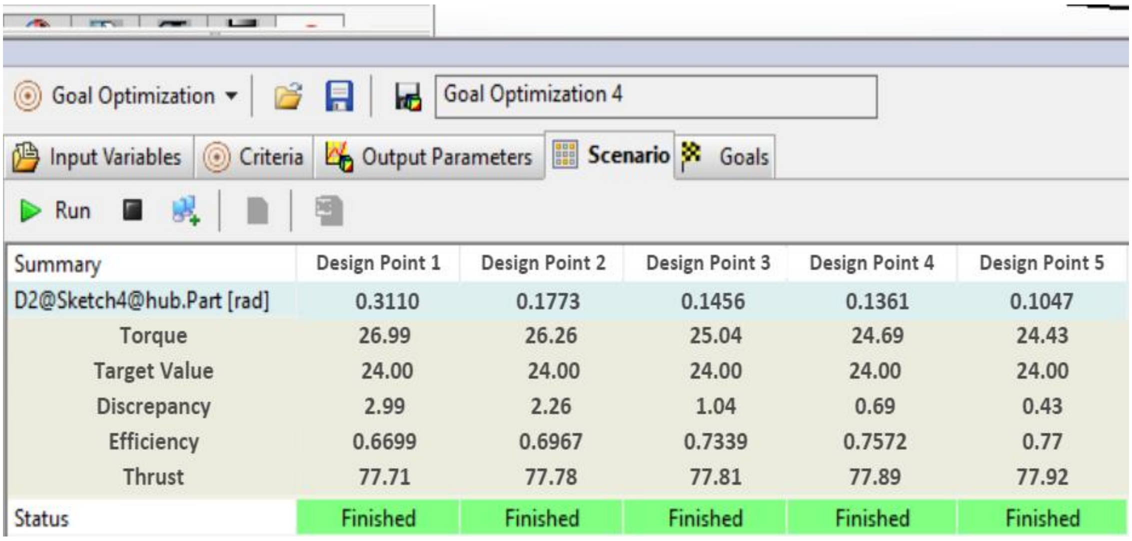
4.5 SIMULATION RESULTS AND ANALYSIS

4.5.1 BLADE OPTIMIZATION FOR EFFICIENCY THROUGH PARAMETRIC STUDIES

The efficiency of a marine propeller depends on the angle at which its blades bite into the water. This angle is known as the tip angle of attack. 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 tip angle of attack was decreased, the torque experienced by the propeller shaft decreased. Torque is essentially the twisting force required to spin the propeller. A reduction in torque translates to less load on the engine or motor that drives the propeller, potentially leading to fuel savings or increased engine lifespan.

The good news is that despite the decrease in torque, the propeller also exhibited a slight increase in thrust. Thrust is the force that pushes the boat forward. This means that the propeller design became more efficient at converting engine power into forward motion. In simpler terms, for a little less effort (reduced torque), the propeller was able to generate slightly more thrust, making the entire propulsion system more effective. The exact reasons behind this phenomenon are likely a combination of factors. The propeller blade itself acts like an underwater wing, and decreasing the angle of attack might have improved its efficiency in generating thrust, similar to how the wing of an airplane produces lift. Additionally, propellers generate swirling water at their tips, which can be a source of energy loss. 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

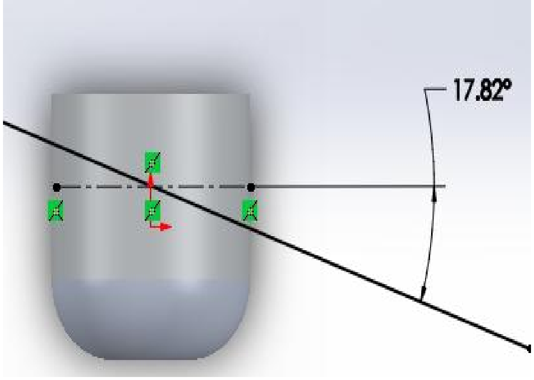


Figure 4.9: Initial Blade Tip Pitch Angle

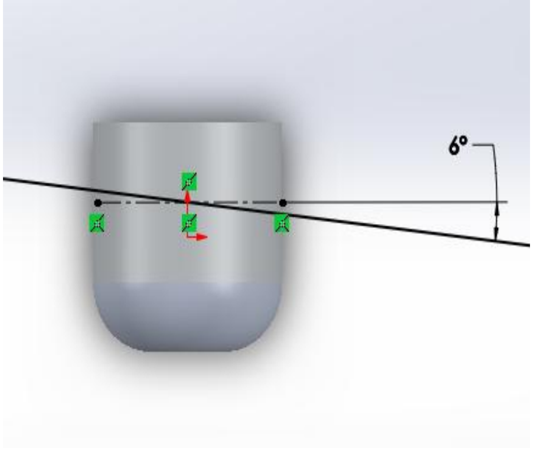
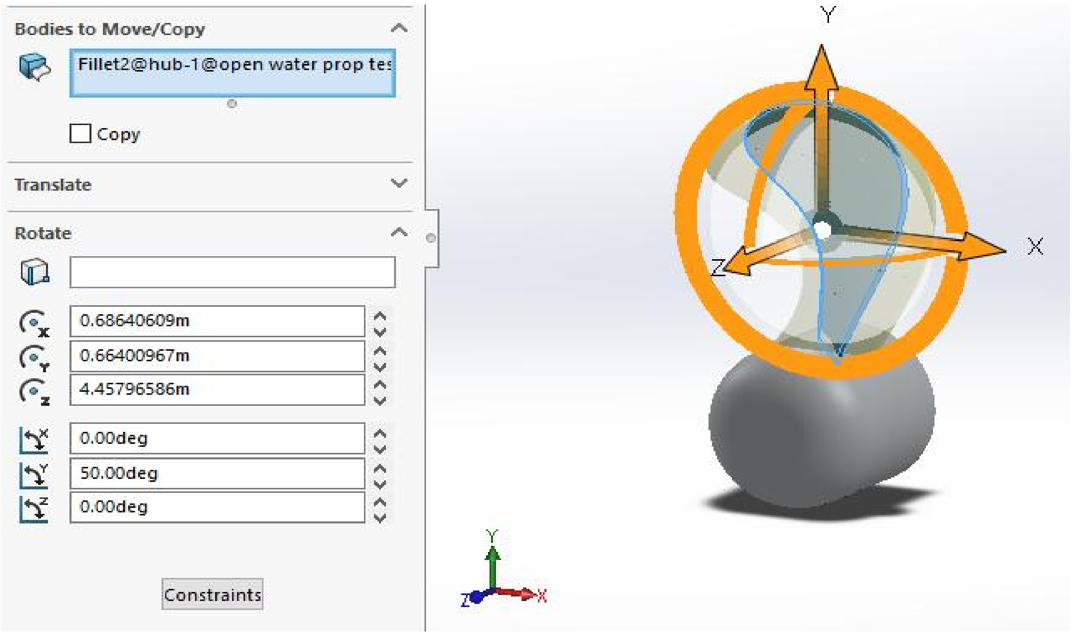


Figure 4.10: Final Blade Tip Pitch Angle

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

Table 4.1 Simulation Result at Design Pitch

4.5.2 ANALYSIS OF CPP PERFORMANCE AT VARYING PITCH CONDITIONS



Bodies to Move/Copy

Fillet2@hub-1@open water prop tes

☐ Copy

Translate

Rotate

0.68640609m
0.66400967m
4.45796586m

0.00deg
50.00deg
0.00deg

Constraints

Figure 4.11: Change in blade pitch angle

The adjustable pitch angle of the controllable pitch propellers (CPP) significantly impacts propulsion. As illustrated in Figure 4.11, a positive pitch angle is achieved by rotating the blade clockwise around the y-axis, while a negative angle results from counter-clockwise rotation.

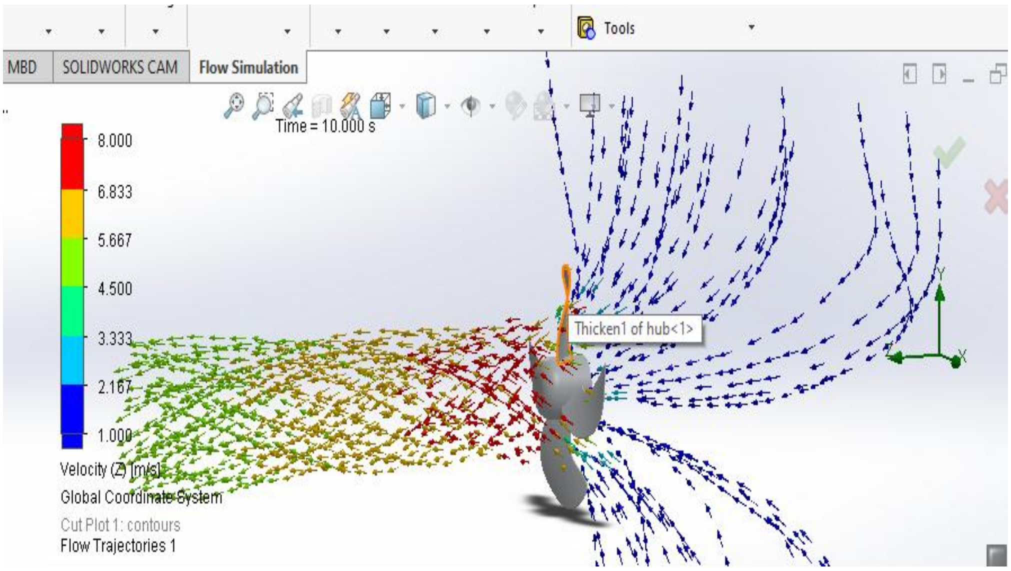


Figure 4.12: Propeller - water interaction at positive thrust Condition (ahead motion)

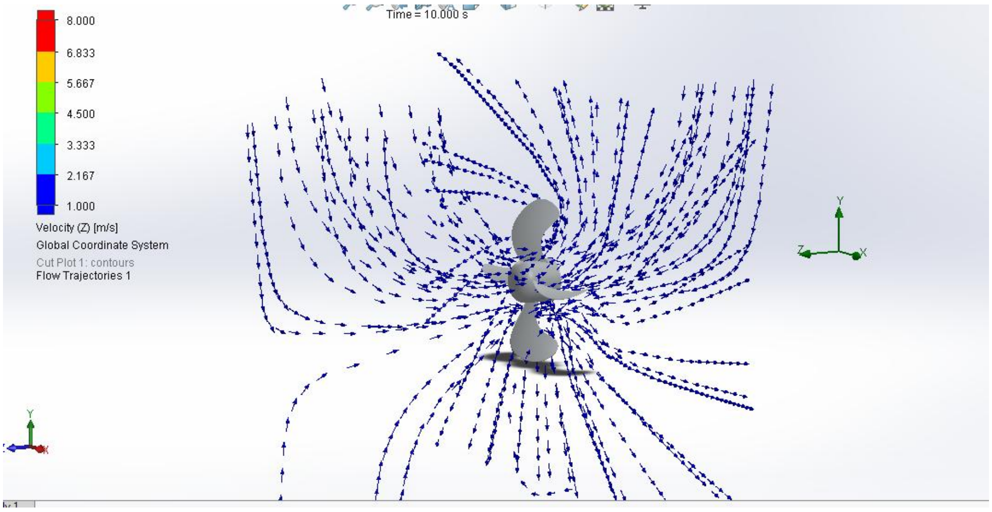


Figure 4.13:Propeller - water interaction under approximate zero thrust Condition

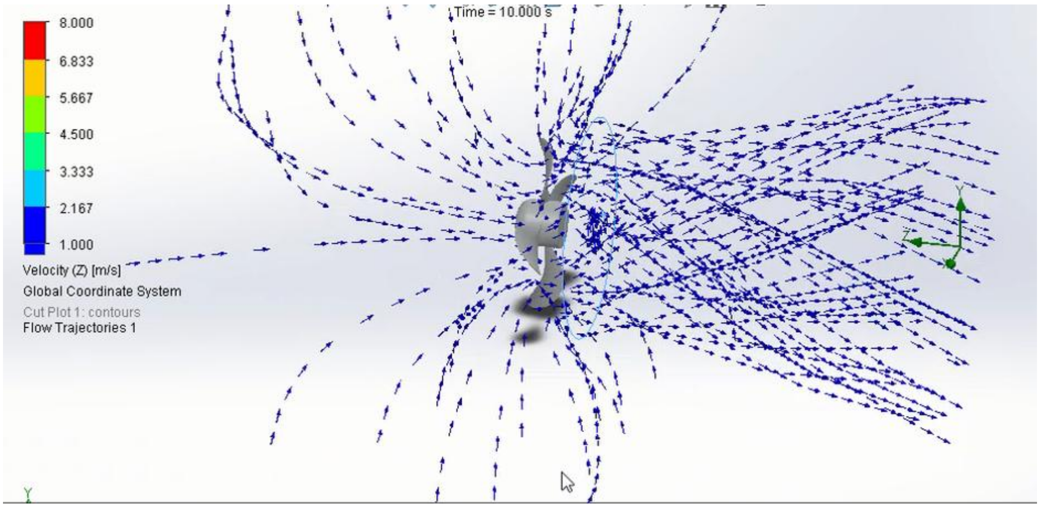


Figure 4.14: Propeller - water interaction at negative thrust Condition (astern motion)

This adjustment in pitch angle influences the magnitude of thrust and torque generated by the propeller as illustrated in figure 4.15 and 4.16. 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 4.13. 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 4.14.

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

Positive thrust = Forward motion of the vessel

Negative thrust = Backward motion of the vessel

Table 4.2:Positive change in pitch angle results

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

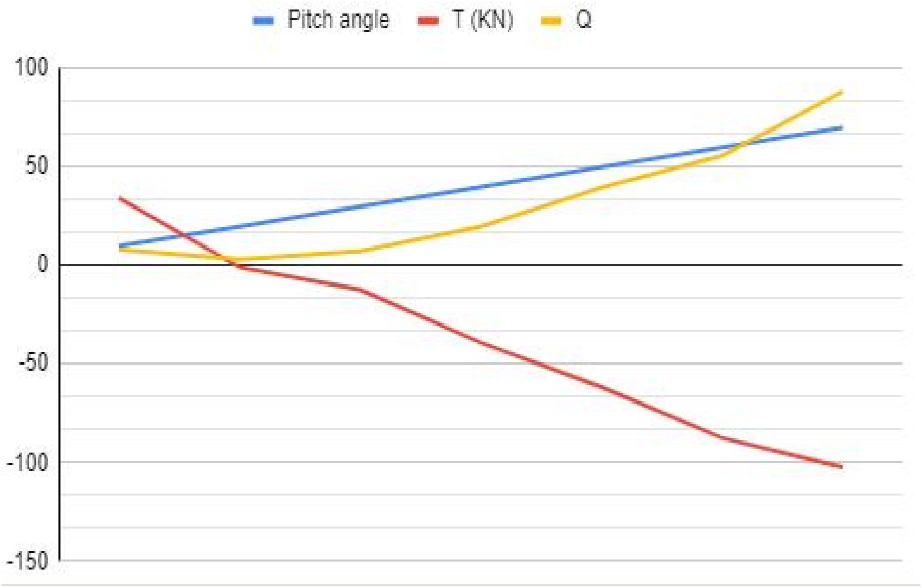


Figure 4.15: Graph showing trend for thrust and torque for positive increase in pitch angle

Table 4.3: Negative change in pitch angle results

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

Figure 4.16: 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 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.

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

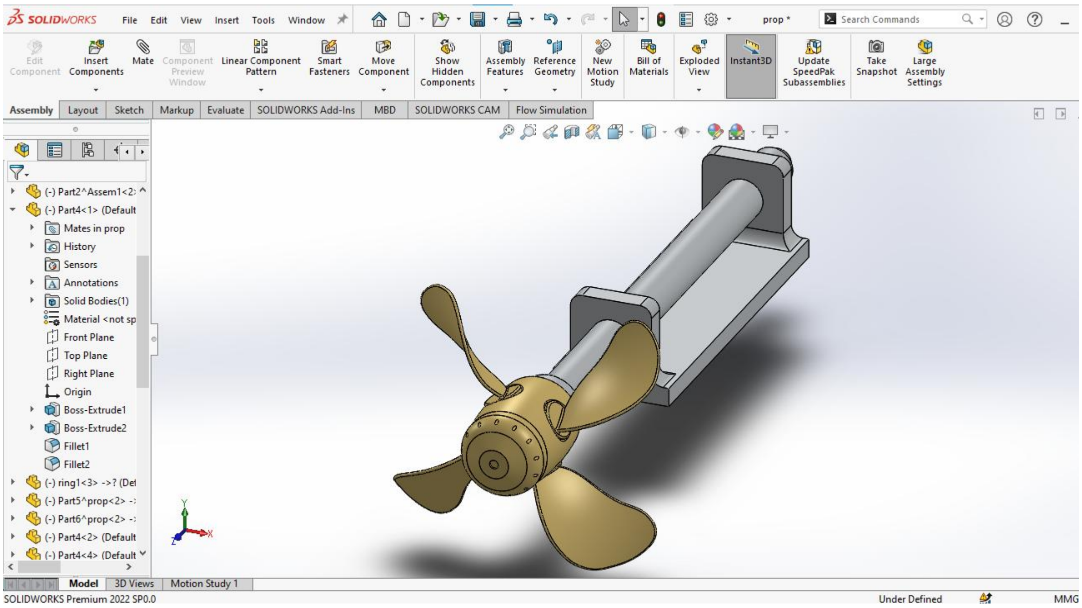


Figure 4.17: 3D view of the Controllable Pitch Propeller design model

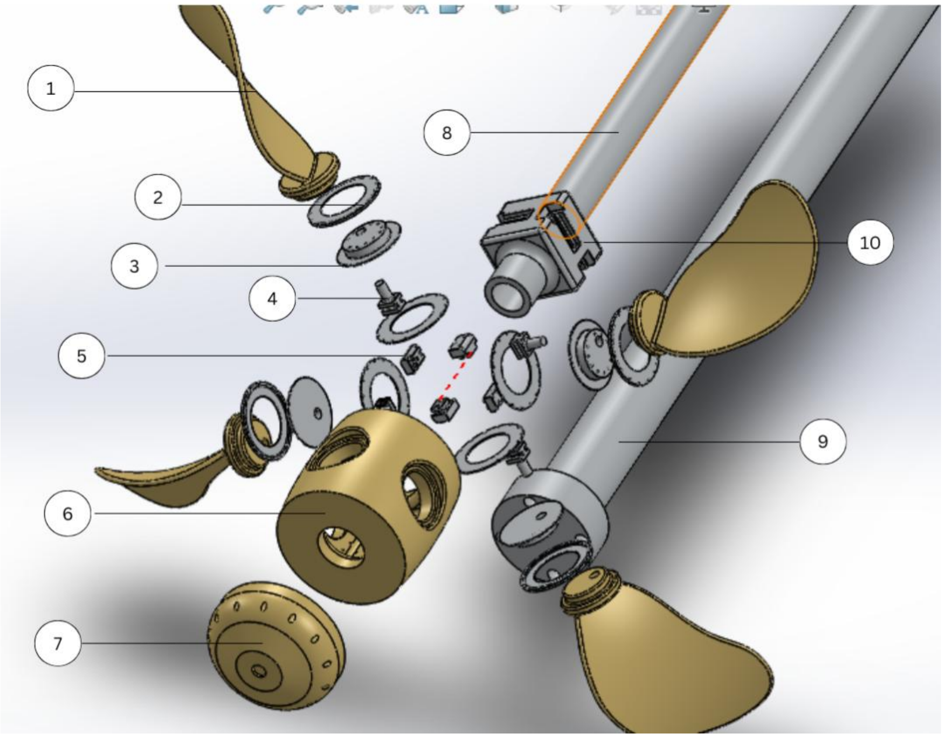


Figure 4.18: Exploded view of a Controllable Pitch propeller.

Key

1. Propeller Blade

2 . Bearing and Rings

3. Pin Slot

4. Yoke Pin

5. Yoke arm

6. Hub

7. Hub Cover

8. Push-Pull Rod

9. Shaft

10. Yoke

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

The project aimed to design and simulate a 4-bladed controllable-pitch marine propeller for small to medium-sized vessels, focusing on enhancing maneuverability and efficiency in different maritime operational conditions. This was achieved through a comprehensive review of literature on marine propulsion, propeller design, and controllable-pitch technologies to establish a solid foundation for the design process. Design theories, series, and charts were studied to formulate a mathematical analysis for the propeller design, which was then realized using SolidWorks 3D modeling software to create a detailed propeller design. Computational Fluid Dynamics (CFD) simulations were conducted with SolidWorks Flow Simulation software to analyze fluid dynamics around the propeller, optimize blade design, and predict performance at different pitch angles. The propeller design was refined based on simulation results to enhance efficiency and performance, ensuring that the propeller meets the project objectives for improved maneuverability and efficiency in small to medium-sized vessels.

The project commenced with an analysis of existing literature on marine propulsion, propeller design, and controllable-pitch technologies. This literature review provided a solid theoretical foundation, allowing for informed decision-making throughout the design and simulation phases.

Utilizing SolidWorks 3D modeling software, a design model of the propeller was created. This design phase was marked by careful consideration of various factors, including blade shape, hub configuration, and overall geometry. These elements were carefully optimized to ensure maximum efficiency and maneuverability.

The Computational Fluid Dynamics (CFD) simulations, conducted with the aid of SolidWorks flow, which was used in analyzing the fluid dynamics around the propeller. These simulations provided crucial insights into the propeller's performance under different operational conditions, enabling the optimization of blade design for enhanced efficiency.

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.

Despite the project's successes, there are several limitations that should be acknowledged. Firstly, the lack of physical prototyping means that the propeller design has not been tested under real-world conditions. While the CFD simulations provide valuable insights, physical testing would be necessary to validate the propeller's performance. Additionally, the simplifications made in the CFD simulations may not fully capture the complexities of real-world operating conditions, such as cavitation effects and underwater turbulence.

For future work, it is recommended to conduct physical testing of the propeller design to validate its performance under real-world conditions. This would involve manufacturing a prototype propeller and testing it in a controlled environment, such as a towing tank or water basin. Additionally, further research could explore more advanced CFD techniques to improve the accuracy of simulations and capture real-world complexities more effectively. The design and simulation of the controllable-pitch marine propeller have laid a solid foundation for future research and development in marine propulsion and propeller design.

This project has contributed to the field of marine propulsion by providing a practical and effective design solution for small to medium-sized vessels, highlighting the importance of controllable-pitch propellers in enhancing vessel performance.

5.2 RECOMMENDATIONS

I. Physical Prototyping and testing should be conducted to validate the simulation results and assess real-world performance. This would provide tangible evidence of the propeller's efficiency and maneuverability.

II. The use of advanced materials and manufacturing techniques should be explored to further improve propeller performance and strength. This could include the use of composite materials or additive manufacturing methods.

III. Validation studies should be conducted with a focus on larger vessels to assess the applicability and scalability of the design. This would provide insights into how the propeller design can be adapted for different vessel sizes and operational requirements.

IV. Real-world complexities such as cavitation effects, underwater turbulence, and interactions with vessel components should be considered in future simulations and analyses. This would provide a more comprehensive understanding of the propeller's performance in actual operating conditions.

V. Continued research and development efforts should be done to refine the propeller design and explore new technologies and methodologies for further enhancing propeller performance and efficiency.

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