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MUSTAFA VARKİ

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# DESIGN OF UNMANNED AIR VEHICLE (UAV) FOR VERTICAL TAKE – OFF AND LANDING (VTOL)

M.Sc. THESIS
IN
AIRCRAFT AND AEROSPACE ENGINEERING

BY
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**M.Sc. Thesis**

**in**

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**Gaziantep University**

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**August 2023**

**I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.**

**Mustafa VARKİ**

# ABSTRACT

## DESIGN OF UNMANNED AIR VEHICLE (UAV) FOR VERTICAL TAKE-OFF AND LANDING (VTOL)

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**Supervisor: Assoc. Prof. Dr. Eyüp YETER**
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In recent years, Vertical Take-Off and Landing (VTOL) aircraft have gained significant attention due to their versatility and capability to operate in constrained spaces. This thesis focuses on the comprehensive design and analysis of a VTOL aircraft with tilt wing technology and its propeller system. A comparative evaluation of various existing VTOL designs from the literature has been conducted to propose a novel aircraft design. Each component of the aircraft and the selected materials were carefully optimized for efficiency and performance. The worm drive mechanism was chosen for the tilt mechanism, enabling the VTOL feature. Different types of propellers were employed on the wings and at the rear of the aircraft to achieve the required thrust during vertical take-off and landing and to maintain moment balance. In the preliminary design, a total of six propellers are chosen, with two 3-bladed propellers at the rear and four 2-bladed propellers on the wings. Then, the performance of the propellers on the wing under various conditions was evaluated by performing Computational Fluid Dynamics (CFD) analyses and optimum configurations were determined for different number of propellers scenarios.

**Key Words:** VTOL, Propeller, CFD

# ÖZET

## DİKEY KALKIŞ VE İNİŞ İÇİN İNSANSIZ HAVA ARACI TASARIMI

**VARKİ, Mustafa**
**Yüksek Lisans Tezi, Uçak ve Uzay Mühendisliği**
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Son yıllarda, dikey iniş ve kalkış uçakları, çok yönlülükleri ve kısıtlı alanlarda çalışabilme yetenekleri sayesinde önemli ilgi görmektedir. Bu tez çalışmasında, tilt-wing teknolojisine sahip bir insansız hava aracı tasarımı ve pervane sisteminin analizi kapsamlı bir şekilde gerçekleştirilmiştir. Literatürde yer alan farklı VTOL tasarımlarının karşılaştırılmalı değerlendirmesi yapılarak yeni bir VTOL uçak tasarımı yapılmıştır. Uçağın her bir bileşeni ve seçilen malzemeleri, verimlilik ve performans gözetilerek oluşturulmuştur. Uçağa VTOL özelliğini kazandıran tilt mekanizması için worm drive mekanizması tercih edilmiştir. Kanatlarda ve uçağın arka kısmında farklı tipte pervaneler kullanılarak dikey kalkış ve iniş sırasında gerekli itki kuvvetinin sağlanması ve moment dengesinin elde edilmesi amaçlanmıştır. İlk tasarımda arka kısımda iki adet 3 kanatlı pervane ve kanatlarda dört adet 2 kanatlı pervane olmak üzere toplamda altı adet pervane tercih edilmiştir. Daha sonra, çeşitli akış analizleri yapılarak, kanatlardaki pervanelerin çeşitli koşullar altındaki performansı değerlendirilmiş ve farklı sayıdaki pervane senaryoları için optimum konfigürasyonlar belirlenmiştir.

**Anahtar Kelimeler:** İHA, Pervane, Hesaplamalı Akış Dinamiği

''Dedicated to my mother, father, sister and brothers''

Rabia, Mehmet, Filiz, Öcal and Hakan

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| | |
|---|---|
| **α** | Angle of Attack |
| **θ** | Pitch Angle |
| **φ** | Induced Angle |
| **π** | Pi |
| **L** | Lift |
| **D** | Drag |
| **T** | Thrust |
| **Q** | Torque |
| $\mathbf{C_L}$ | Lift Coefficient |
| $\mathbf{C_D}$ | Drag Coefficient |
| $\mathbf{C_M}$ | Moment Coefficient |
| $\mathbf{C_T}$ | Thrust Coefficient |
| $\mathbf{C_Q}$ | Torque Coefficient |
| **Re** | Reynolds Number |
| **ρ** | Density |
| **V** | Velocity |
| **µ** | Dynamic Viscosity |
| **J** | Advance Ratio |
| $\mathbf{n_P}$ | Propeller Efficiency |

## LIST OF ABBREVIATIONS

| | |
|---|---|
| **UAV** | Unmanned Aerial Vehicle |
| **MAV** | Manned Aerial Vehicle |
| **VTOL** | Vertical Take-Off and Landing |
| **MALE** | Medium Altitude Long Endurance |
| **HALE** | High Altitude Long Endurance |
| **PTUAV** | Practical Tiltrotor Unmanned Aerial Vehicle |
| **HARVee** | High-Speed Autonomous Rotorcraft Vehicle |
| **QTW** | Quad Tilt Wing |
| **CFD** | Computational Fluid Dynamics |
| **LQR** | Linear Quadratic Regulator |
| **PID** | Proportional Integral Derivative |
| **RPM** | Revolution Per Minute |
| **FEM** | Finite Element Method |
| **FVM** | Finite Volume Method |
| **RANS** | Reynolds Averaged Navier Stokes |
| **CAD** | Computer-Aided Design |

# CHAPTER 1
# INTRODUCTION

## 1.1 General Introduction

The adventure of aviation, which started with the desire of people to fly in the sky, opens to new horizons by putting new technologies on it every year. After many trials and countless studies, humanity succeeded in this desire and did not even think about their lives while achieving it. They reached their destination first with non-motorized aircraft such as balloons and zeppelins, and then with airplanes. In the light of these developments, the idea of flying airplanes without a pilot has always been on the minds of researchers interested in aviation. It was not surprising that this idea emerged and started to be talked about because the death of the personnel, who had a very low chance of surviving in any accident, would no longer be talked about. In addition, UAVs, which have many indisputable advantages such as production cost and ease of production, have started to stand out compared to conventional aircraft.

High-capacity unmanned aerial vehicles, which have increased their popularity since the 1970s, are mostly used for military surveillance, data collection and armed engagement to critical points, but also in civilian areas such as agriculture and ground research. Unmanned aerial vehicle technology, which has become widespread, has begun to be designed in three different wing motions, namely fixed-wing, rotary-wing and flapping-wing (**Figure 1. 1**), to be used in different targets and missions Mohsan et al. (2023). None of these different wing types of UAV is more dominant. Each vehicle has advantages and disadvantages over each other.

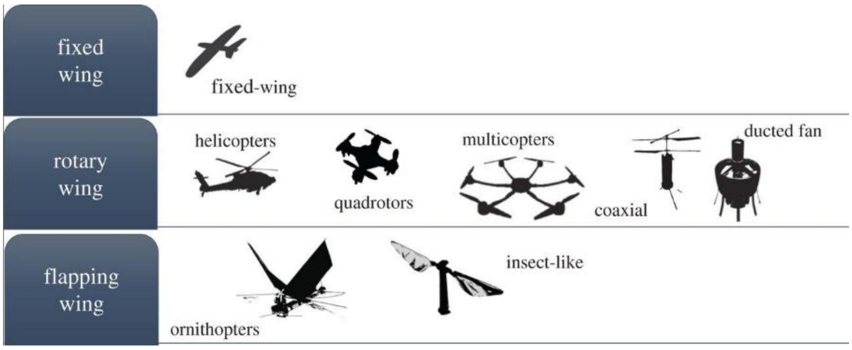


**Figure 1. 1.** UAV types (Karydis et al. (2017))

Fixed-wing aircraft require a necessary runway for take-off and landing, and are also more efficient in long flights, but can be used for limited purposes due to their inability to fly at low speeds and their low maneuverability. Differently, rotary and flapping wing-type vehicles can take off and land from any region and can be controlled easily in mountainous areas due to their high maneuverability, but their efficiency is lower.

All these complementary features and different uses led to the design of a different aircraft that combined them all. This aircraft, called VTOL (Vertical take-off and landing), does not require any runway but also has horizontal flight capability like a conventional aircraft. VTOL has 3 different configurations in itself: wing type, helicopter type and ducted type. In the wing type, it is divided into two categories: fixed or tilt-wing. In the early days of VTOL's development, it was first used in different wing types for military purposes, and then more advanced and different configurations were designed. It is called Hybrid VTOL because they accommodate different configurations. Also, Different types of Hybrid VTOL shown in **Figure 1. 2**.

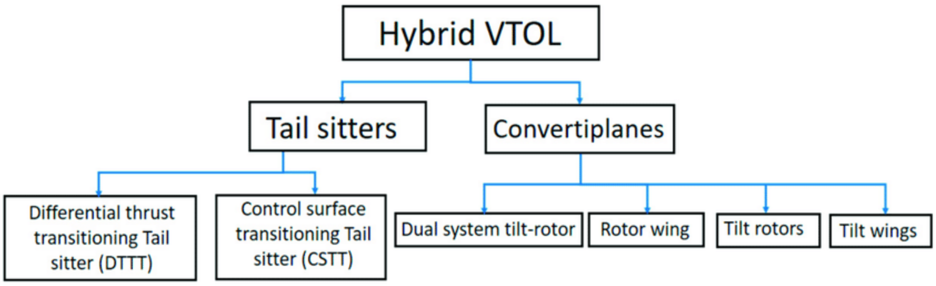


**Figure 1. 2.** Hybrid VTOL types (Panigrahi et al. (2021))

The main purpose of this study is to combine the advantages of UAV vehicles and make the necessary analyses for a more efficient tilt-wing VTOL.

## 1.2 Motivation of Study

In recent years, the designs of unmanned aerial and land vehicles have been increasing due to the fact that the struggles are in narrower areas and against smaller groups and in order to prevent the loss of expert personnel. It is important to have these systems, where time is more important, that can serve as soon as possible and that can take off and land from anywhere, regardless of geographical conditions. It is essential to integrate such vehicles into our national technology, especially in order to be a deterrent in the world and to have an independent defense industry. In addition, the increase in these developments, which will increase the probability of successful operations, will also make great contributions to the country's economy.

## 1.3 Problem Statement

Studies in the field of aviation around the world have increased in recent years due to the competition between countries. These studies have brought their own difficulties. One of the biggest challenges in VTOL studies is the use of multiple modes. In particular, there are large aerodynamic changes in the transition mode from low speeds to high speeds, which makes it difficult to control. There are very few examples of a controller that can fly vertically, transitionally and horizontally at the same time. Structurally, one of the biggest problems for a VTOL with a tilt wing is its high power and torque. This vehicle, which has a tilt wing, may cause structural deterioration during the movement of the wings. Therefore, a design with higher structural safety and material reliability should be made. Finally, the position and number of the propellers that will provide the lift force are among the issues to be considered.

## 1.4 Scope of Thesis

This thesis focuses on VTOL aircraft, which is an important topic in the field of aviation and aircraft design. VTOL aircraft are effectively used in different missions, offering greater maneuverability and flexibility compared to other aircraft. However, the performance, stability and efficiency of VTOL aircraft are affected by several factors such as complex aerodynamic interactions and propeller configurations. In this thesis, an effective design and propeller analysis has been made by examining the aerodynamic performance and optimized design parameters of VTOL aircraft.

In this sense, this study will investigate the effect of different propeller arrangements and wing geometry on the performance of VTOL aircraft through CFD analyses and numerical simulations. In addition, the data obtained as a result of analyses using different propeller configurations and type separation distances in this thesis will provide design recommendations for VTOL aircraft to provide more efficient and stable flights. This study aims to contribute to the design and development processes for the aviation industry and future VTOL aircraft.

Chapter 1 highlights the general background, research motivation, problem statement, and objectives of the thesis. Chapter 2 presents the literature related to VTOL and rotor interaction. Chapter 3 presents the working principle of aircraft and the blade element theory. Chapter 4 presents detail design of VTOL aircraft and the analysis of propellers under various scenarios. Chapter 5 provides an overall summary and conclusion of the study.

# CHAPTER 2
# LITERATURE SURVEY

## 2.1 Introduction

In this section, a literature review of unmanned aerial vehicles and VTOL vehicles, including historical, design, and analysis, is presented.

## 2.2 Overview of UAV and VTOL

Since the beginning of the 20th century, various research and flight trials have been carried out and the foundations of aviation have been laid. Although the military use of various unmanned aerial vehicles (UAVs) started to increase in the late 1990s, their utilization in the civilian domain was still in the early stages of growth (Van Blyenburgh (1999)). In the adventure that started with unpowered aircraft trials, many platforms have emerged, from fixed-wing aircraft to multi-rotor types, as well as vertical take-off and landing vehicles with the accumulating and developing technology in the following years. Among them, fixed-wing and rotor-based unmanned aerial vehicles currently have more practical applications compared to hybrid VTOLs.

Fixed-wing unmanned aerial vehicles with medium altitude long endurance (MALE) and high altitude long endurance (HALE) flight capabilities have to fly above a certain speed due to the lack of hover capability. It is one of the most critical points that they do not fall below the stall speed. These UAVs can carry more payloads for longer periods using less power than VTOL UAVs. This makes them attractive for long distance missions. Especially miniature fixed-wing drones are widely used due to their low cost, high efficiency, and ease of design (Cai et al. (2010)). In addition, it needs a long runway if it has a landing and take-off system and wheels, and a launcher if these systems are not available.

Multi-rotor UAVs are the easiest and least expensive option to design a flying vehicle in the sky. Maneuverability and ease of use are other reasons that attract them. Because they consume more power than fixed-wing aircraft, and their payload capacity is lower. In addition, since they have limited endurance and speed, they are insufficient in missions such as long-range scanning and surveillance. In their comprehensive research on unmanned aerial vehicles, Chaurasia et al. (2021) highlighted that the major issue associated with these types of multi-rotor unmanned aerial vehicles is the significant energy expenditure required to maintain their balance in the air and counteract gravity.

A single rotor UAVs are similar in design and structure to helicopters. These vehicles have a relatively large rotor and also a tail rotor for stability. These single rotor helicopters need less energy as they can use a longer propeller but also the length and weight of a single rotor can pose hazards.

Unmanned aerial vehicles called hybrid VTOL, which include different configurations such as tilt wing, tilt rotor and so on, have recently increased in popularity. Hybrid vehicles, born from the combination of different aircraft, are capable of both hovering and advanced flight capabilities at the same time. But the biggest challenge of these combinations is to design the controller. Saeed et al. (2018) have provided a comprehensive presentation by categorizing hybrid UAVs. This study particularly highlights that a portion of these vehicles has not achieved success primarily due to control difficulties. Additionally, it is mentioned that maintaining the UAV in the vertical mode consumes a high amount of power, rapidly depleting the used batteries, and consequently reducing the range of these vehicles.

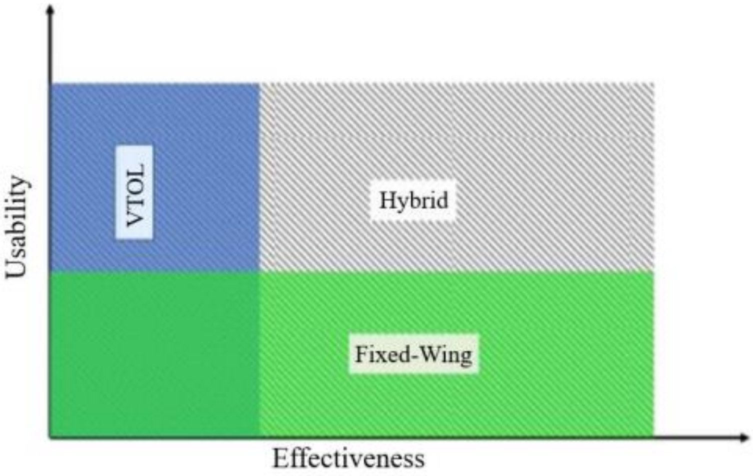


**Figure 2. 1.** Comparison of aerial vehicles (Kaparos et al. (2019))

As a result, the comparative graph of these vehicles is provided in **Figure 2. 1**. Also, **Table 2. 1** provides an insight into the mission profiles of different UAV classes by comparing their capabilities. For missions that involve the need for vertical take-off and landing or hovering capability, aircraft with rotating blades like single rotor or multi rotors are the most appropriate choice. But, their aerodynamic efficiency is relatively low, which makes them less suitable for long-endurance missions. In contrast, fixed-wing aircraft are the preferred option when it comes to durability and range. If a combination of these capabilities is required, the most suitable solution is to develop a hybrid VTOL aircraft.

**Table 2. 1.** Comparison of UAV Types in the Literature

| **Capability** | **UAV TYPES** | | | |
|---|---|---|---|---|
| | Airplane | Single rotor (Helicopter) | Multirotor | Hybrid ( Tilt-Wing, Tilt Rotor ) |
| VTOL | Negative | Positive | Positive | Positive |
| Hover | Negative | Positive | Positive | Positive |
| Weight | Neutral | Neutral | Positive | Neutral |
| Endurance | Positive | Negative | Negative | Neutral |
| Range | Positive | Negative | Negative | Positive |
| Level Flight | Positive | Negative | Negative | Positive |
| Efficiency | Positive | Negative | Negative | Positive |
| Payload | Positive | Negative | Negative | Positive |
| Control System | Positive | Neutral | Positive | Negative |
| Stability | Positive | Negative | Negative | Positive |
| Maneuverability | Negative | Neutral | Positive | Positive |

.

As seen from the comparisons, Hybrid VTOL aircraft are air vehicles that use the aerodynamic principles of conventional airplanes to move in the air, while utilizing the rotor systems of helicopters for vertical take-off and landing, which makes them popular. These aircraft, which have different designs and structures such as rotary wings, rotors, and tail sitters, provide many benefits due to their high-speed transportation capabilities, ability to perform short-range vertical take-offs and landings, and ease of use for unmanned operations. The aviation industry has taken notice of Hybrid VTOLs, which have been increasingly featured in the aviation literature in recent years.

Zhou et al. (2020) have studied the vertical take-off and landing capabilities of unmanned and manned aerial vehicles (UAV and MAV), which are aircraft used for many different purposes such as aerial reconnaissance, surveillance, transport and so on. In addition, different VTOL aircraft designs and their performances are compared and information about their current usage areas is given. Today, VTOL technology is crucial to many industries, and as the article states, this trend is anticipated to last into the future.

Hirschberg (2006) demonstrates how the concepts and technologies of VTOL have evolved and diversified according to different military requirements and the needs of the aviation industry. Based on these differences, we examine VTOL aircraft in six different categories.

Compound aircraft are vehicles that possess helicopter capabilities but incorporate additional wing or propulsion systems to achieve extended range and higher speeds. By combining the advantages of vertical take-off and landing (VTOL) and fixed-wing aircraft, compound aircraft expand their potential applications. Edi et al. (2008) have conducted research on compound aircraft, considering the aerodynamic limitations that prevent traditional helicopters from exceeding a forward speed of 400 km/h. They have adopted a new design approach in their studies. It has been found that the newly designed concept aircraft exhibits favorable aerodynamics for transportation aircraft at higher speeds. The first study conducted within the framework of compound aircraft is Focke-Wulf Fw 61 (Wall et al. (2022)).

This aircraft was equipped with helicopter rotors as well as front and rear stabilizing propellers as shown in **Figure 2.2**. As a result, it could perform helicopter-like flights while achieving higher speed and performance. Focke-Wulf Fw 61 is recognized as a precursor to the compound aircraft concept.

**Figure 2.2.** Focke-Wulf Fw 61 Compound Aircraft (Wall et al. (2022))

Tail Sitter is another aircraft design capable of vertical take-off and landing. They are structurally the simplest VTOL vehicles as they do not require additional thrust vectoring mechanisms, and this simplicity eliminates production complexities. However, the performance of the aircraft in terms of hovering or performing takeoff and landing is significantly affected by wind disturbances. In this design, the aircraft can perform vertical take-off and landing while in a horizontal position. Once it is airborne in the vertical orientation and reaches its destination, the aircraft transitions to a horizontal position for forward flight.

Stone et al. (1996) study a preliminary design and multidisciplinary design optimization of a tandem-wing tail-sitter unmanned aerial vehicle (UAV) were addressed. The study focused on the initial design phase of the UAV, considering factors such as aerodynamics, structures, and performance requirements. Since this type of aircraft has a simple mechanical structure, it has recently started to attract attention and has begun to be designed in different models. Moore (2010)  has presented studies on NASA Puffin (**Figure 2.3**), an electric tail sitter VTOL concept. Aims of this study include the assessment of the potential benefits and applications of the Puffin concept. With its electric propulsion system and vertical take-off/landing capabilities, the Puffin aircraft presents advantages such as reduced noise levels, environmentally friendly operations, and improved urban mobility. The Puffin concept serves as a valuable reference point in the advancement of VTOL technology within the aviation industry. Also, Hochstenbach et al. (2015) have developed a tail sitter VTOL design called VertiKUL, which is not controlled by control surfaces. This design focuses on the transition capability that allows the UAV to smoothly transition from vertical take-off to forward flight.

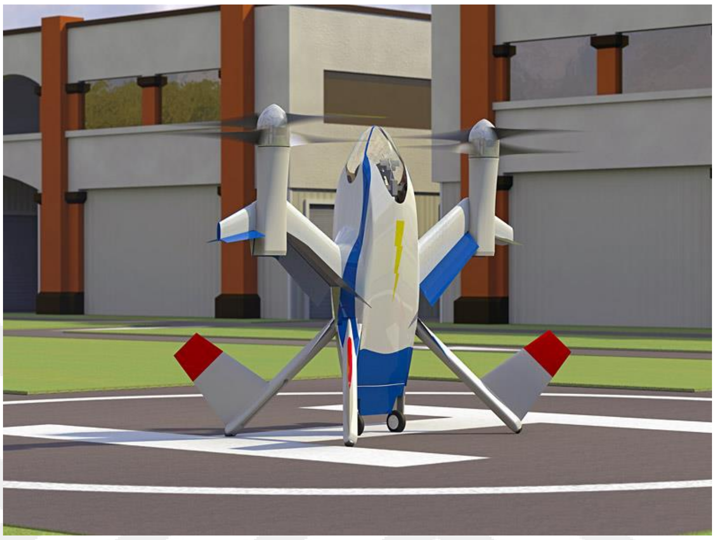


**Figure 2.3.** Nasa Puffin Tail-sitter (Moore (2010))

Ducted Fan VTOL vehicles utilize one or more directional fans mounted on the aircraft to enable vertical take-off and landing. These vehicles offer higher speed and performance compared to helicopters and generate less noise pollution than helicopter rotors. They emerged in the literature in the 1950s and further advanced in the 1960s with the development of VTOL vehicles. Intwala et al. (2015) provides information about the pioneering ducted fan VTOL vehicles such as Yak-38 Forger and Harrier. These vehicles, discussed within the context of these advancements, are considered as significant representatives of ducted fan VTOL technology. Jagdale et al. (2018) presented an overview of the initial studies in the field of VTOL and the current research being conducted. Additionally, they highlighted the strengths and weaknesses of unmanned aerial vehicles in various configurations. The Yakovlev Yak-38 aircraft (**Figure 2.4**), designed and developed by the Soviet National Aerospace in Russia, was primarily intended for military purposes, particularly for naval operations. However, due to its limited performance and payload capacity, it achieved only limited success.

**Figure 2.4.** Yak-38 (Goebel (2023))

Vehicles that resemble a helicopter with four rotors are generally referred to as quadrotors. These aircraft have the ability to take off and land vertically, and they typically achieve this through the use of rotating propellers around the vertical axis. This design allows them to consume significantly less fuel compared to vehicles that rely on fuel as their propulsive force, such as rockets. Quadrotor VTOL vehicles have become more popular among multirotors due to their simple structure, low cost, and enhanced stability.

Ghazbi et al. (2016) have presented studies on the historical development of quadrotors, along with different rotor configurations and dynamic models. Gupte et al. (2012) discuss various aspects of quadrotors, including their structural design, control systems, autonomous flight capabilities, navigation techniques, and application areas. Additionally, the advantages, disadvantages, and current challenges of quadrotors are also evaluated.

Quadrotor aerial vehicles have different configurations within themselves based on wing types and usage conditions. kalpa Gunarathna et al. (2018) present the design and development process of a hybrid unmanned VTOL vehicle that combines the features of a fixed-wing aircraft and a quadrotor. In this mini-sized design weighing 1350 grams, flight tests are discussed. It has been observed that although it achieves stable takeoff, it experiences altitude loss during the transition to forward flight. Also, Lyu et al. (2017) have designed a novel configuration by combining the structures of a tail sitter and a quadrotor, resulting in an autonomously operating system. Compared to two-rotor tail sitter VTOLs, their design has shown increased stability and easier controllability in windy conditions. Furthermore, experimental results have demonstrated its capability to perform maneuvers without significant altitude loss even in the presence of crosswinds. In addition, Su et al. (2022) have presented examples of quadrotor VTOL vehicles designed with advanced technologies in recent times and discussed the concepts of such vehicles. Latitude Engineering LLC is one of the leading companies in the field of aviation and fixed-wing quadrotor VTOL (Vertical Take-Off and Landing) research. They have developed innovative designs such as HQ-60, FVR-10, FVR-90 (**Figure 2.5**), and are currently working on the development of FVR-55, aiming for high speed and range capabilities. Their focus is on creating cutting-edge designs that push the boundaries of technology.

**Figure 2.5.** FVR-90 (L3Harris (2021))

Tilt-rotor is a type of hybrid/convertible configuration UAV equipped with a tilting mechanism, providing the advantages of both a rotary-wing UAV's VTOL capabilities and a fixed-wing UAV's horizontal flight. However, the motors of tilt-rotors are typically located at the wingtips, which results in a thicker airfoil and a shorter wingspan. This, in turn, leads to increased drag and a lower wing aspect ratio, resulting in poor aerodynamic performance (Castillo et al. (2005)).

The foundations of these aircraft, which emerged in the 1930s, can be traced back to the early designs of Leonardo da Vinci. In the following years, Bell company developed prototypes such as the XV-3 and XV-15. Building upon the knowledge gained from these aircraft, with the financial support of Bell and Boeing, the V-22 Osprey military tiltrotor was developed. It possesses vertical takeoff and landing capability, along with the ability to achieve higher speeds in forward flight, earning it the nickname "the dream machine" for its exceptional performance. (Whittle (2010)).

McVeigh et al. (1997) have conducted a detailed presentation. The presentation covers various aspects, starting from the design phase of the V-22 Osprey tiltrotor (**Figure 2.6**) and extending to the efforts made to enhance its aerodynamic performance. The study emphasizes the V-22's versatile capabilities due to its flexible structure, enabling it to successfully fulfill multiple mission requirements. Furthermore, the performance of the V-22 has been extensively analyzed in various scenarios, demonstrating its effectiveness in different operational contexts.

**Figure 2.6.** V-22 Osprey Tilt Rotor (Maisel (2000))

Tilt rotor technology has gained significant recognition in academic literature through research conducted in this field. Recent studies have addressed various aspects of tilt rotor, including its design, aerodynamic performance, flight controls, energy efficiency, and operational usage.

Korea Aerospace Research Institute has developed a full-scale tiltrotor UAV within the SMART UAV program. Subsequent studies led to the design and production of a smaller-scale Practical Tiltrotor UAV (PTUAV) for ease of landing in small areas and cost-effective manufacturing, which is 60% smaller in size. This aircraft, equipped with rotors at the wingtips, has a maximum take-off weight of approximately 180 kg and a top speed of 240 km/h. With a wingspan of 3 meters, the tiltrotor has an endurance approximately 5.5 hours (Choi et al. (2012)).

Ozdemir et al. (2014) have conducted a study and analysis on the design of a vehicle called TURAÇ. Unlike conventional tilt rotor designs, TURAÇ features a unique configuration with an actively used ducted fan located in the main body for VTOL and hover phases. Additionally, it incorporates a dual electric tilt rotor positioned at the front, which remains active throughout all stages of flight.

Carlson et al. (2021) focused on the rapid prototyping design of a small Tricopter/Fixed-Wing Vertical Take-Off and Landing UAS that can be recharged using solar energy. This UAS is capable of performing repeated landings and take-offs without requiring physical intervention or external maintenance devices or platforms. In terms of flight configuration, the Tricopter Tiltrotor features a single stopped rotor for forward flight and a pair of forward-tilted rotors that are optimized for efficient forward flight while still maintaining the ability to hover and provide lift.

Yeo et al. (2009) conducted separate performance and design calculations for traditionally 2-rotor and 4-rotor tilt rotors weighing approximately 67 kilograms each. It was observed that changing the direction of rotor rotation significantly reduced the lift-to-drag ratio of the aircraft for both designs. Additionally, the interference effect improved the lift-to-drag ratio of the 2-rotor aircraft, while it reduced the performance of the 4-rotor aircraft due to the accumulated total induced power in the rear wing.

Hwang et al. (2006) presented a study on tilt rotor aircraft, comparing three different concepts of stud wing designs, which are extended wings added after the nacelle, separate from the main wing. Through their analysis, they observed that the extended wing concept improved performance in terms of endurance and range.

In the tilt-wing configuration, another category within the hybrid VTOL (Vertical Take-Off and Landing) systems, the entire wing assembly, including the propulsion system, can be tilted to transition between vertical and horizontal flight modes. This innovative design offers various advantages such as the ability to operate in rugged terrain, rapid transition between flight modes, and increased efficiency during forward flight. Unlike systems with only rotating rotors or propellers, having the entire wing tilting enhances the aerodynamic flow over the lifting and control surfaces during transition and minimizes the loss of lift caused by downwash during hover (Ransone (2002)).

The concept of a tilt-wing configuration has been researched and developed over the years for both military and civilian applications. Particularly, with the advancement of thrust producers incorporating tilt mechanisms, a new concept of a tiltable VTOL with the entire wing and mounted propellers rotating has emerged.

In the late 1950s, sparked by growing interest, the United States Navy collaborated with Kaman Aviation to develop the K-16B tilt wing aircraft (**Figure 2.7**) using the fuselage and other existing components of a Grumman JRF-5 Goose amphibious aircraft, aiming to reduce costs and time. Unlike other tilt wing aircraft, Kaman's design was limited to a 50-degree rotation instead of the full 90 degrees. However, the project was ultimately canceled before the aircraft could achieve free flight (Swanborough (1964)).

**Figure 2.7.** Kaman K-16B (Goebel (1960))

In the same era, the Hiller Aircraft Company designed the X-18 Tilt wing experimental cargo aircraft. During its experimental flights, the aircraft encountered a propeller pitch control problem, which became the major challenge and ultimately led to the termination of the project. The issue of control proved to be the primary obstacle. Additionally, the positioning of the propellers in relation to the tilt axis was found to be crucial for several reasons. Specifically, it was discovered that the rotational moment due to translation was vital for the stability of hovering, and keeping the propellers low reduced this derivative (Nichols (1990)).

Research and development efforts continue in the field of tilt wing technology. More recent studies will be provided in section 2.3. Furthermore, comparisons of different VTOL categories are presented in **Table 2.2**.

**Table 2.2.** Comparison of VTOL UAV Types

| | **VTOL UAV TYPES** | | | | | |
|---|---|---|---|---|---|---|
| | Compound Aircraft | Tail Sitter | Ducted Fan | Quadrotor | Tilt Rotor | Tilt Wing |
| Controllability | 4 | 2 | 3 | 4 | 3 | 3 |
| Hover Efficiency | 5 | 1 | 3 | 4 | 3 | 4 |
| Cruising Efficiency | 1 | 4 | 2 | 2 | 4 | 4 |
| Transition | 4 | 2 | 4 | 4 | 3 | 3 |
| Cost | 3 | 2 | 1 | 3 | 2 | 3 |
| Safety | 5 | 1 | 3 | 4 | 3 | 3 |
| Mechanical Complexity | 5 | 4 | 2 | 5 | 3 | 4 |

According to the table, it is evident that tilt-wing aircraft exhibit both optimal and average values. Consequently, this study will concentrate on a UAV with tilt-wing VTOL capability and emphasize propeller research.

### 2.3 Design of Tilt-Wing VTOL

Currently, there is ongoing research and numerous studies in the literature focusing on various innovations and improvements to enhance the performance, aerodynamic efficiency, safety, and efficiency of tilt-wing aircraft. These efforts aim to achieve better overall flight characteristics.

The miniature aircraft designed within the scope of the High-Speed Autonomous Rotorcraft Vehicle (HARVee) project features a conventional fuselage, a single wing, and four rotors. Due to its simplicity and practicality, the design exhibits relatively crude aerodynamic performance Dickeson et al. (2007).

QTW-UAS FS4 is a tilt wing VTOL unmanned aerial system designed in collaboration between GH Craft and Chiba University. It features a four-rotor configuration and tandem wing design. Belonging to the Quad Tilt Wing class, this aircraft has a maximum endurance of 60 minutes and can reach a top speed of 150 km/h (GH Craft Staff (2009)).

The QTW VTOL UAV stands out as a highly promising configuration among unmanned aerial vehicles due to its unique design featuring tandem tilt-wings and propellers positioned at the midpoint of each wing. This configuration offers both exceptional VTOL capability and impressive cruise performance (Suzuki et al. (2010)).

The QUX-02A, designed as a small-scale prototype of the QTW VTOL, aims to examine the aerodynamic characteristics and flight control system design of the vehicle. This two-winged and four-rotor vehicle has a takeoff weight of 4.2 kilograms and achieves a maximum speed of approximately 20 m/s (Muraoka et al. (2012)).

AVIGLE, unlike other tilt-wing aircraft, features a unique design with only two rotors, one on each wing. Additionally, there is an additional propeller near the tail for moment balancing. This aircraft is entirely made of carbon fiber. However, its major disadvantage is that in the event of any rotor failure, the aircraft becomes completely uncontrollable (Ostermann et al. (2012)).

Çetinsoy et al. (2012) have developed a quad tilt-wing design called SUAVI, which utilizes two tandem wings that are identical and placed one after another. The aircraft features a total of four rotors, with two located on the front wings and two on the rear wings. It has a wingspan of 1 meter and a lightweight construction with a takeoff weight of 4.5 kg, with all components made from carbon fiber. Due to its simple design, the SUAVI tilt-wing aircraft has a less complex control system. However, the aerodynamic performance is negatively affected by the interaction between the rear wing and the front wing due to their symmetric arrangement.

LightningStrike is a VTOL project developed by Aurora Flight Sciences, and it features a unique design that sets it apart from traditional tilt-wing concepts. It incorporates a total of 24 ducted fan propulsion systems, with 18 in the main wing and 6 in the canard wing, both of which can tilt along with the wing. This configuration increases the total disc area of the propellers, providing high hover efficiency and enabling high-speed performance in horizontal flight. It serves as an excellent example of combining tilt-wing technology with other innovations (Carl G. Schaefer (2016)).

After the concept that caught NASA's attention, a new experimental aircraft design was developed with tilt-wing technology. This aircraft, named GL-10, utilizes ten electric motors and propellers distributed along its wings, with eight of them located on the main wing and two on the tail. It can tilt its wings to transition between hovering and forward flight modes. With a maximum takeoff weight of approximately 30 kg, the GL-10 achieves a maximum lift-to-drag ratio (L/D) of 7.2 at an average speed of 23 m/s and a 5-degree angle of attack (McSwain et al. (2017)).

Cakir et al. (2022) conducted a study where he devised a tilt-wing configuration reminiscent of the NASA GL-10. In his design, the front wing features four rotors, while the rear section incorporates two rotors. By eliminating the need for a vertical tail, the aircraft achieves a 5% reduction in weight and a 4% decrease in drag.

The literature provides a comprehensive overview of various examples of tilt-wing UAVs, which are presented in detail in **Table 2.3**.

**Table 2.3.** Tilt Wing VTOL Types

| | **QTW-UAS FS4** | **The QUX-02A** | **AVIGLE** | **SUAVI** | **NASA GL-10** | **Lightning Strike** |
|---|---|---|---|---|---|---|
| Configuration | Quad-Tilt Wing | Quad-Tilt Wing | Tilt Wing | Quad-Tilt Wing | Tilt Wing | Tilt Wing |

**Table 2.3.** Continued

| | | | | | | |
|---|---|---|---|---|---|---|
| Material | Composite | Foam | Composite | Carbon Fiber | Composite | Composite |
| Wing Type | High Wing | High Wing | High Wing | Mid Wing | High Wing | High Wing |
| MTOW | 30 kg | 4.2 kg | 10 kg | 4.5 kg | 28 kg | 4535 kg |
| Propulsion | 4 rotor | 4 rotor | 3 rotor | 4 rotor | 10 rotor | 24 ducted fan |
| Wing Span | 1.8 m | 1.381 m | 2 m | 1 m | 3.16 m | 2.74 m |
| Fuselage | 1.863 m | 1.1 m | N/A | 1 m | 1.85 m | 1.85 m |
| Aspect Ratio | N/A | 6.4 | N/A | 4 | 13.6 | N/A |
| Speed | 0-150 km/h | 0-25 m/s | 0-40 m/s | 0-60 km/h | N/A | 0-154.33 m//s |
| Endurance | 60 min | N/A | 60 min | 60 min | N/A | N/A |

As seen in Table 2.3, in most studies related to the tilt-wing aircraft concept, the rotors are symmetrically placed to reduce control complexity. However, the use of symmetric and tandem wings reduces their performance by influencing the airflow over each other.

## 2.4 Analysis and Control of Tilt-Wing VTOL

VTOL aircraft offer unique advantages in terms of their capabilities, but they also pose challenges in terms of control and stability due to their distinctive design features such as rotor systems and tilting wings.

The complex interaction among multiple rotors, control surfaces, and propulsion systems adds complexity to the control architecture, making the control of VTOL aircraft a demanding task. Furthermore, another factor that contributes to the instability in control during the transition phase of a tilt-wing aircraft is the interaction between thrust and aerodynamic forces and moments. Hence, the goal is to achieve a transition without any altitude changes or with minimal errors (Holsten et al. (2012)).

A control system has been designed for the SUAVI aircraft, which is a quadrotor tilt-wing configuration, to investigate and mitigate aerodynamic disturbances and external wind effects during hovering. Experimental analysis has been conducted, and a controller has been simulated in Matlab, yielding satisfactory results Hancer et al. (2010). In another study, the dynamic modeling of the same aircraft has been performed for different flight modes, and an LQR-based controller has been designed and integrated into the vertical flight mode (Oner et al. (2008)).

The quest for improved efficiency in the NASA GL-10 aircraft has brought about the challenge of developing control and aerodynamic models. Rothhaar et al. (2014) have conducted studies on the control concept of this aircraft using small-scale prototypes. Flight tests have also been performed, although no specific results regarding control performance have been provided.

The aerodynamic analysis of a tilt-wing aircraft with 6 rotors and no vertical tail was conducted using Ansys CFD. The Spalart-Allmaras turbulence model was chosen for its suitability in the low Reynolds number regime, and pressure distributions generated by the wing at different tilt angles were observed. Additionally, the transition phase was divided into seven segments, and a separate controller was designed for each segment. Linear Quadratic Regulator (LQR) and PID controllers were designed for the respective linear models (Çakır (2020)).

A dynamic model of the Dual Tilt-wing was derived using the Newton-Euler formulation. To validate the model, PD controllers were developed for altitude and attitude control specifically during vertical flight mode. Real-time flight tests were conducted, confirming the aircraft's stable performance in vertical flight (Sanchez-Rivera et al. (2020)).

Transition between flight modes for a small quad tilt wing with four rotors was implemented by gradually changing the tilt angle at several pre-set tilt angles using a routine control method, and a control system was designed for control capability throughout all flight modes (Muraoka et al. (2009)).

The modeling and control of a mini tilt-wing design with two propellers on the main wing and an electric ducted fan for stability on the rear tail have been simulated. Due to the requirement for fast and accurate responses, it was determined that having a P-PI controller instead of a PID controller is more suitable for attitude control (Small et al. (2016)).

The dynamic model of a single-tilt-wing UAV with a tail rotor was studied, considering the forces and moments acting on its components. To analyze the dynamic characteristics, a linearized model was used. The results of the analysis show that the designed single-tilt-wing UAV demonstrates stable dynamic properties during cruise mode, while it exhibits unstable poles during hover mode (Jeong et al. (2015)).

## 2.5 Rotor to Rotor Interactions of UAV

Rotor-to-rotor interaction pertains to the mutual influence and interplay of aerodynamic and mechanical forces among multiple rotors in a system, such as a quadcopter or tilt-wing aircraft. These interactions have notable implications for the aircraft's overall performance, stability, and control. Exploring ways to harness the positive effects arising from this interaction involves optimizing rotor spacing and arrangement, fine-tuning rotor speeds and directions, and employing advanced control algorithms that account for the influence of these interactions.

Yoon et al. (2016) investigated the aerodynamic interaction between the rotors of a quadrotor aircraft. The distances between the rotors, as well as the distances between the rotors and the body/wings, were analyzed using a turbulence model to assess the efficiency of the aircraft. The results showed that as the distance between the rotors decreased, the efficiency of the quadrotor system also decreased. Additionally, it was observed that the wings slightly reduced the vertical force generated by the rotors.

The flow field generated by the air from a propeller or rotor, known as the wake, creates an interaction zone that affects other vehicles or rotors as well. This interaction also impacts performance. In this context, Shukla et al. (2018) analyzed the interactions between the wakes of two adjacent rotors, considering variations in the distances between them and the Reynolds number. They observed a decrease in performance at low Reynolds numbers and when the two rotors were very close to each other. Additionally, at low Reynolds numbers when the tip vortices had weaker circulation, resulting in relatively less interaction between the rotors when they were at the same distance.

Zhou et al. (2017) conducted a study on rotors with different horizontal distances in the same plane for small-sized drones. Based on the results from all test cases, although the variation in thrust coefficient of the rotor remained limited at around 2 percent, the standard deviation of thrust significantly increased as the distance between the rotors decreased.

Otsuka et al. (2016) conducted tests on birotor, coaxial, and sliding parallel rotor configurations to measure the generated thrust force. In the birotor configuration, it was observed that the change in thrust remained relatively constant as the horizontal distance between the rotors varied. Subsequently, an optimal design was achieved by providing both horizontal and different plane distances, resulting in an increase in thrust.

Kaya et al. (2017) presented a study focused on determining the optimal gap distance between rotors. The research aims to examine the effects of the gap distance on the aircraft's performance, particularly in terms of thrust generation and stability. Through high RPM analyses, it has been determined that the influence of the gap distance on thrust force becomes more pronounced. Using three different propellers in the study, an optimal range of gap distance that provides the highest thrust output while maintaining stable flight characteristics has been identified.

Varki et al. (2022) presented another study that investigates the interaction between propellers. According to their research, they observed that as the tip separation distance between the propellers decreases, the thrust also decreases.

### 2.6 Conclusion on Literature Review

The results obtained from the literature review are as follows:

- Among VTOL aircraft, tilt-wing aircraft exhibit both optimal and average values. Additionally, for efficiency purposes, a single main wing is sufficient instead of symmetric or tandem wings.

- In tilt-rotor VTOLs, during takeoff, the wings are in a horizontal position while the rotors are in a vertical position, creating an additional moment. However, in tilt-wing VTOLs, the wings are located at the center of gravity, and the rotors are parallel to the wings, eliminating the extra pitch moment caused by the rotors.
- Various studies have investigated the effects of rotor spacing on the performance of multi-rotor UAVs, but there is limited research specifically focusing on tilt-wing and tilt-rotor configurations.

The main objective of this thesis is to design tilt wing VTOL and analyze the number of rotors and the spacing between them for a simple and lightweight tilt-wing aircraft in order to determine the optimal values.

# CHAPTER 3
# AIRCRAFT WORKING PRINCIPLE AND THEORY

## 3.1 Introduction

In this chapter, the working principle of tilt wing aircraft will be explained, and information will be provided about the fluid dynamics and propeller theories that are important for aircraft.

## 3.2 Tilt Wing VTOL Working Principle

The working principle of a tilt-wing aircraft is based on the ability of the wings to tilt relative to the fuselage using a rotating mechanism. This allows the aircraft to perform vertical takeoff and landing, as well as fly horizontally like a conventional airplane. During the vertical takeoff and landing phase, the wings are tilted upwards to a vertical position. In this configuration, the wing-mounted engines or propellers generate vertical thrust, enabling the aircraft to ascend. After vertical takeoff, the wings are brought into a horizontal position, and the aircraft continues to fly like a regular airplane. During the horizontal flight, the wings are aligned to generate more lift and maintain stability. These flight modes are shown in **Figure 3. 1**.

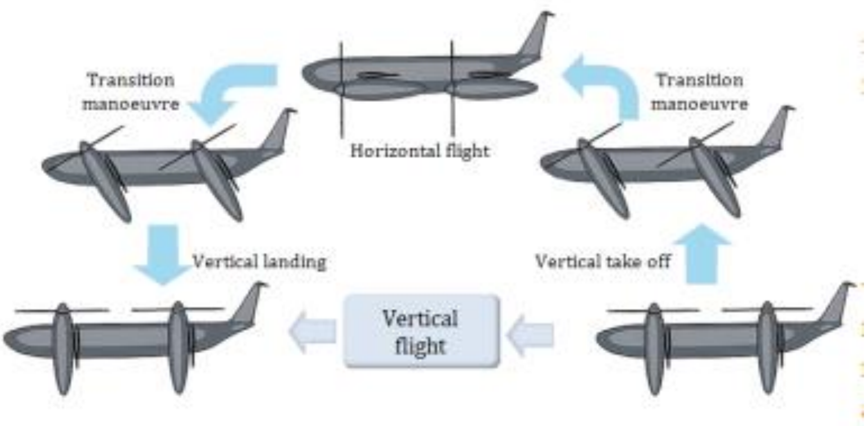


**Figure 3. 1.** Tilt Wing’s Flight Mode Benkhoud et al. (2016)

Tilt wing aircraft combine the characteristics of a rotorcraft and a winged aircraft, allowing for seamless transitions between different flight modes. These aircraft can have different rotor configurations, including tandem rotors, coaxial rotors, and trirotors, each with its own advantages and disadvantages. For instance, a tandem rotor tilt wing aircraft can provide greater thrust and lift despite its low efficiency for the rear wing, while a coaxial rotor aircraft can have a more compact design. The working principles of tilt wing aircraft are heavily influenced by aerodynamic and propeller theories. The interaction between the wings and rotors, and the fluid dynamics involved, play a significant role in generating lift and drag forces. Additionally, the choice of rotors and their configuration, including their number, is important for providing the necessary thrust during vertical takeoff and landing, as well as for control purposes.

### 3.3 Aerodynamic Theory

Aerodynamic principles are the fundamental factors that determine and influence the performance, efficiency, safety, and maneuverability of aircraft. For tilt wing aircraft, these factors arise from the interaction of both the wings and the rotors. The analysis of fluid interaction and aerodynamic forces between the wings and rotors, as well as between multiple rotors, is crucial. All these aerodynamic interactions affect the generation and behavior of the main forces acting on the aircraft depicted in **Figure 3.2**.

**Figure 3.2.** Force Acting on a Aircraft (NASA (2011))

Aerodynamic principles explain the formation of lift, especially through the shape of wings, wing profiles, and their effects on airflow, and they are also described by

Bernoulli's equations. The thrust force is generated through the rotors, and blade element theory is used for this purpose.

The main source of lift in aircraft is the airfoil profiles used in wings, and all the forces and moments on the wing can be divided into two components: pressure distribution and shear stress distribution on the surface. With the combined effect of these integrated distributions, a resultant force R and a resultant moment M are generated on the body (**Figure 3.3**).

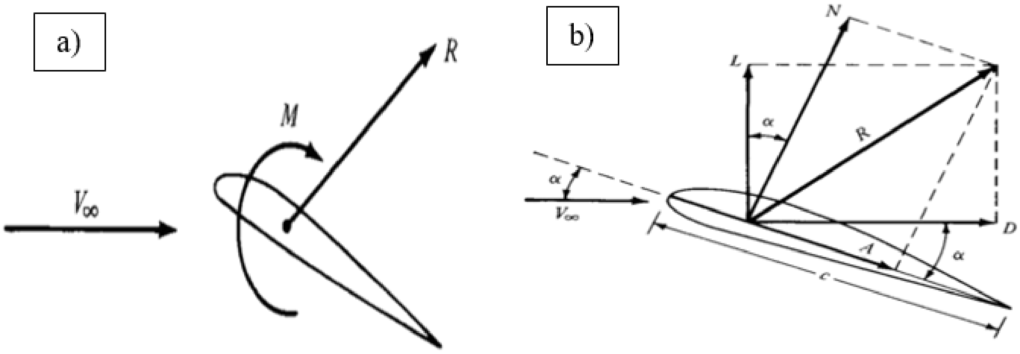


**Figure 3.3.** Aerodynamic Moment (a) and Forces (b) Acting on an Airfoil

The resulting force can be separated into two components, tangential to and perpendicular to the relative wind, also known as the airflow velocity in front of the object. These additional forces are respectively called lift (L) and drag (D) (Anderson (2011)). These forces can be expressed as follows:

$$L = N\cos\alpha - A\sin\alpha \tag{3.1}$$

$$D = N\sin\alpha - A\cos\alpha \tag{3.2}$$

Assuming the density of the freestream flow ahead of the airfoil is represented by $\rho_\infty$ and the velocity by $V_\infty$, we can express a dimensional quantity known as dynamic pressure and the dimensionless coefficients of force and moment in the following manner:

$$q_\infty = \frac{1}{2}\rho_\infty {V_\infty}^2 \tag{3.3}$$

$$C_L = \frac{L}{q_\infty S} \tag{3.4}$$

$$C_D = \frac{D}{q_\infty S} \tag{3.5}$$

$$C_M = \frac{M}{q_\infty S l} \tag{3.6}$$

There is a direct relationship between these dimensionless coefficients and the wing area denoted by S. The wing area is an important parameter that affects the performance, maneuverability, payload capacity, and stability of an aircraft. Additionally, different wing profile designs can be used to tailor the aircraft for different missions. Similarly, propellers also have profiles similar to wings, and the thrust generated by them will be investigated.

## 3.4 Blade Element Theory

Many theories are used for rotor and propeller designs, including Vortex Theory, Momentum Theory and Blade Element Theory. Blade element theory is a method used to analyze the aerodynamic performance of propellers or rotors.

Blade Element Theory is founded on the principle of dividing the blade into small elemental sections. Each section experiences unique flow conditions, including variables such as rotational speed, chord length, and twist angle. The forces acting on each section are computed individually and then integrated from the root to the tip of the blade (**Figure 3.4**). By employing numerical integration, the comprehensive performance characteristics of the wing can be established. This theory is used to understand the flow over each blade section and calculate the associated lift, drag, and moment forces (Karaalioğlu et al. (2018)).

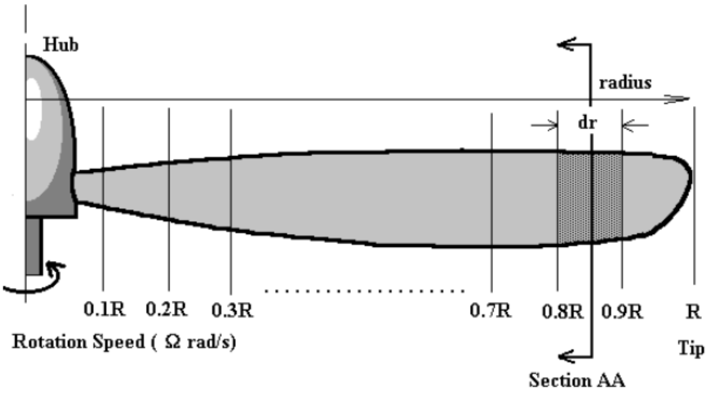


**Figure 3.4**. Blade Element Subdivision

The main objective of this theory is to analyze a small section of each propeller or rotor blade and calculate the forces and moments associated with the flow in that section. As shown in **Figure 3.5**, in each section, the airflow accelerates in a direction perpendicular to the blade, resulting in the generation of lift force. Additionally, there is also a parallel component of the airflow that causes drag force.

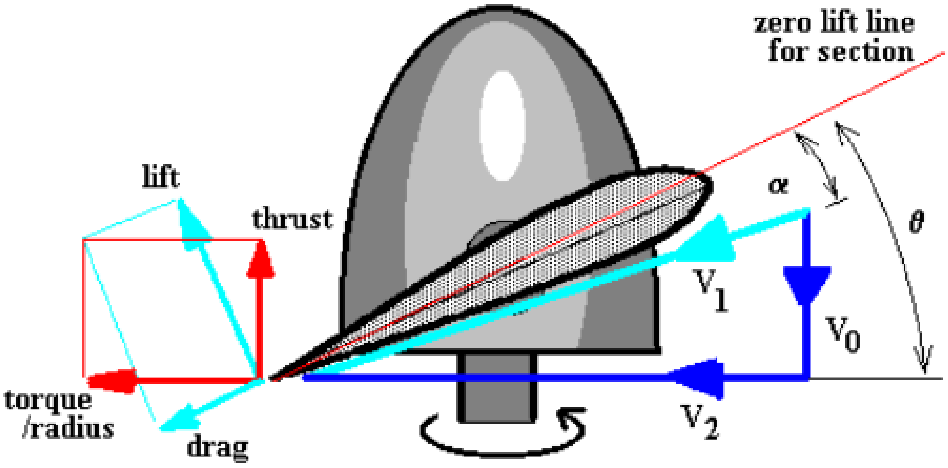


**Figure 3.5.** Force and Flow Vectors on Blade

The local flow velocity vector, $V_1$, is formed as the resultant of the axial flow velocity, $V_0$, in the propeller disc, and the tangential flow velocity, $V_2$, which represents the rotational motion. The angle $\varphi$ is referred to as the induced angle for the selected blade element, and it is expressed as the difference between the pitch angle and the angle of attack. Also, the fundamental thrust and torque of this blade element can be expressed as:

$$\varphi = \theta - \alpha \tag{3.7}$$

$$\Delta T = \Delta L\cos(\varphi) - \Delta D\sin(\varphi) \tag{3.8}$$

$$\frac{\Delta Q}{r} = \Delta D\cos(\varphi) + \Delta L\sin(\varphi) \tag{3.9}$$

Incremental lift and drag components for each section:

$$\Delta L = \frac{1}{2} C_L \rho V_1^2 c.dr \tag{3.10}$$

$$\Delta D = \frac{1}{2} C_D \rho V_1^2 c.dr \tag{3.11}$$

where $\rho$ is the density of air and c is the chord length of selected blade. Thus, the lift-producing area of the blade element is referred to as $c.dr$.

If the number of propeller blades is denoted as N, it can be formulated as follows:

$$\Delta T = \frac{1}{2}\rho V_1^2 c(C_L\cos(\varphi) - C_D\sin(\varphi))N.dr \tag{3.12}$$

$$\Delta Q = \frac{1}{2}\rho V_1^2 c(C_D\cos(\varphi) + C_L\sin(\varphi))N.r.dr \tag{3.13}$$

The assumptions can be made that V0 velocity is low, the induced angle is very small, and the drag force is negligibly small compared to lift. (Leishman (2006)) With these assumptions, the simplified equations can be rewritten as follows:

$$\Delta T = N\Delta L \tag{3.14}$$

$$\Delta Q = N(\Delta D + \varphi\Delta L)r \tag{3.15}$$

The total propeller thrust and torque, which will be utilized in the analyses conducted in this study, are derived by aggregating the outcomes of all individual radial blade elements.

$$T = \sum \Delta T \qquad\qquad Q = \sum \Delta Q \tag{3.16}$$

The propeller advance ratio is another important parameter used to analyze the performance of a propeller. It is a crucial factor to consider in evaluating and improving propeller performance. A high advance ratio, which means a high ratio of forward speed to rotational speed, allows the propeller to generate more lift and provide greater thrust. Low advance ratios, on the other hand, mean that the propeller will produce less lift and provide less thrust. The formula resulting from taking n as the rotational speed for in rev/sec and D as the propeller diameter is;

$$J = \frac{V_\infty}{nD} \tag{3.17}$$

The dimensionless thrust and torque coefficients are determined along with the calculated advance ratio as follows:

$$C_T = \frac{T}{\rho n^2 D^4} \tag{3.18}$$

$$C_Q = \frac{Q}{\rho n^2 D^5} \tag{3.19}$$

As a result, the efficiency of a propeller can be expressed based on the advance ratio and these coefficients as follows:

$$n_{propeller} = \frac{J C_T}{2\pi C_Q} \tag{3.20}$$

**Figure 3.6** illustrates an example of propeller efficiency curves, which showcase the relationship between efficiency and advance ratio.

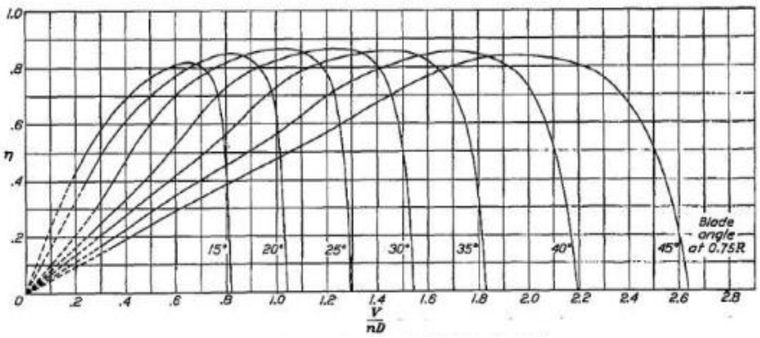


**Figure 3.6.** Typical propeller efficiency curves (McCormick (1994))

# CHAPTER 4

# DESIGNING AND ANALYSIS OF TILT WING VTOL

## 4.1 INTRODUCTION

In this section, the mechanical design of a tilt-wing aircraft, along with the selection of various components including electronics and propellers, will be presented, along with an analysis of the chosen propeller. The design process has progressed incrementally, taking into account the target average speed and the weight of the aircraft.

## 4.2 DETAIL DESIGN

The tilt wing VTOL aircraft has been designed with a unique monocoque structure made of Carbon Fiber material, which is durable, lightweight, aerodynamically efficient, and provides high maneuverability. It features a mid-positioned high-efficiency wing and a Boom tail configuration. Detailed information about these components will be provided next section. Additionally, the performance requirements of this aircraft are listed in **Table 4. 1**.

**Table 4. 1**. Design Requirements

| **Requirements** | **Values** |
|---|---|
| Endurance | 30 min |
| Payload | 2.5 kg |
| Average Speed | 10-20 m/s |
| Motor Type | Electric |
| Rotor Number | 6 or 8 |
| VTOL Capability | YES |

### 4.2.1 Wing Design

Wing design is one of the fundamental aspects to consider when designing an aircraft, and it has a significant impact on the aircraft's performance, stability, maneuverability, efficiency, and takeoff/landing capabilities. It is responsible for generating lift and the control surfaces located on the wing enable aircraft maneuvering. Properly designing and optimizing the wing is crucial for achieving the desired performance and safety based on the aircraft's mission requirements. Wings can be analyzed in two stages based on their positions and the chosen wing types (**Figure 4. 1** and **Figure 4.2**). Careful selection has been made in this study to ensure the most suitable choices are made.

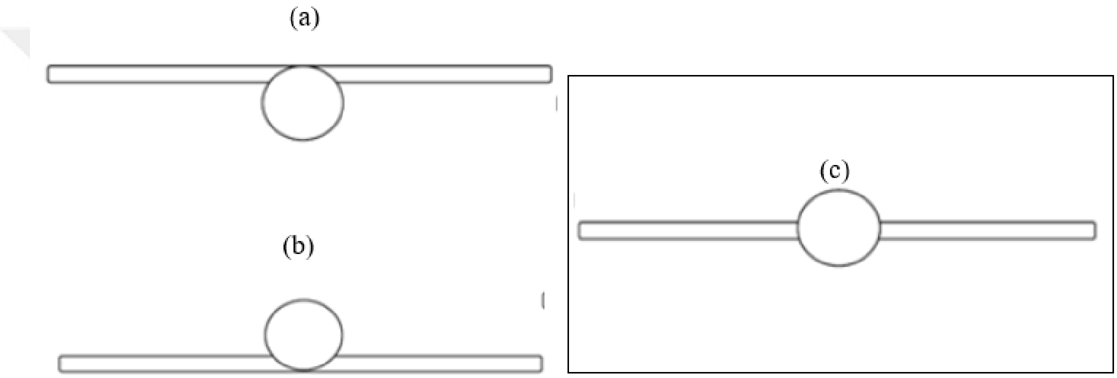


**Figure 4. 1.** Wing Positions (a) High wing (b) Low wing (c) Mid wing

In high wing configuration, with the wing located above the fuselage, it assists the aircraft in better ground handling and takeoff capabilities. Additionally, the wing structure integrated with the engines under the wing provides easy maintenance and accessibility. This type of wing configuration is commonly used in turboprop aircraft, cargo planes, and some general aviation aircraft, where maneuverability, especially in crosswind conditions, may be limited.

In the low wing configuration, having the wing located close to the underside of the fuselage provides advantages such as a lower center of gravity and enhanced vertical maneuverability. However, one of the drawbacks is the potential for lateral instability. Additionally, low wing aircraft are more susceptible to ground effects, which can impact their performance.

In the mid-wing configuration, the aircraft experiences less drag resistance compared to others, resulting in improved aerodynamic performance. It also exhibits better response to roll and yaw maneuvers from an aerodynamic standpoint. The mid-wing configuration offers advantages in terms of both stability and maneuverability.

With all these comparisons taken into account, the mid-wing position has been chosen as the preferred wing configuration for the designed aircraft.

During the selection of wing planform, the focus was on choosing a wing geometry that is producible, aerodynamically efficient, and capable of providing sufficient lift. The wing shapes were compared, as shown in Figure 4.2, to make the selection.

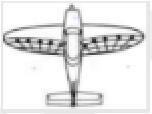
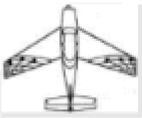
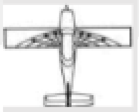
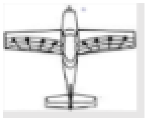
| WING PLANFORM | Elliptical | SweepBack | Rectangular | Trapezoidal |
|---|---|---|---|---|
| |  |  |  |  |

**Figure 4.2**. Wing Planforms

The elliptical wing provides low drag and high lift characteristics; however, it is difficult to manufacture and can be costly. Additionally, the wingtip may introduce stability issues.

The swept-wing design reduces supersonic effects at high speeds and provides high maneuverability. However, in the conducted study where high speeds are not attainable and low speeds are expected, it may compromise performance.

Trapezoidal wings exhibit reduced drag at the wingtip and have good load-carrying capacity. However, due to cost and production difficulties, they were not preferred in the study.

Rectangular wings have a simple and cost-effective structure, are easy to manufacture, perform well at low speeds, and are a suitable choice for general use. This design was preferred in the study. As for the wing material, a lightweight and high-strength option Carbon Fiber Composite was considered.

The wing design with a 1.7-meter wingspan, as shown in **Figure 4.3**, will be constructed by laser-cutting duralit wing profiles and assembling them at 10 cm intervals using carbon fiber rods inserted through holes. This skeleton structure will be covered with cardboard to provide structure and durability.

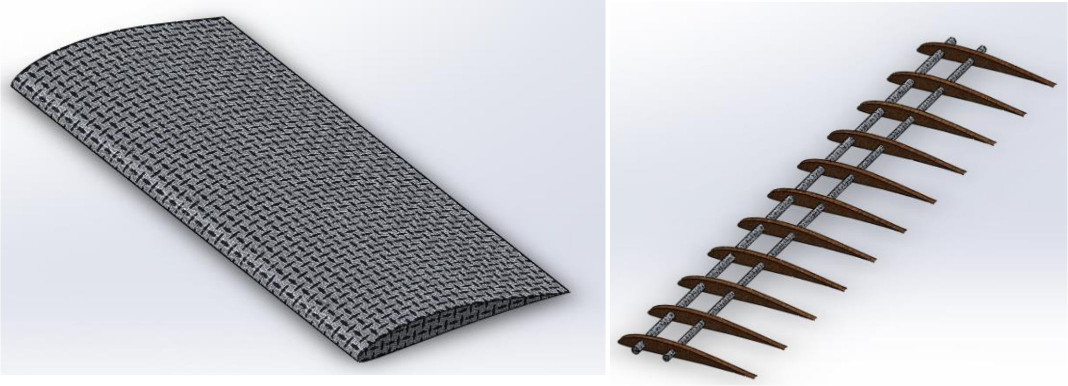


**Figure 4.3.** 3D Cad Model of Wing

#### 4.2.1.1 Airfoil Selection

The selection of the wing profile is a critical factor that determines the aerodynamic performance, lift force, and drag of an aircraft. Choosing the right wing profile allows the aircraft to generate maximum lift force within the desired speed range. In order to achieve a stable, fast, and highly maneuverable aircraft, a profile with a high lift coefficient (Cl), low drag coefficient (Cd), and the Cl/Cd alpha value corresponding to the highest value at a 5-degree angle of attack was carefully selected. Additionally, for the challenging phase of transition from takeoff to level flight, a high maximum lift coefficient is also required.

In the selection of a wing profile, the first step is to calculate the Reynolds number. The Reynolds number is a dimensionless quantity used to categorize fluid flow systems where viscosity effects are significant. It takes into account the fluid velocities or the size of the flow model. The Reynolds number is expressed as follows:

$$Re = \frac{\rho V L}{\mu} \tag{4.1}$$

The Reynolds number was calculated to be 240,000, taking into account an average flight speed of 12-13 m/s, an average wing chord length of 0.275 m, and an air density of 1.225 kg/m3 for VTOL. To ensure a sound selection and comparison in line with the desired objectives, a pool of wing profiles was created and these profiles were analyzed using the XFLR5 program (**Figure 4.4**). Furthermore, during the selection process, attention was given to choosing an airfoil with a low and negative cm value in order to counteract the pitching moment.

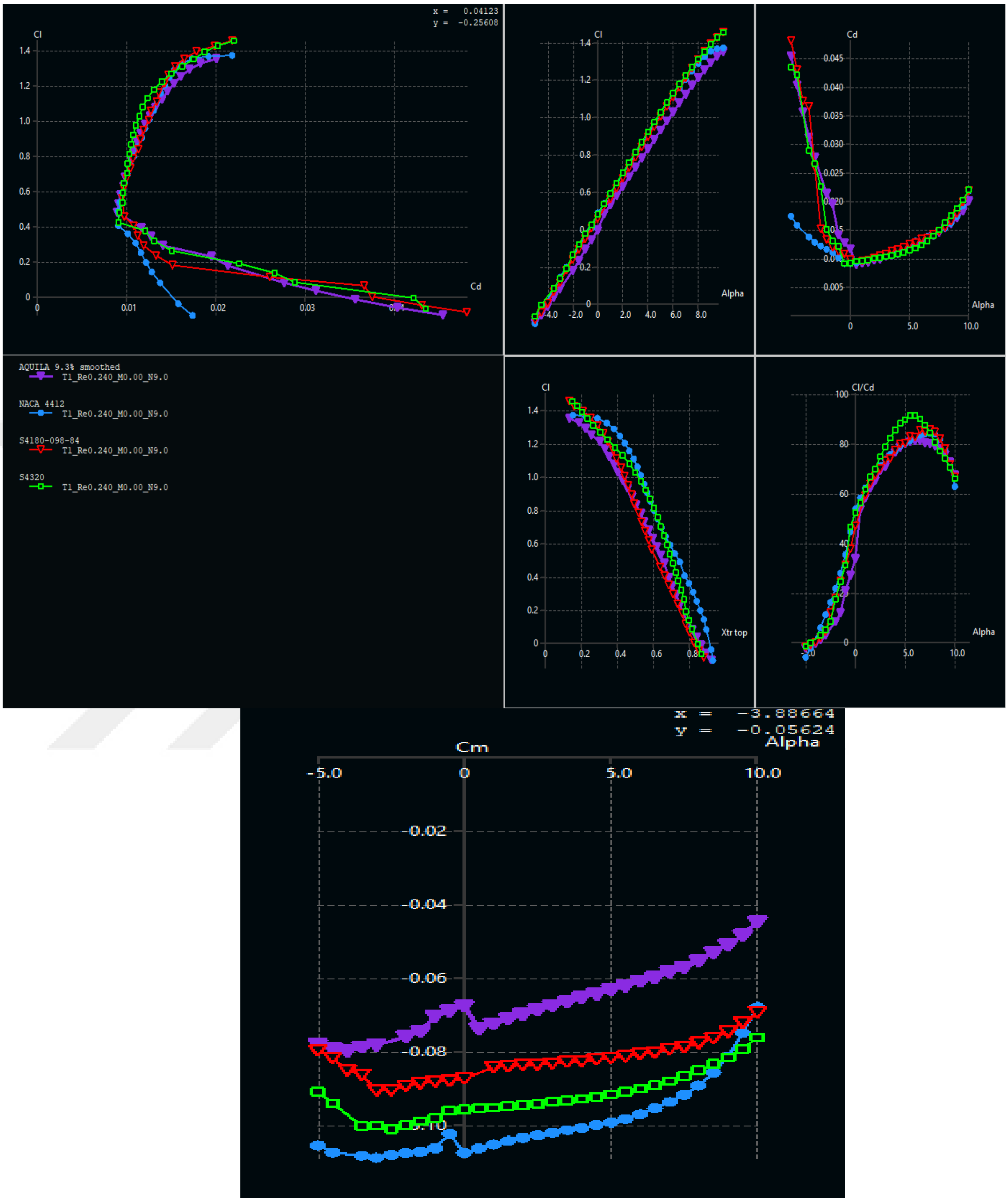


**Figure 4.4.** Aerodynamic Comparisons of Airfoils

**Table 4.2.** Parameter Values of Airfoils

| Parameters(240000 Re and 5° AoA) | AQUILA 9.3 | NACA 4412 | S4180-098-84 | S4320 |
|---|---|---|---|---|
| $C_L$ | 0.94 | 0.98 | 1 | 1.03 |
| $C_D$ | 0.012 | 0.013 | 0.013 | 0.012 |
| $\frac{C_L}{C_D}$ | 78 | 80 | 81 | 88 |

As a result of this analysis, the S4320 wing profile was selected as the most suitable profile (**Table 4.2**).

### 4.2.2 Tail Design

The tail, also known as the empennage, plays a crucial role in the stability, control, and maneuverability of an aircraft, comparable to that of the main wing. It consists of the vertical stabilizer, which controls yaw movements in the horizontal plane, and the horizontal stabilizer, which manages pitching motions around the aircraft's longitudinal axis. These components enable precise control over pitch and yaw, allowing for smooth and controlled flight. Furthermore, an optimized tail design can minimize drag and enhance the lift-to-drag ratio, ultimately contributing to improved overall performance and efficiency. Various tail configurations are depicted in **Figure 4.5**.

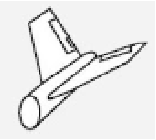
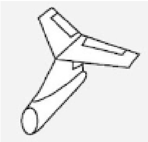
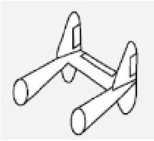
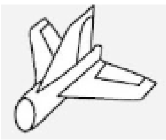
| TAIL PLANFORM | V-tail | T-tail | Boom Tail | Conventional Tail |
|---|---|---|---|---|
| |  |  |  |  |

**Figure 4.5**. Tail Planforms

T-tail provides a high climb rate, but it generates high drag at low speeds and comes with a higher cost. V-tail reduces drag resistance, but it introduces control complexity due to the combination of elevator and rudder on the same control surface.

Conventional tails, on the other hand, are the most traditional and widely used type, offering sufficient stability and control. However, it can be affected by the wing wake effect, which may reduce its effectiveness and increase drag resistance.

The boom tail provides better aerodynamic performance by being less affected by the wing wake effect and has a lightweight and easily producible structure. Research has shown that the boom tail has a higher drag coefficient compared to other tail types. However, due to its balanced flight characteristics and unique design, the boom tail has been selected. Carbon Fiber Composite has been considered as the tail material due to its lightweight and high strength properties. Instead of mounting the wings directly to the tail, they will be supported by dual carbon fiber rods attached to the fuselage, allowing for tilting. The CAD drawings and dimensioning are provided in **Figure 4.6**.

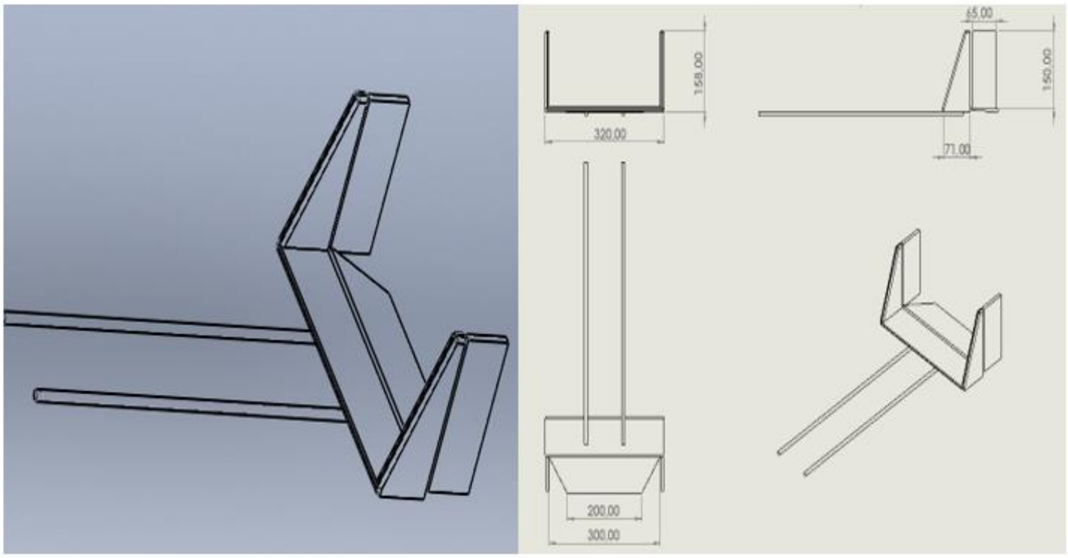


**Figure 4.6.** Tail 3D CAD Design

### 4.2.3 Body Design

The design of the fuselage emerges as another critical factor in the construction of small-scale UAVs, following the wings. The primary function of the fuselage is to protect and safely carry the internal electronic systems, sensors, and other equipment. It is also a key area for weight savings. In addition to being lightweight, it should be designed for strength and aerodynamic efficiency without disrupting the airflow. A well-designed fuselage provides low drag, enabling the UAV to achieve longer flight durations and increased efficiency. Furthermore, it influences stability by maintaining balanced flight and ensuring stability in the air.

The fuselage has been designed to be efficient and unique in order to withstand the airflow encountered during flight. To ensure that the designed fuselage fulfills its functions successfully, it has been optimized for weight and dimensions. During the design process, attention was given to the flatness of the lower section of the fuselage to accommodate the assembly of landing gear. 193 GSM Carbon Fiber has been chosen as the material for the fuselage. The CAD drawing of the fuselage, which includes electronic components, is shown in

**Figure 4.7**. Additionally, the dimensions of the fuselage are provided in **Figure 4.8**.

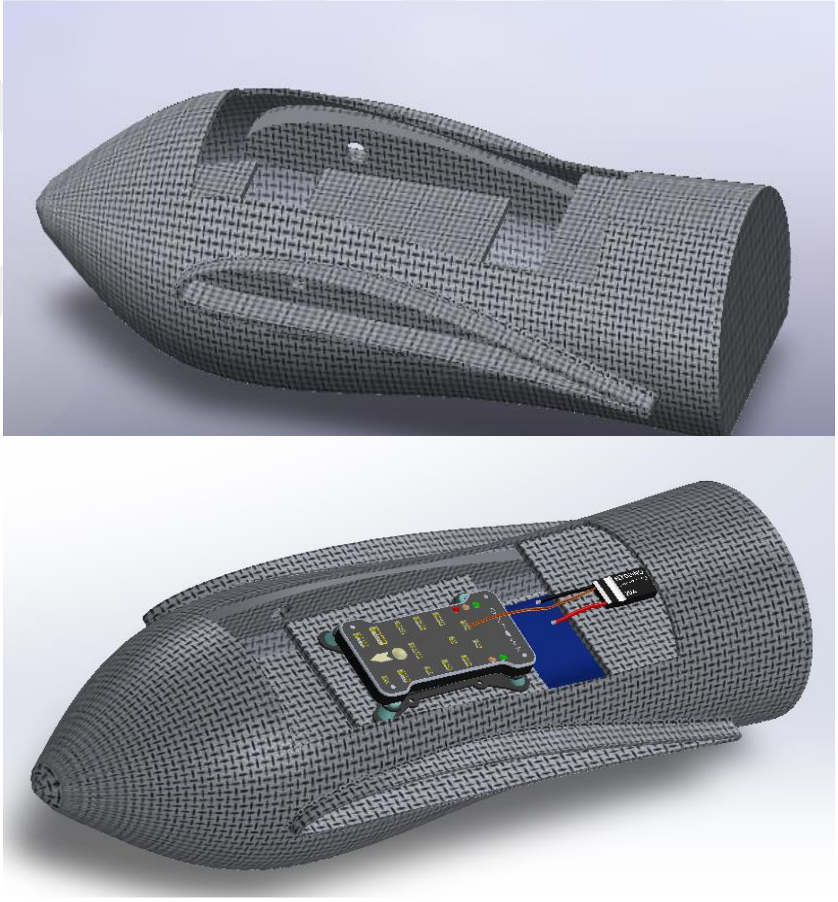


**Figure 4.7.** Body 3D CAD Design

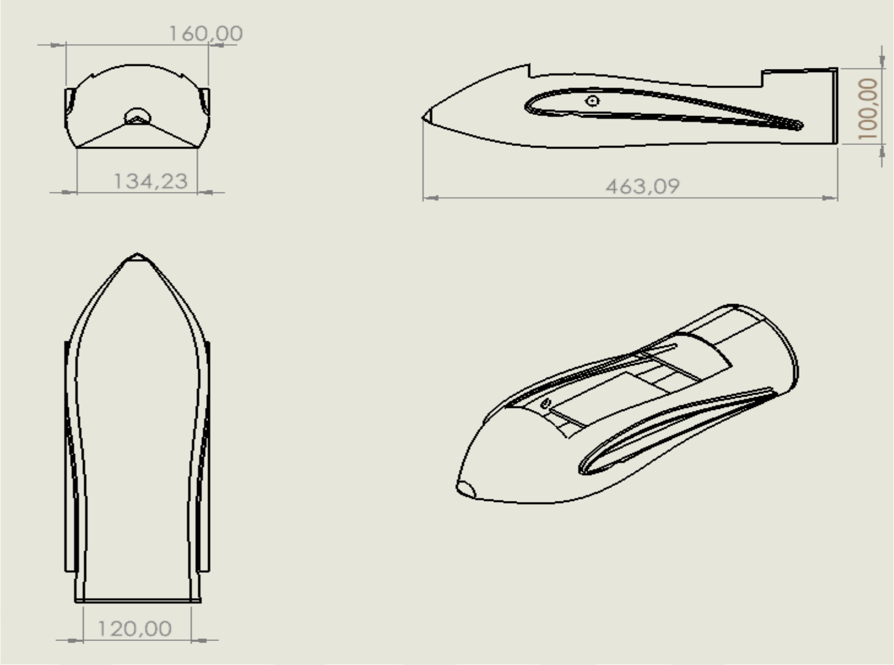


**Figure 4.8.** Technical Drawing of Body

### 4.2.4 Landing Gear Design

Landing gears are designed to minimize aerodynamic effects and ensure fast and safe landings of aircraft. The design of landing gear depends on factors such as the total weight of the aircraft, landing and takeoff speeds, the intended use of the aircraft, and its flight characteristics. Factors such as reliability, durability, lightweight construction, drag resistance, and ground traction are taken into consideration in landing gear design.

The landing gear designed for this aircraft emphasizes uniqueness. The joint area indicated by the red arrow in the technical drawing of the landing gear, given in **Figure 4.9**, will be designed to allow movement in order to dampen the forces experienced during landing. The main material for the designed landing gear, like other components, will be 193 GSM Carbon Fiber Composite. The landing gear will be positioned with one wheel at the front and two wheels at the rear.

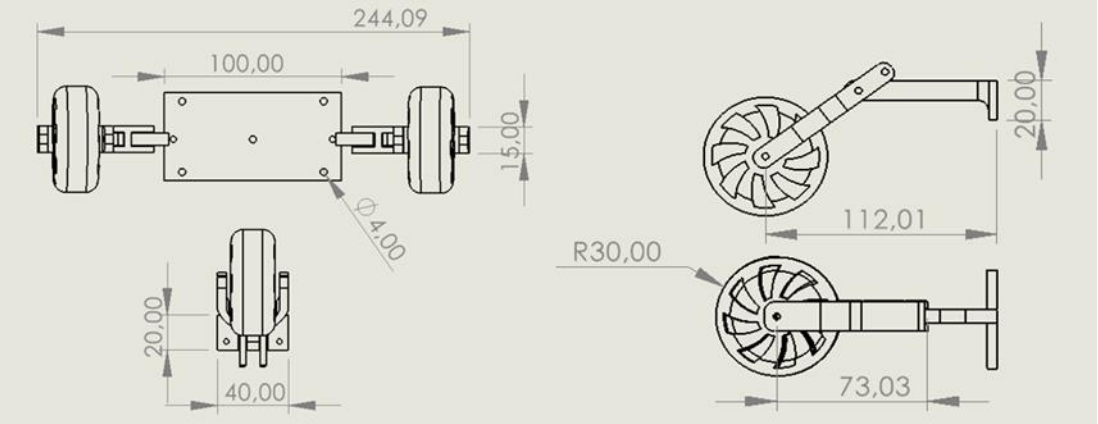


**Figure 4.9.** Cad Model of Landing gear

### 4.2.5 Tilt Mechanism Design

A tilt mechanism has been employed to rotate the wing between 0 and 90 degrees. For this tilt mechanism, a worm drive mechanism has been chosen and integrated into the fuselage. The mechanism is illustrated in

**Figure 4.10**

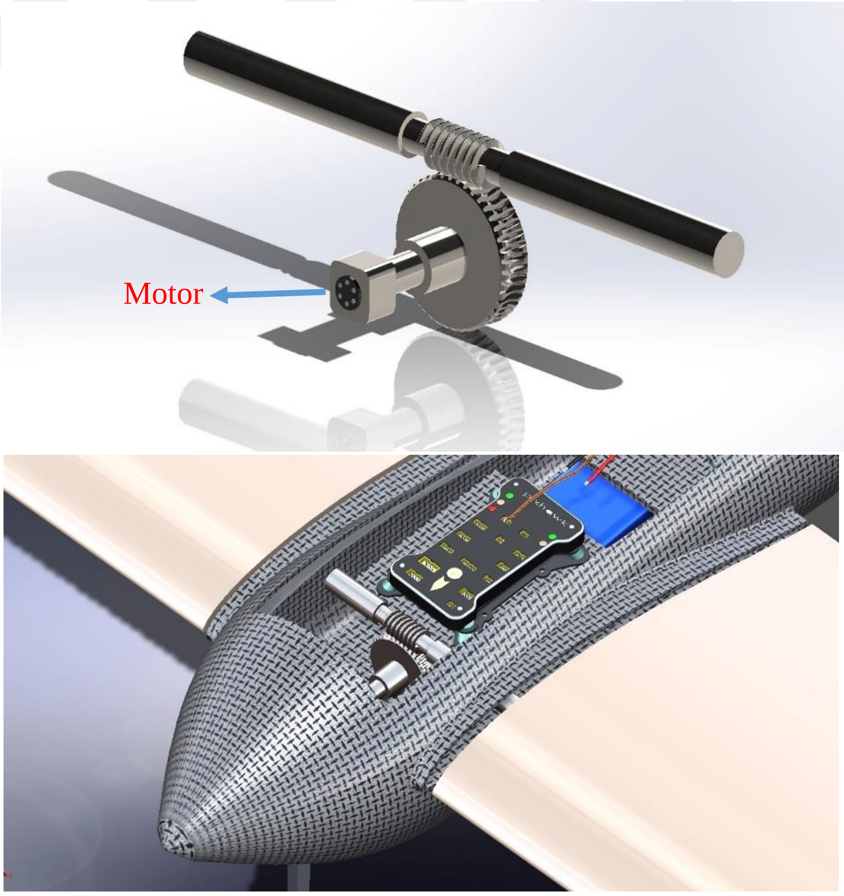


**Figure 4.10.** Cad Model of Tilt Mechanism

The main reason for using the worm drive mechanism is its ability to prevent the load from rotating in the opposite direction, thanks to its self-locking feature. This ensures that the tilt wing remains in the desired position and prevents unintended movements caused by external factors like wind. Moreover, the worm drive mechanism occupies less space compared to other mechanisms. This allows for space-saving in the design of the VTOL aircraft, resulting in a more compact structure.

## 4.3 Electric Electronic and Power Systems

Electric, electronic, and power systems play a vital role in the operation and functionality of Unmanned Aerial Vehicles (UAVs). These systems encompass various components and technologies such as power supply, data and communication management, control of embedded systems, and ensuring overall performance and reliability of the UAV. A well-designed and optimized electric, electronic, and power system is crucial for the successful operation and completion of missions for UAVs.

### 4.3.1 Control Systems

The selected equipment for the control system has been specified.

#### 4.3.1.1 Servo Motor

Servo motors are specialized motors utilized in control systems to direct motion. They are intended for controlling surfaces and potentially rotating a yet undecided tilt mechanism. These motors need to possess high quality and generate substantial torque. Tower Pro MG90S servo motors, weighing 14 grams, have been selected due to their utilization of metal gears.

#### 4.3.1.2 ESC (Electronic Speed Controller)

ESC's (Electronic Speed Controllers) enhance the flight performance, response time, and control precision, enabling vehicles to move in a more stable and safe manner. Choosing the right-sized and appropriately powered ESC is important for optimizing the performance of motorized vehicles.

An ESC (Electronic Speed Controller) has been selected that can adjust the appropriate current level in case of full throttle at any given moment. The chosen ESC is the Hobbywing Skywalker model, specifically the 80A 2S-6S variant, which is capable of drawing a constant current of 80 amperes.

#### 4.3.1.3 Flight and Radio Control

The Pixhawk 2.4.8 model has been chosen for the unmanned aerial vehicle (UAV) as the flight controller due to its practicality in performing necessary operations and its affordability compared to other models.

XBee Pro 63 mW RPSMA model has been deemed suitable for wireless communication between the UAV and the ground station.

### 4.3.2 Power Systems

Power systems in UAVs consist of three main components: motor, battery, and propeller. The combination of these components has been adjusted through analyses to achieve the most efficient, lightweight, and durable configuration that meets the aircraft's performance parameters.

#### 4.3.2.1 Motor and Propeller Selection

In order for the aircraft to meet its requirements, it needs to have high speed and maneuverability, and the motor used should have sufficient power. To achieve these parameters, the thrust-to-weight ratio should be adjusted minimum within the range of 0.8 to 1. During take-off, this ratio should be 1 or greater than 1.

$$Thrust = Weight \times Thrust\ Weight\ Ratio \tag{4.2}$$

The average weight of the aircraft is provided in **Table 4.3**.

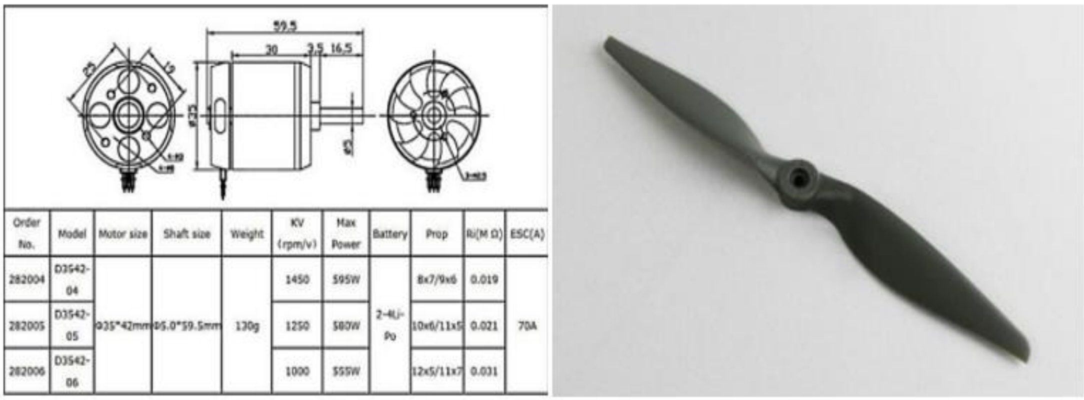
**Table 4.3.** Weight of VTOL

| Part | Weight(gr) |
|---|---|
| Body | 250 gr |
| Wing | 400gr |
| Tail | 180gr |
| Landing Gear | 180 gr |
| Electronic System and Tilt Me | 1500 gr |

The weight of the aircraft is approximately 2500 grams, and as a result, the required thrust is found to be higher than 25 N based on formula 4.2. Of course, obtaining thrust higher than this value will allow for easier takeoff.

For the designed aircraft, a total of 6 propellers will be used, with 4 mounted on the front wing for lift and 2 in the rear for moment balancing. The front propellers, APC 10X7E, can generate approximately 490 grams of thrust at 7000 RPM and a speed of 12 m/s. The rear propellers are 3 blade and each can produce 350 grams of thrust. This configuration ensures that the desired thrust force is achieved. Through the analyses conducted in this study, the optimal propeller selection and the precise spacing between them will be determined more accurately. Also, based on preliminary calculations, the DYS 3542 1450 KV motor has been deemed suitable for the aircraft.

Furthermore, one of the reasons for selecting APC 10X7E propellers for the wings is that we have experimental data available. This allows us to compare and calculate the optimal distances between the propellers and the thrust generated. Having this data will greatly aid us in our analysis and decision-making process. The motor and propeller are shown in **Figure 4.11**.



| Order No. | Model | Motor size | Shaft size | Weight | KV (rpm/v) | Max Power | Battery | Prop | Ri(M Ω) | ESC(A) |
|---|---|---|---|---|---|---|---|---|---|---|
| 282004 | D3542-04 | Φ35*42mm | Φ5.0*59.5mm | 130g | 1450 | 595W | 2-4Li-Po | 8x7/9x6 | 0.019 | 70A |
| 282005 | D3542-05 | | | | 1250 | 580W | | 10x6/11x5 | 0.021 | |
| 282006 | D3542-06 | | | | 1000 | 555W | | 12x5/11x7 | 0.031 | |

**Figure 4.11.** Motor and Propeller

### 4.3.2.2 Battery Selection

The battery is one of the heaviest components among the aircraft's Electrical-Electronic Systems. Considering factors such as battery weight and flight duration, the most suitable battery, based on research and calculations, has been selected as the Leopard Power 14.8V 3300 mAh 30C Li-Po battery.

## 4.4 Final Aircraft

The designed aircraft has reached its final form through analysis and selection, with the electronic equipment and tilt mechanism placed inside the designated compartments within the fuselage. An airfoil shape is given to the connection point of the wing to the fuselage, aiming to minimize flow disturbances in the small gap. For the aircraft that utilizes six propellers in total, the most efficient wing is selected to achieve optimal lift. The propellers on the wing and the ones at the rear produce different thrust forces. The main thrust generators are the motors on the wing, while the rear motors are used for moment balancing. During forward flight, only the propellers on the wing are operational since the horizontal stabilizer is active to balance the pitching moment. The rear motors are particularly important for providing thrust and balance support during takeoff.

According to the final design, it is considered that the aerodynamic design parameters should be as specified in **Table 4.4** for safe straight flight.

**Table 4.4.** Design Parameters

| | | | |
|---|---|---|---|
| **Wing Span** | 1.7 m | **Aspect Ratio** | 6.15 |
| **Wing Area** | 0.47 $m^2$ | **Airfoil** | S4320 |
| **Chord** | 0.3 m | **Wing Type** | Mid Wing |
| **Length** | 1 m | **Material** | Composite |
| **Mass** | 2.5 kg | **Wing Loading** | 5.532 kg/$m^2$ |

The final design model of the tilt wing aircraft is presented in **Figure 4.12**, illustrating different orientations and an isometric view.

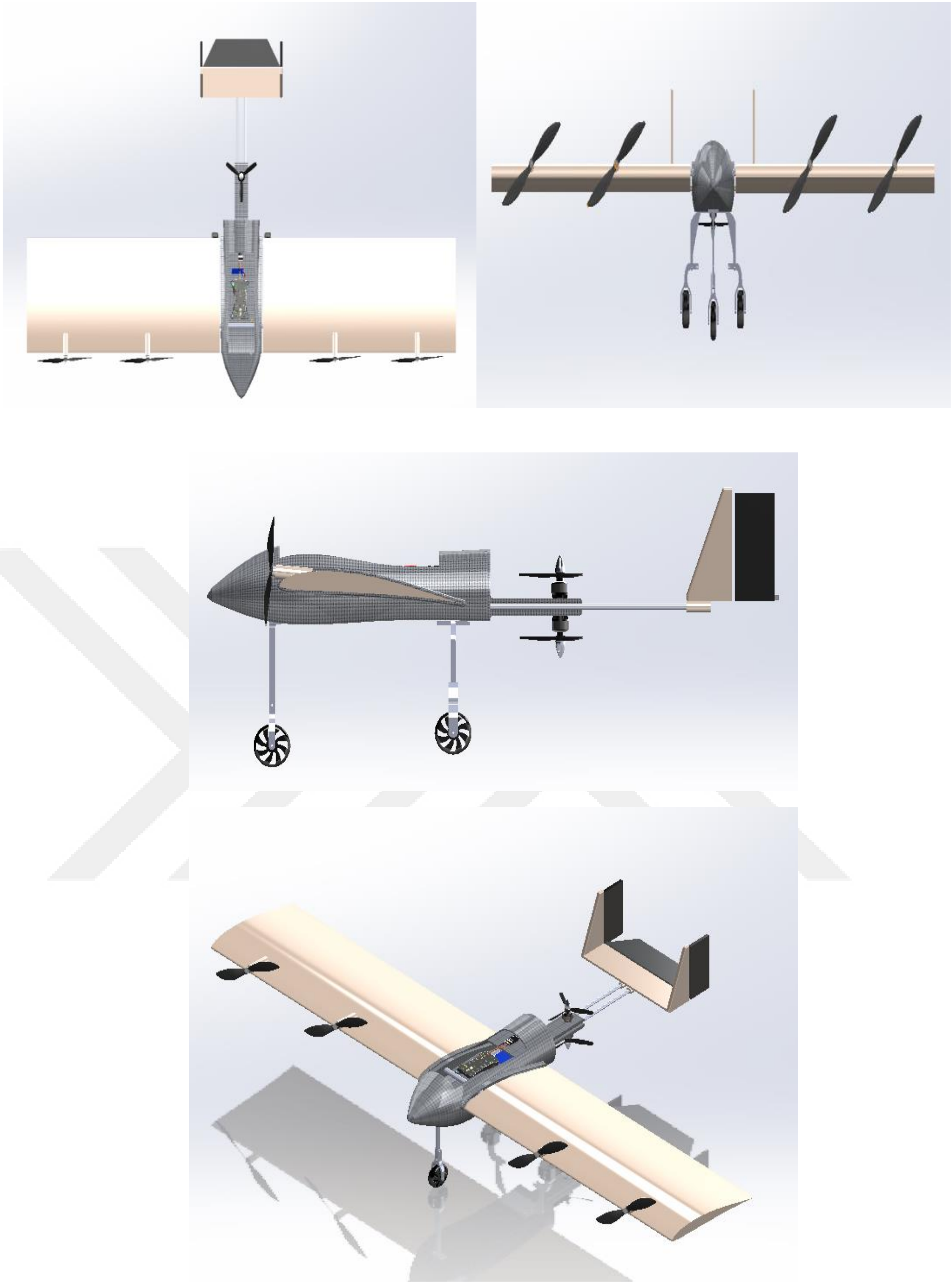
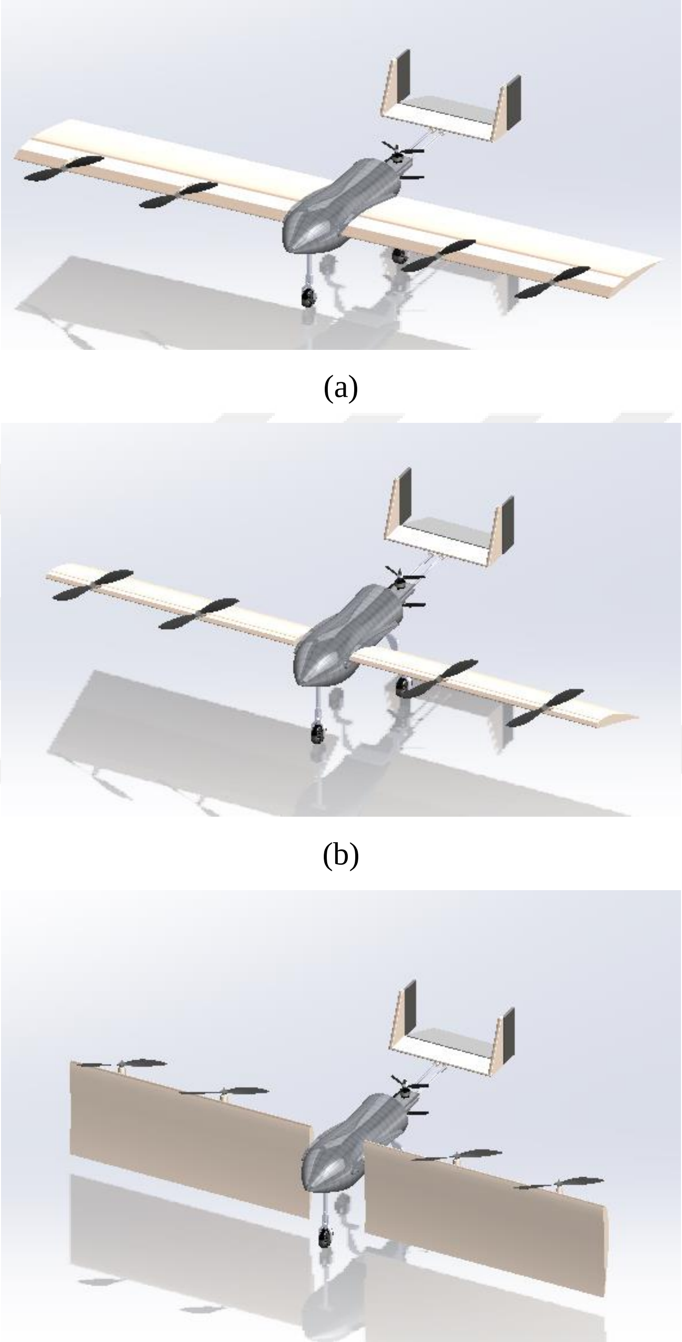


**Figure 4.12.** Cad Model of Final Design

In the side view orientation of the aircraft, it is evident that the front landing gear is longer than the rear one. If a conventional takeoff is preferred instead of vertical takeoff, it is expected to lift off quickly. For this reason, the front landing gear is mounted on the fuselage with an additional 1 cm length, ensuring that the wings are inclined at a 4-degree angle when on the ground. The purpose of having the wings inclined at a 4-degree angle on the ground is to contribute significantly to the aircraft's takeoff. The appearance of the aircraft in different wing positions, namely 0, 30, and 90 degrees corresponding to takeoff, transition, and forward flight, is also provided in **Figure 4.13**.



(a)

(b)

(c)

**Figure 4.13.** Different Angles Orientation of Wing a) 0°, b) 30°, c) 90°

## 4.5 Propeller position design for VTOL

The component known as a rotor or propeller is one of the most critical elements for unmanned aerial vehicles. It plays a crucial role in determining flight efficiency, performance, control, and maneuverability by directly affecting thrust generation. The selection of appropriate propellers for a designed aircraft enables it to achieve desired speeds, generate sufficient lift, and maintain a smoother flight. Therefore, the impact and significance of propellers on performance and efficiency are considerable.

In the selection of the rotor for this study, attention was given not only to generating appropriate thrust for the designed aircraft but also to the presence of experimental results in the literature for verification purposes.

In the studies conducted by Brandt et al. (2011) and McCrink et al. (2015), 9 and 10-inch rotor types for UAVs were generally experimentally analyzed. Due to the availability of experimental data and the need for the required propeller geometry in CFD analysis, the APC 10X7E rotor has been chosen. As observed in the available studies, it is known that part of the error margin in the analyses will stem from the difficulty in obtaining original rotor geometries.

### 4.5.1 Propeller Geometry

The geometric model of the APC 10X7E rotor, with a diameter of 0.254 m, a hub diameter of 0.02 m, and a hub thickness of 0.010 m, is shown in **Figure 4.14**.

**Figure 4.14.** APC 10x7E Cad Model

The chord distribution and twist angle of the propeller are also important in terms of affecting the thrust produced. In particular, the twist angle changing along the wing profile adapts to the wing angles in different regions and creates a homogeneous thrust. Their distributions are shown in **Figure 4.15** and **Figure 4.16**.

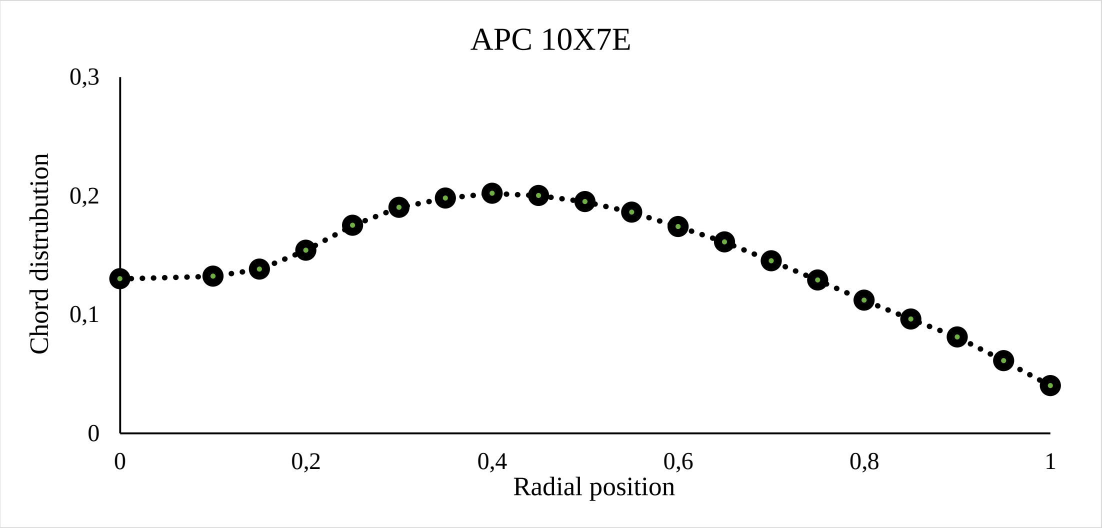


**Figure 4.15.** Chord distribution of APC 10x7E

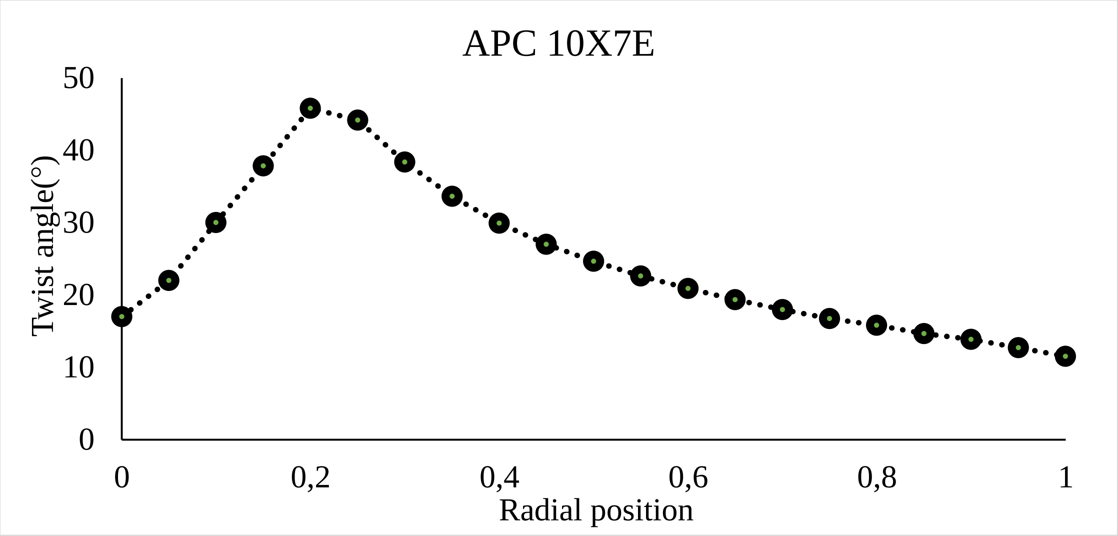


**Figure 4.16.** Twist distribution of APC 10x7E

### 4.5.2 Computational Fluid Dynamics

CFD is an analysis method that solves fluid mechanics numerically. Generally, it makes solutions with numerical approaches such as finite volume method (FVM), finite element method (FEM). These approaches solve fluid motions with mathematical equations and each method has its own calculations. Although FEM and

FVM serve similar purposes as numerical analysis methods, they take different approaches. These approaches can be expressed as:

- FEM divides the structure into small parts and tries to find solutions in these elements, while FVM divides the structure into control volumes and solves using integral equations in these volumes.
- While FEM creates the mathematical model and equation of each element, FVM creates integrals that express physical properties in control volumes.
- FEM provides a more flexible approach to modeling complex geometries, while FVM directly applies principles such as mass, energy and momentum conservation.
- In FEM, discretization relies on partitioning the solution into segmented representations based on specified basis functions, while in FVM, discretization depends on the integral form of the PDE.

**Figure 4.17** shows the structured mesh for the two method techniques.

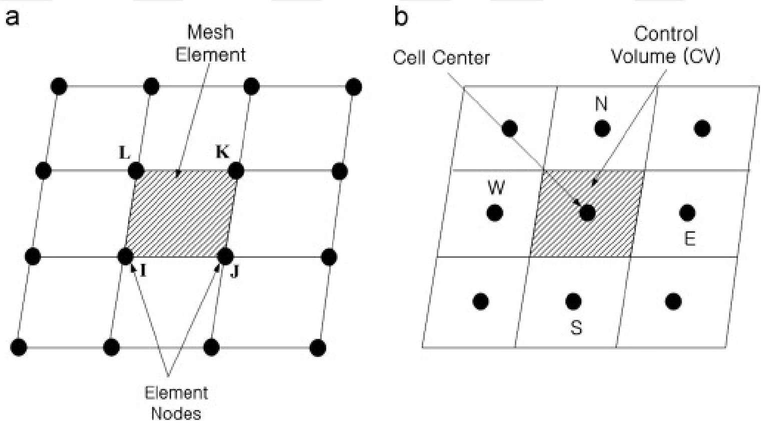


**Figure 4.17.** Structured Mesh for (a) FEM (b) FVM

In conclusion, FEM has a wide range of applications, but FVM has the advantage of obtaining more accurate results in fluid-related problems. In this context, Wooman et al. performed CFD analysis based on FEM and FVM and compared these two methods. For the same number of meshes, the computation time was found to be approximately five times longer in the FEM-based module. It has been observed that the mesh type quality and mesh element number of the FEM-based module are not better than the FVM-based module, and it has been stated that these should be taken into account for the CFD solution.

In this thesis, Siemens Star CCM+ software was preferred for Propeller CFD analysis. This program, which solves using the Finite Volume Method, performs the simulation of the flow by numerically solving the Euler equations of the fluids. The finite volumes method, which STAR CCM+ also uses, provides an effective solution for modelling complex flows and interactions of regions, as well as creating quality mesh.

#### 4.5.2.1 Fluid Domain

In CFD analysis, it is important to choose an appropriate fluid domain to accurately evaluate the effect of propellers. In order to accurately simulate the effect of the propellers, a flow field must be created in which the propellers are completely contained. The dimensions of the fluid domain depend on the flow parameters to be considered in the analysis and the diameter of the propellers. Correct domain size is so important to accurately obtain the effect of propellers and to accurately model the influencing flow field.

All of the analyzes are performed in the subsonic region since the desired Mach speed is 0.3 or below. Bullet shape domain is preferred for incompressible flow and subsonic regime based on STAR-CCM+ documentation.

According to the domain dimensions in the literature, the best option was determined as 10D for the front of the propeller and 20D for the back of the propeller. The main reason why the back domain of the rotor is long is to minimize the effects of flow disturbances originating from the point of analysis and to make the analysis results more reliable. The outer domain and rotating domain formed by assuming that the propeller diameter is D are shown in **Figure 4.18** and **Figure 4.19**.

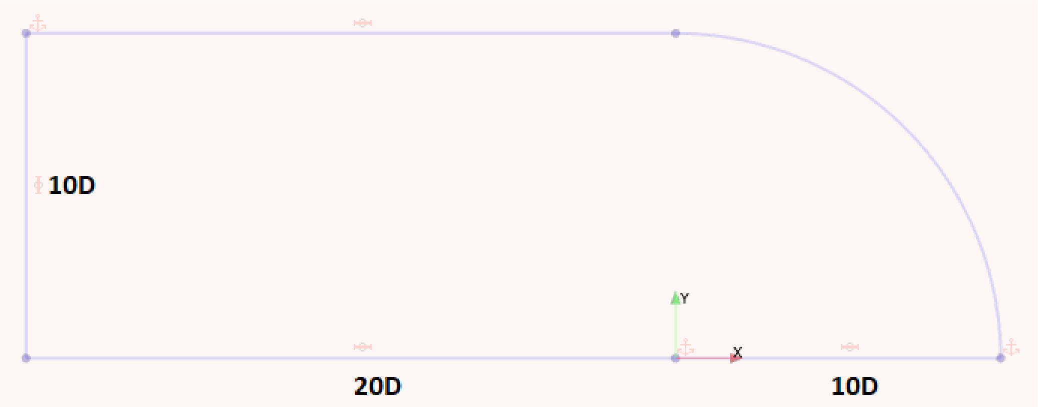


**Figure 4.18.** Outer Domain Size

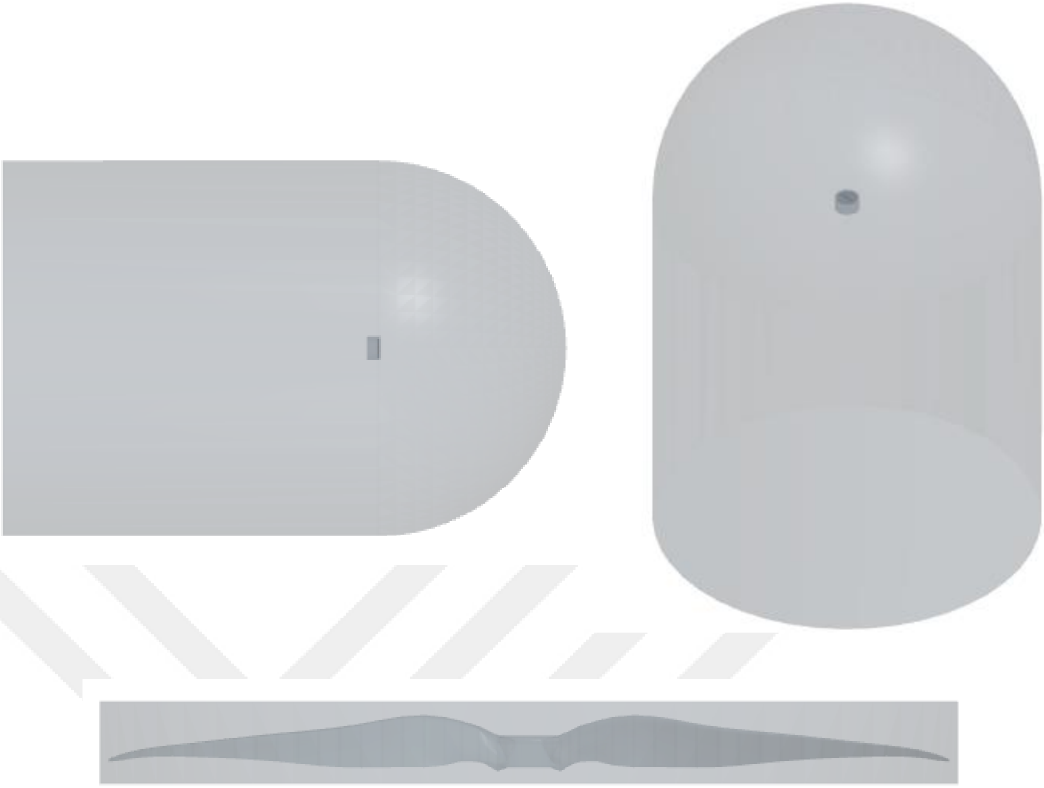


**Figure 4.19.** Simulation Domain Top: Outer. Bottom: Rotating

### 4.5.2.2 Boundary Conditions

The selected boundary conditions also affect the accuracy of the analysis as well as a good mesh applied. For this study, as seen in **Figure 4.20**, the point where the domain is spherical is defined as the velocity inlet boundary, the cylinder surface is defined as the freestream and the bottom of the domain is defined as the pressure outlet. In addition, stagnation inlet is used instead of velocity inlet for static thrust calculations where velocity is not required.

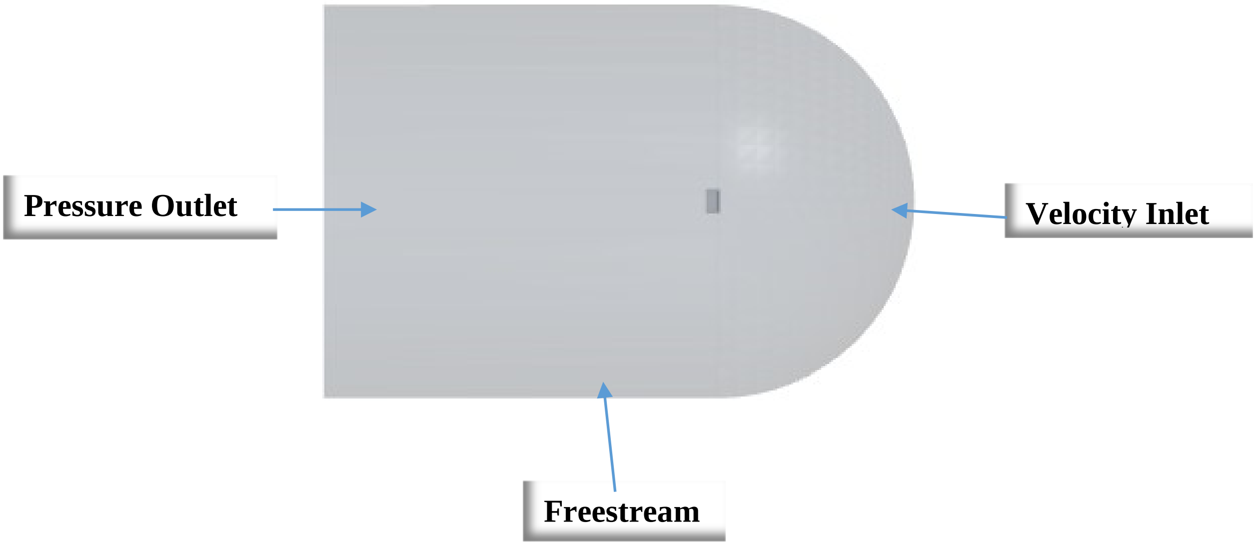


**Figure 4.20.** Boundary Conditions

### 4.5.2.3 Mesh Generation

RANS (Reynolds Averaged Navier-Stokes) turbulence model is a method used for modeling turbulent flow. In the RANS model, the mesh structure is an important factor to obtain accurate results and to accurately model turbulence. Analysis with an appropriate mesh structure provides more reliable and valid results. Most of the analysis time is spent on the mesh model. For the analyses, the most accurate mesh models were obtained by comparing the analysis results with experimental results and also using the information about mesh structure given in the STAR CCM+ manuals.

Trimmed Cell mesher is used for the fluid domain and surface remesher is used to optimize the mesh structure of the surface to obtain a better mesh quality. Also, Surface remesher reduces solution errors with a more uniform representation of the surface. A better mesh structure provides a more accurate resolution for more accurate results.

The main reason for using a trimmed cell mesher for the fluid domain is to ensure that the mesh is used less in areas where flow is unnecessary. Because there is no need for a detailed mesh structure in the regions where there is no flow and these regions can be represented by larger cells. In this way, it is possible to create a denser mesh structure in the regions where the flow is relevant, ensuring accurate results of the analysis while reducing the calculation cost and time. The mesh structure created for the fluid domain is given in **Figure 4.21**.

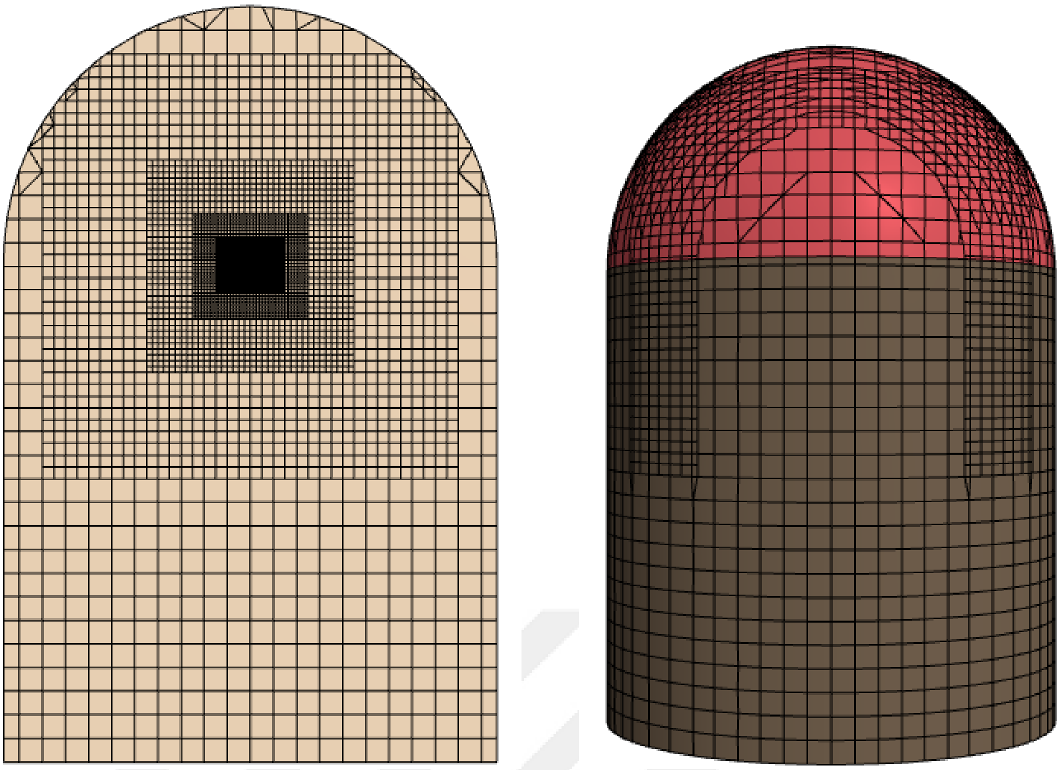


**Figure 4.21.** Fluid Domain Trimmed Cell Mesher

The good meshing of the areas where the flow field is effective ensures that the flow properties are captured and calculated accurately. The mesh used in these areas should be tighter and able to capture the flow in the best way. Therefore, polyhedral mesh and prism layer mesher selections were made for the rotating domain.

Polyhedral mesh has a flexible structure to adapt to different geometries and flow conditions. It can adapt better, especially in complex geometries and regions where the flow changes locally. Also, with adaptive meshing techniques, the polyhedral mesh can be locally refined to achieve better resolution. The polyhedral mesh used around the propellers in the rotating domain has a structure that can better capture the complex geometry of the propellers and accurately represent the details. Curvature, corners and sharp edges of propeller blades can be captured more precisely.

Prism layer mesh is a boundary layer created attached to the surface of a rotating component. This layer better captures the movement of the flow in the boundary layer region. It provides high resolution modeling of the boundary layer, especially for propellers. This allows better capture of flow details in the boundary layer. This mesh structure better captures the rotation effect and produces accurate results according to the rotational speed and direction of the flow field.

The detailed mesh parameters used for this analysis are presented in **Table 4.5**. Also, the Mesh structure for the Rotating domain is shown in **Figure 4.22**.

**Table 4.5.** Mesh Parameters

| **Size Function** | **Values** |
|---|---|
| Base Size | 1 m |
| Target Surface Size | 0.1 m |
| Minimum Surface Size | 0.01 m |
| Surface Curvature | 75 |
| Number of Prism Layer | 5 |
| Prism Layer Total Thickness | 0.001 m |
| Surface Growth Rate | 1.1 |
| Volume Growth Rate | 1.05 |

Coarse mesh has less and equal 1 million element sizes, the fine mesh has close to 3 million element sizes, and very fine mesh has over 10 million element sizes.

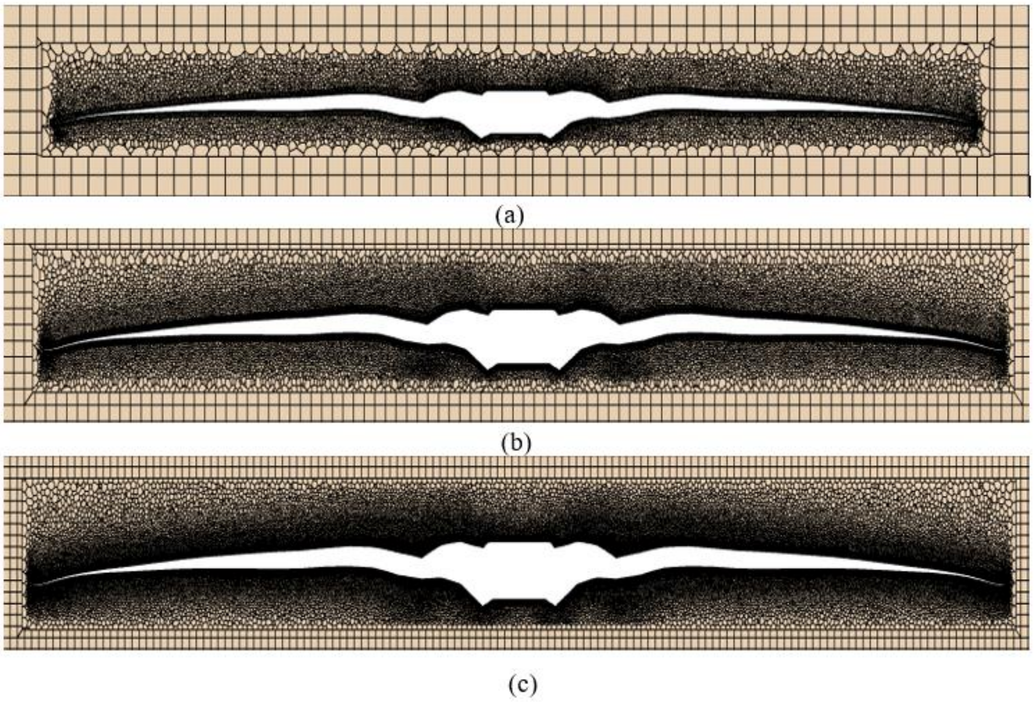


**Figure 4.22.** Rotation Domain Mesh Top to Bottom (a) Coarse, (b) Fine, (c) Very Fine

### 4.5.2.4 Physic Models Generation

The physic model includes the selection and use of mathematical equations that describe the characteristics and behavior of the fluid phenomenon to be analyzed. It is necessary to carefully select a physics model suitable for the purpose of the analysis and the characteristics of the fluid phenomenon. The model parameters to be used for the propeller analysis are given in **Table 4.6**.

**Table 4.6.** Physic Model Parameters

| **Parameters** | **Settings** |
|---|---|
| Time | Implicit Unsteady |
| Material | Gas |
| Flow Type | Coupled |
| Equation of State | Ideal Gas |
| Viscous Regime | Turbulent |
| Turbulence Model | K-Omega Turbulence |

Implicit solvers can more accurately capture temporal effects. This allows to simulate correct the dynamic behavior and transition states of the fluid. Phase changes are not usually taken into account in propeller analysis. In addition, the ideal gas model is simple and computationally easier, as the operating range is below Mach 0.3.

The K-Omega turbulence model is a type of turbulence model that is widely used in computational fluid dynamics analysis. This model is based on two different transport equations, k and $\omega$. Where k represents turbulent kinetic energy, $\omega$ represents turbulent viscosity or mixing ratio. The k- $\omega$ turbulence model is preferred in propeller analysis because it is effective for accurately calculating the turbulent characteristics of the flow around the propeller. It also performs well in directed flows and boundary layer flows.

### 4.5.3 Validation of Analysis

Validation is needed to verify whether the model, method and simulation results used are compatible with real-world events and experiments. Single propellers were used during the validation process before proceeding to the two-propeller analysis and were compared with the experimental studies by Ohio State University and McCrink et al. (2015).

Static analysis of APC 10x7E propeller at different rpm values was preferred as a validation method. For the appropriate number of mesh elements to be used, 6000 rpm with the highest thrust error rate was selected. In order to reduce this error rate, necessary improvements were made especially in the propeller boundary layer. The number of Prism Layers has been increased from 3 to 15. In addition, the overall base size of the domain has been reduced until the thrust value improves. As seen in **Figure 4.23**, after approximately 3.4 million elements, the change in thrust decreased below 1 percent depending on the mesh element number and converged.

Along with this mesh accuracy, 3.5 million meshes were used in each analysis for single propellers. Naturally, this number doubled in the analyzes to be made with two propellers.

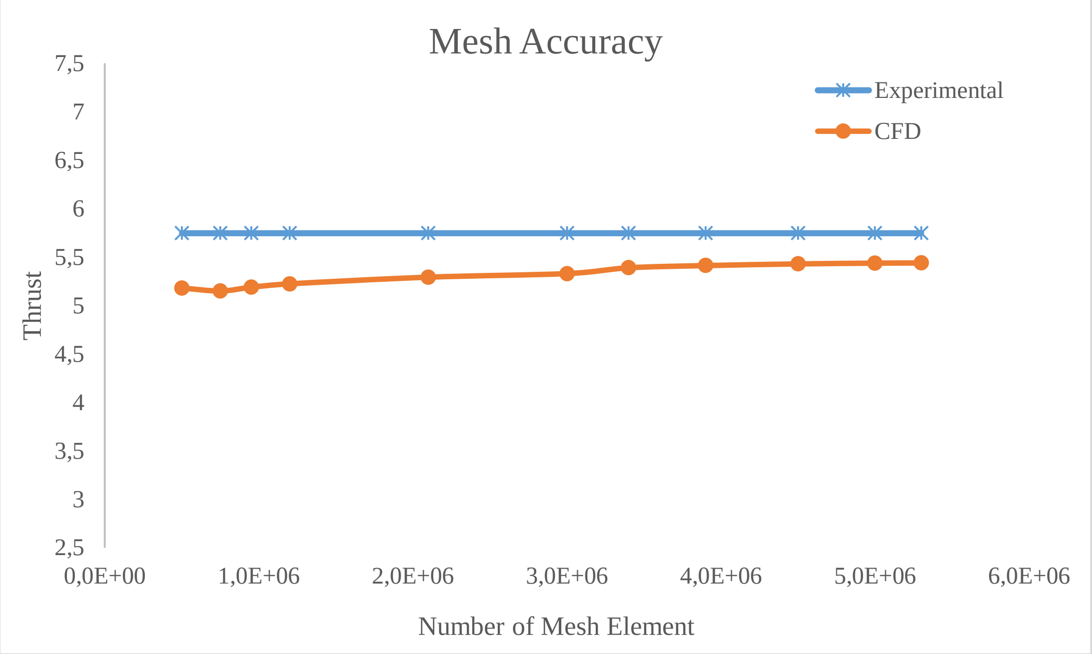


**Figure 4.23.** Mesh Accuracy

The static thrust analysis is conducted under hovering condition, or in other words, without velocity inlet. The results of this analysis are compared with experimental data. **Table 4.7** presents the error percentage of thrust for different RPMs, also **Figure 4.24** and **Figure 4.25** show the comparative thrust coefficient and comparative power coefficient graph.

**Table 4.7.** Static Thrust Analysis

| **RPM** | **Experimental Thrust (N)** | **CFD Thrust (N)** | **Error Percentage** |
|---|---|---|---|
| 2000 | 0,555 | 0,5525 | 0,45% |
| 3000 | 1,305 | 1,272 | 2,52% |
| 4000 | 2,373 | 2,29 | 3,49% |
| 5000 | 3,79 | 3,612 | 4,70% |
| 6000 | 5,748 | 5,40 | 6,05% |

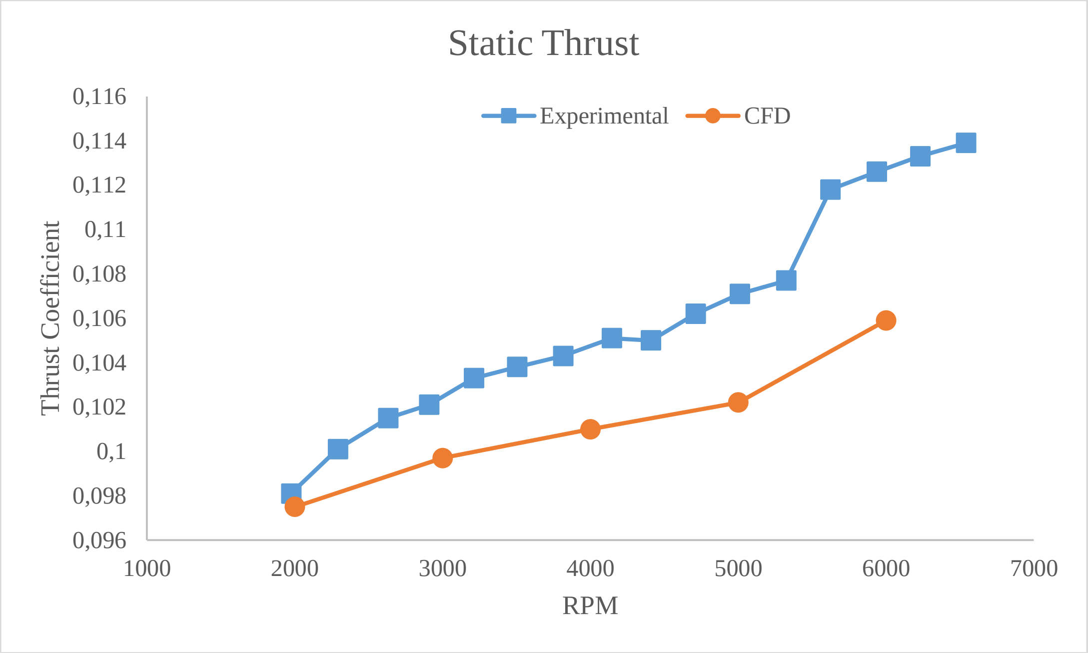


**Figure 4.24.** Comparison of Thrust Coefficient

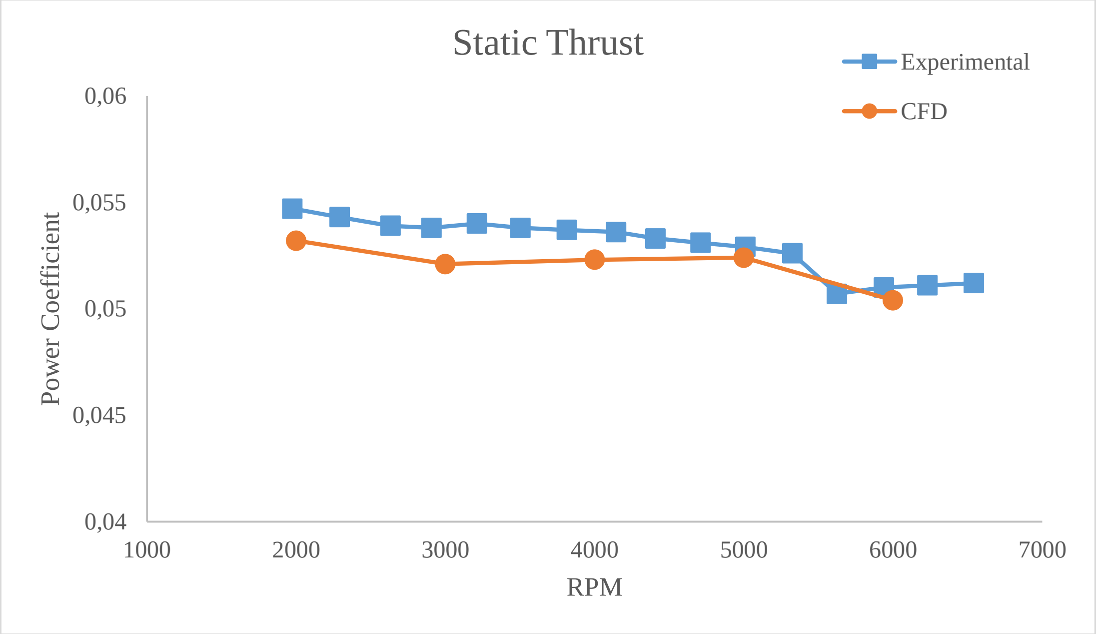


**Figure 4.25.** Comparison of Power Coefficient

As seen from the figures and error rates, our CFD analyses yielded results that closely matched the experimental data. Through these analyses, we precisely determined the number of mesh elements and the settings of the physical model and solver. Particularly, in the static analysis conducted at low RPMs, our error rate remained very low. However, as the RPM value increased, the error rate also increased proportionally. This behavior can be attributed to the following factors:

- At high rpm values, the precise aerodynamic effects of propellers cannot be better captured in approximate models and the amount of error may increase.
- At high rpm values, fast and precise calculations are required depending on the rotational speed of the propellers. However, the processing power used can limit this.
- At high rpm, sufficient numbers of high-quality mesh elements are required to properly capture the airflow around the propellers than at lower rpm. In this case, the computation time can increase dramatically.

### 4.5.4 Analysis Results

In this study, the analysis of optimal propeller distances and required thrust for VTOL is divided into three categories: single propeller, two propellers, and three propellers. For the single propeller case, velocity inlet was utilized to compare advance ratios and efficiencies at different RPM values with the available experimental data.

#### 4.5.4.1 Single Propeller Case

The single-propeller analyses were conducted as a kind of validation before the multi-propeller analyses. Since the geometry of the used APC 10x7 Thin Electric propeller was not exactly identical to the original, the aim was to observe the differences in the analyses solved using velocity inlet.

The mesh parameters and physics model used for the single propeller analysis are the same as provided in the previous section. For the single propeller analysis, the only difference is that different velocity inlet values were entered for different advance ratio values, and the mesh count is approximately 3.5 million. In **Figure 4.26**, the experimental results conducted by Ohio State University and the CFD results are compared for 6000 rpm. For this analysis, 7 different advance ratios were used.

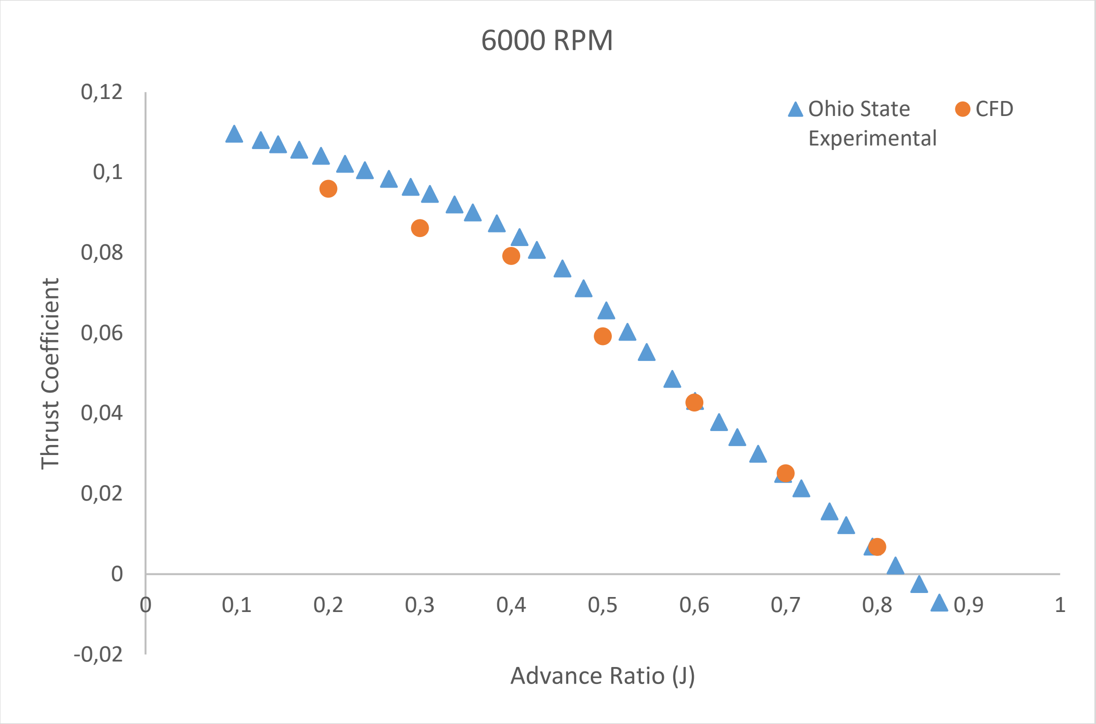


**Figure 4.26.** Comparison of advance ratio and thrust coefficient at 6000 RPM

In **Figure 4.27**, the same comparison is made for 4000 RPM at 4 different advance ratios.

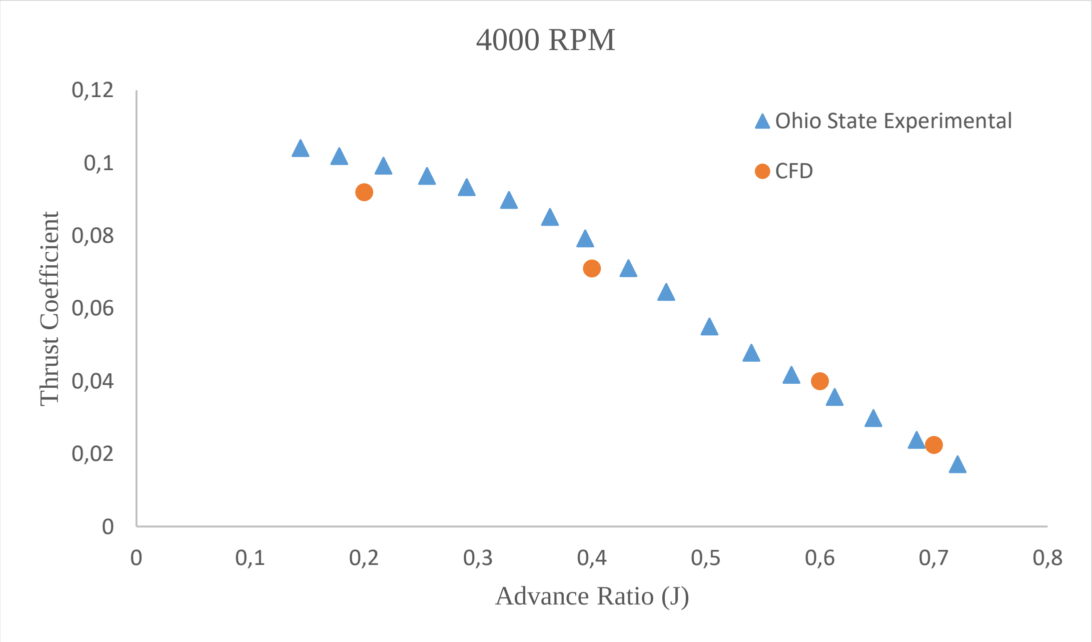


**Figure 4.27.** Comparison of advance ratio and thrust coefficient at 4000 RPM

**Figure 4.28** and **Figure 4.29** provide efficiency graphs against advance ratio for two different RPM values.

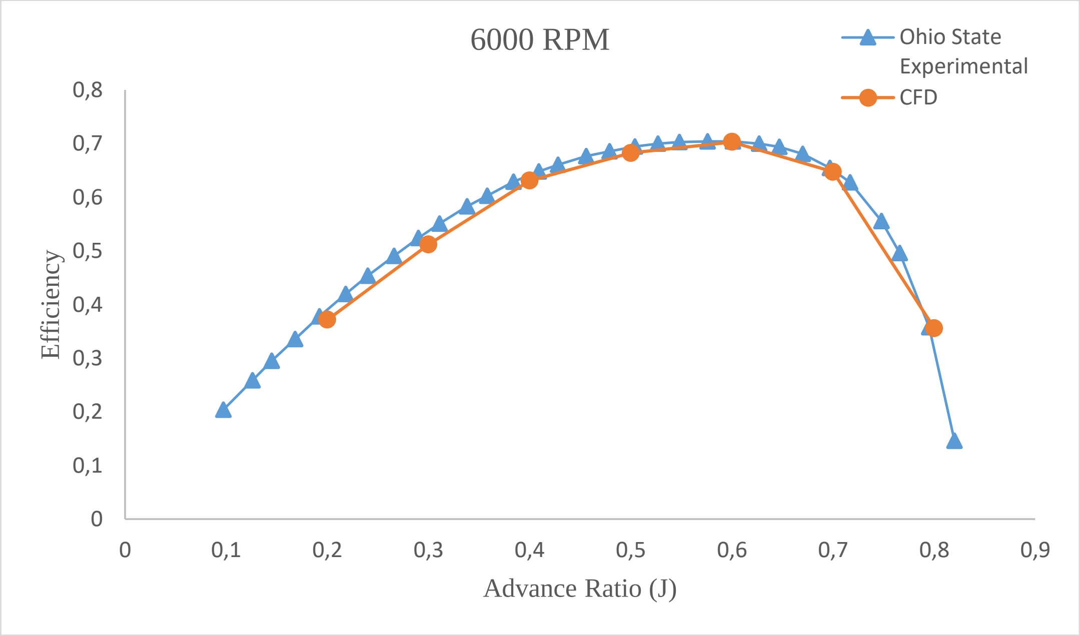


**Figure 4.28.** Comparison of advance ratio and efficiency at 6000 RPM

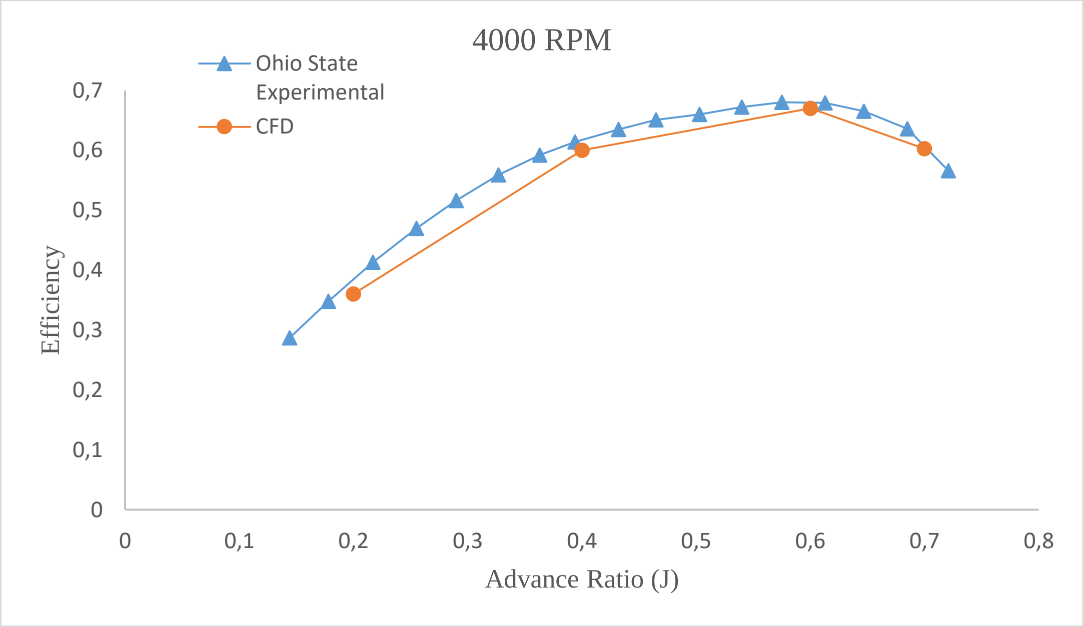
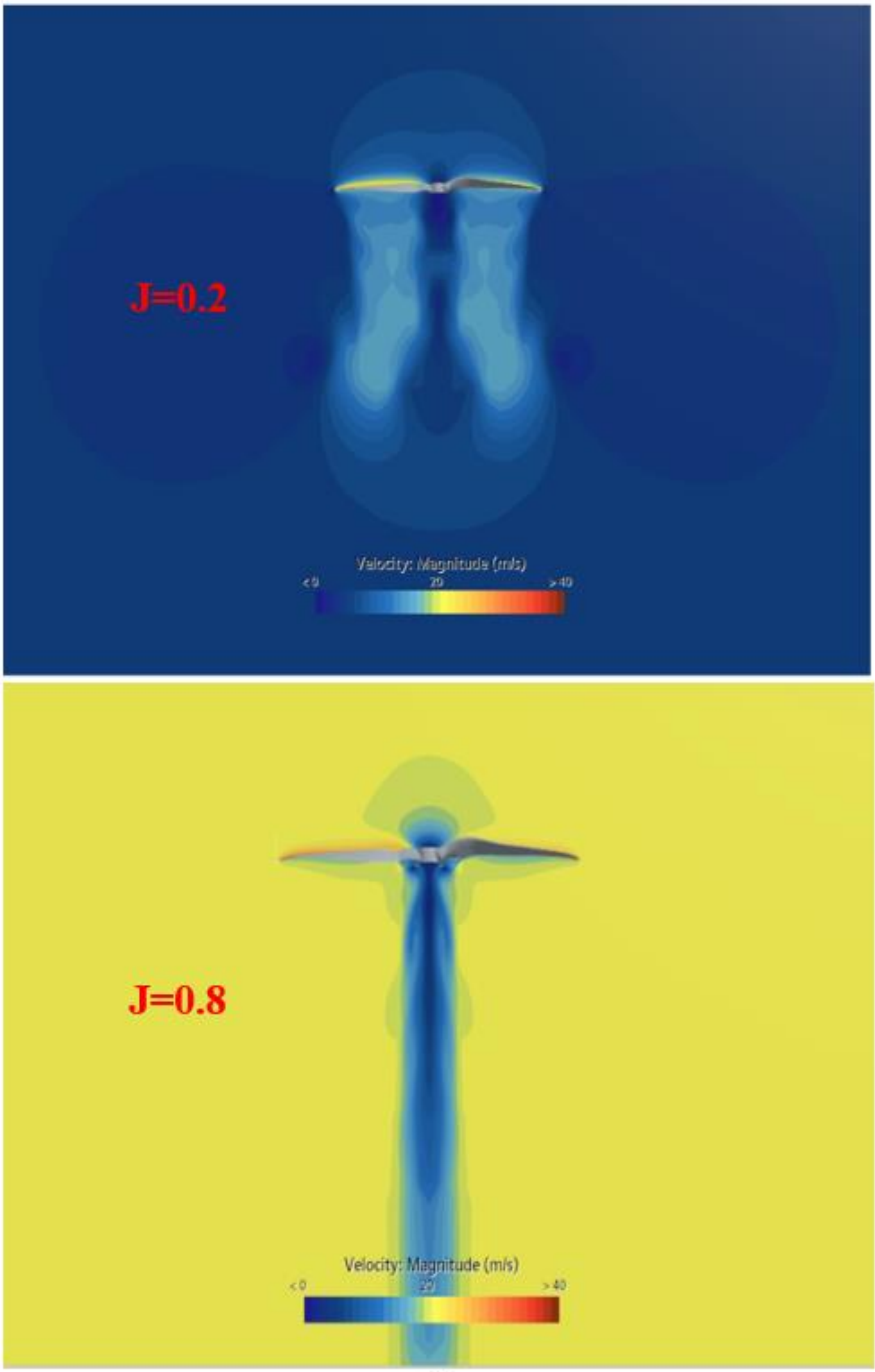


**Figure 4.29.** Comparison of advance ratio and efficiency at 4000 RPM

As seen from the graphs, CFD results follow the trend of experimental results. Especially in the Thrust coefficient, the error rate does not exceed 8%, and at high advance ratios, which correspond to high velocity values, they almost match with experimental data.

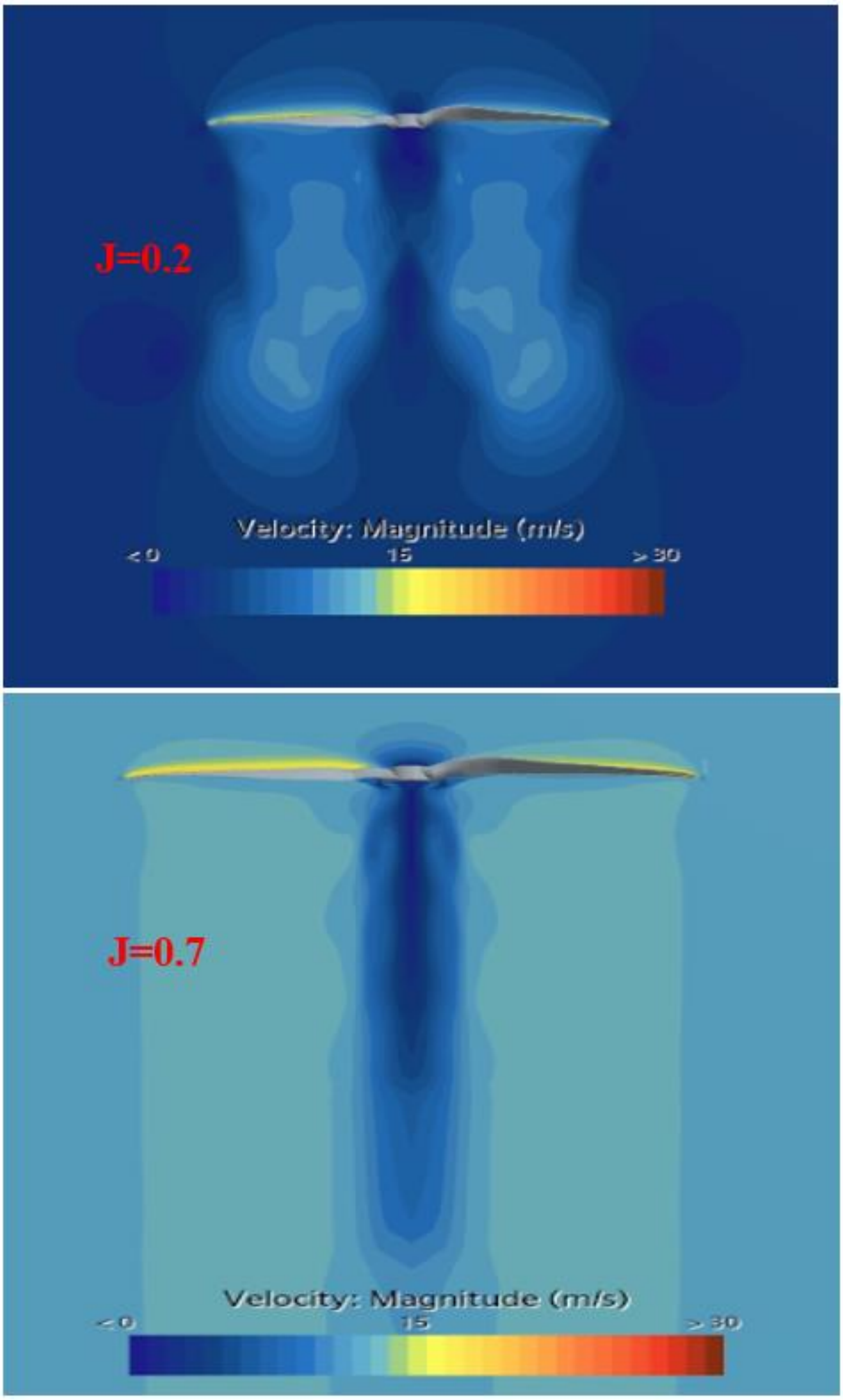
To compare the velocity contours, the smallest and largest advance ratio values were selected for each RPM value in the analysis, and they are shown in **Figure 4.30**.

As shown in this figure, at low advance ratio values, the flow field behind the propeller becomes more complex and turbulent. This leads to irregular flow distribution and the formation of vortex structures, resulting in larger error values in the analyses and confirming the accuracy of our analysis results. On the other hand, at high advance ratio values, the propeller operates at higher speeds, and the flow field behind it becomes smoother and more regular. This situation also has been showed in **Figure 4.31**.



(a)

**Figure 4.30.** Velocity Contour at (a) 6000 RPM (b) 4000 RPM



(b)

**Figure 4. 30.** Velocity Contour at (a) 6000 RPM (b) 4000 RPM (Cont.)

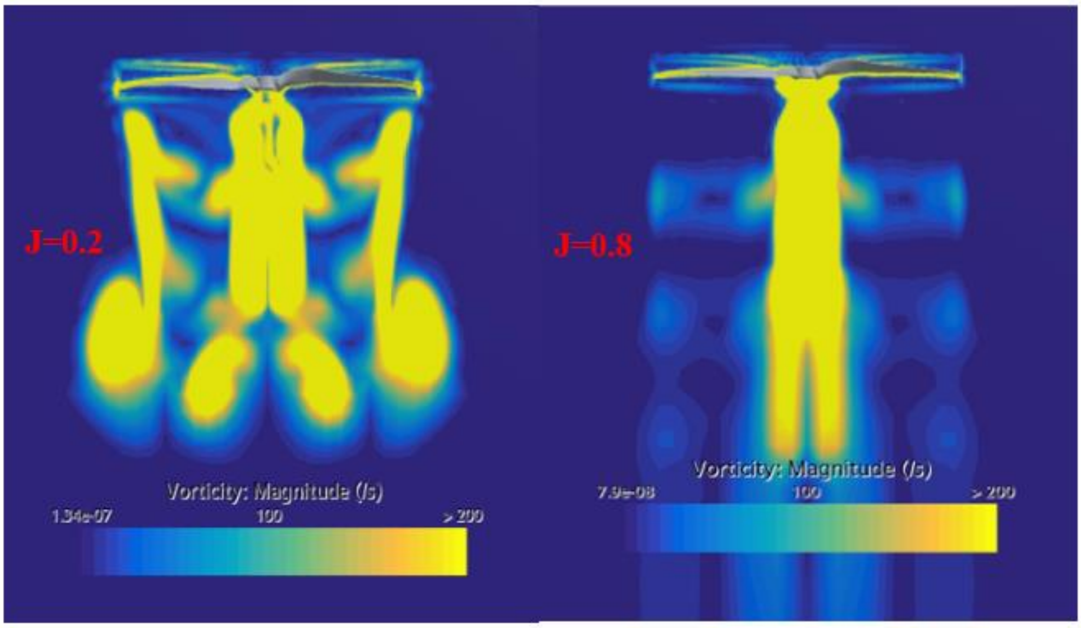


**Figure 4.31.** Vorticity Contour at 6000 RPM

#### 4.5.4.2 Two Propeller Case

At the initial stage of the designed VTOL aircraft, it was preferred to have 4 propellers, with 2 propellers on each wing. The total thrust produced by the rear two rotors at 12000 rpm was found to be 7 N. To determine the minimum thrust required for this aircraft, APC 10x7E propellers were analyzed at 7000 rpm with an advance ratio of 0.4. Through a single propeller analysis, considering a 5% validation error, a thrust of 4.95 N was achieved.

Analyses were conducted to find the optimal positions of the two propellers to be used in the wing, based on their tip separation distances. In this case, five different scenarios were observed for the tip separation distance, ranging from 0.05D to 1D. Compared to the single propeller case, the number of mesh elements has increased by approximately two-fold due to the additional rotating domains. Furthermore, as shown in **Figure 4.32**, a refined mesh region was created to better capture the interaction between the propellers and improve its representation in the results.

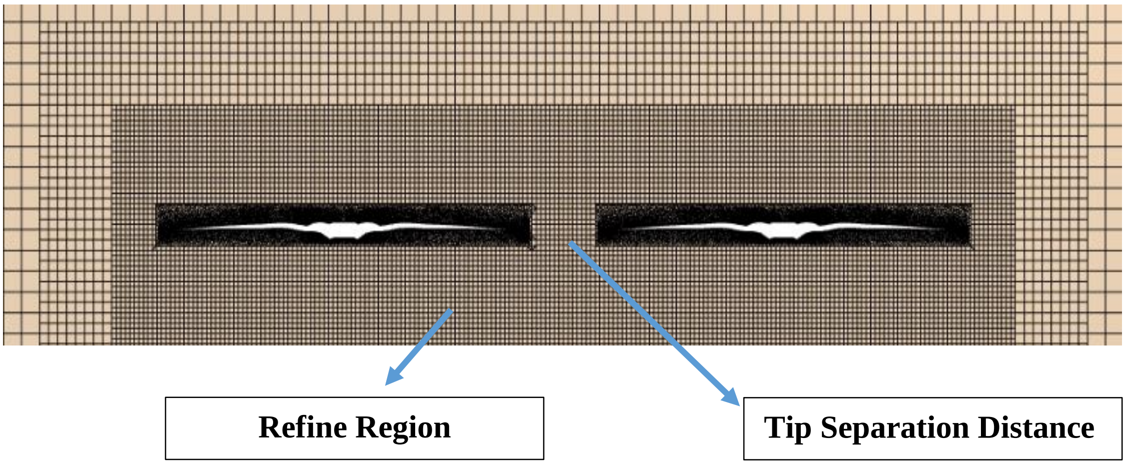


**Figure 4.32.** Mesh View for the Two-Rotor Analysis

As seen in **Figure 4.33**, the maximum thrust decrease was determined to be around 2%. Among similar studies in the literature, Yoon et al. (2016) found this rate to be around 4%, while Zhou et al. (2017) found it to be around 1%.

Although the thrust variation may seem small, when two propellers are used with different tip separation distances, thrust fluctuation occurs. This variation is also shown in **Figure 4.34**.

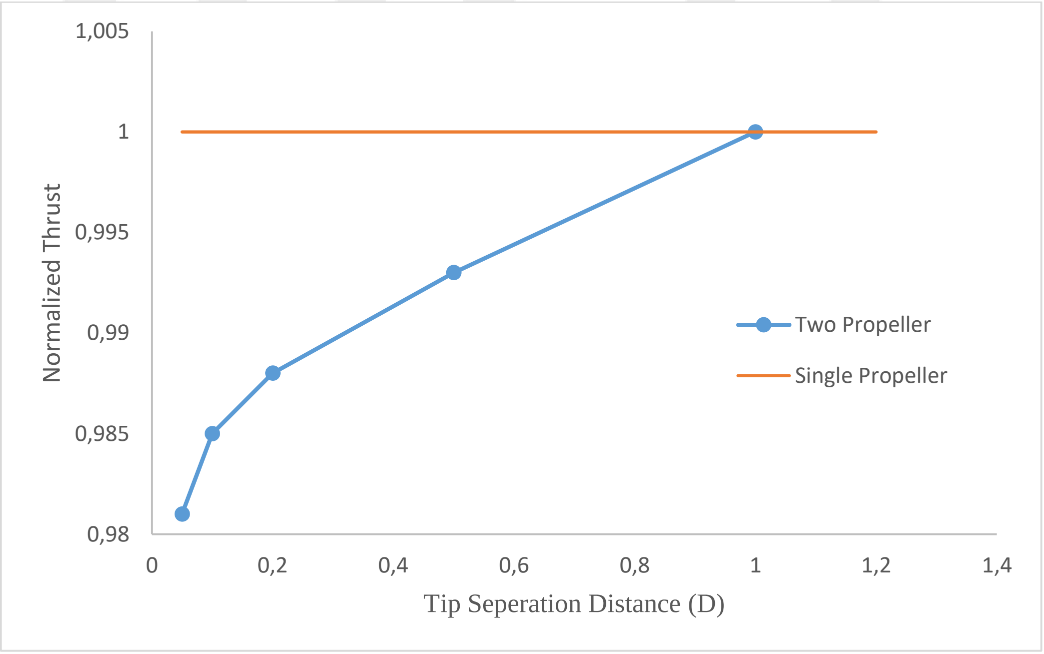


**Figure 4.33.** Effect of Separation Distance on Normalized Thrust

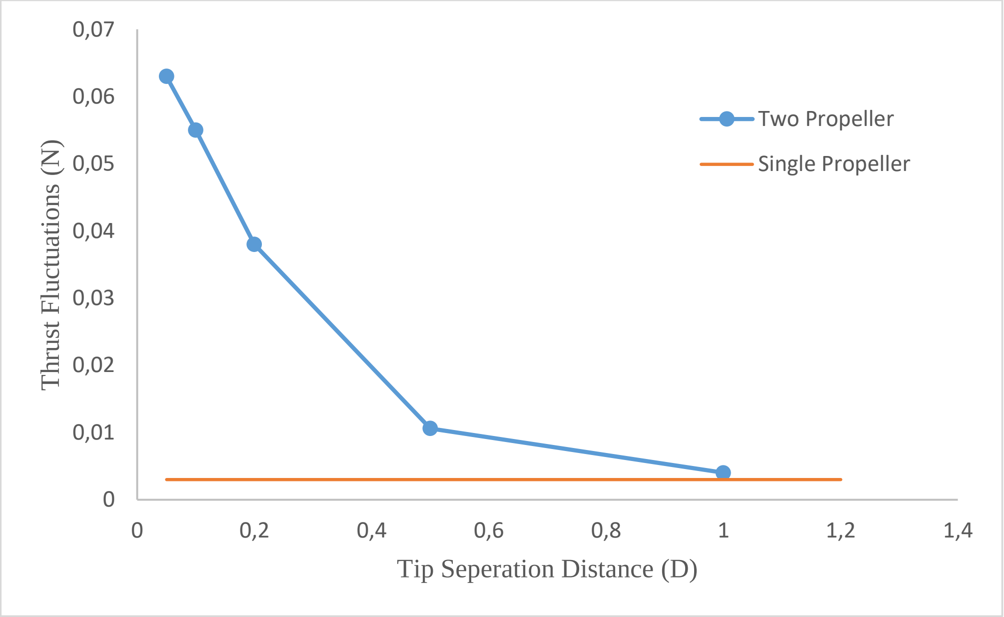
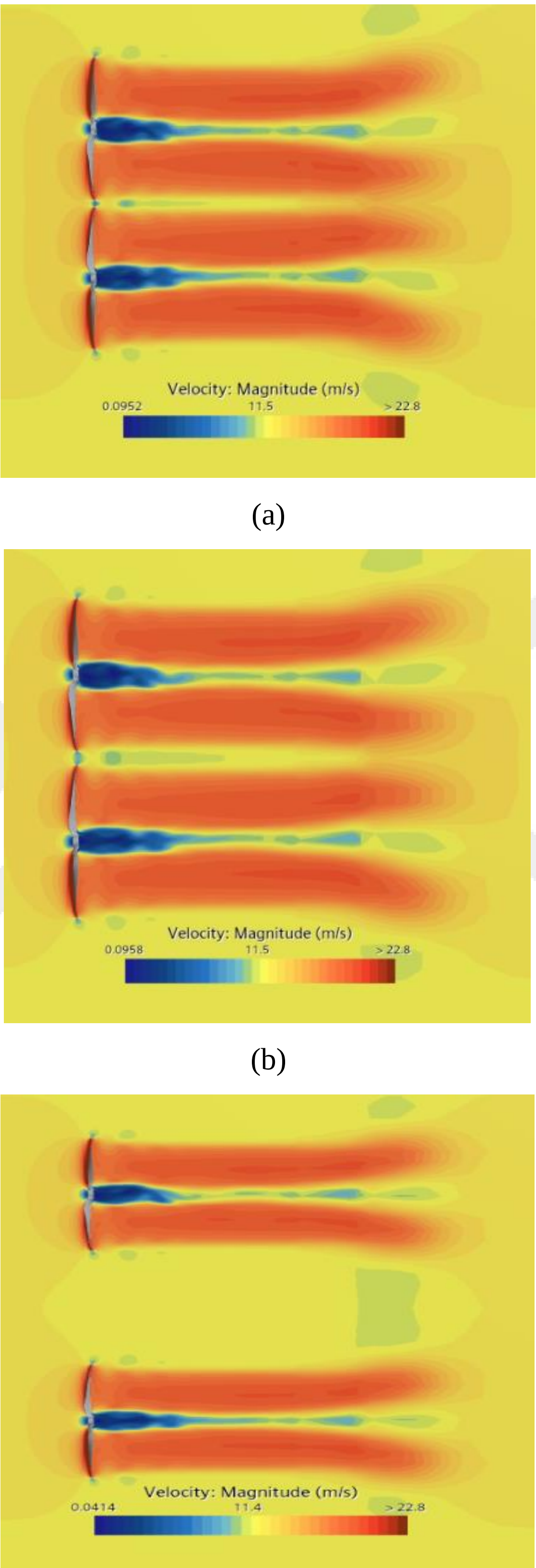


**Figure 4.34.** Effect of Separation Distance on Thrust Fluctuation

When compared to the single propeller case, combining two propellers with a tip separation distance of 0.05D results in a fluctuation that is 20 times greater. While the %2 variation in thrust may seem insignificant, fluctuation plays a critical role in the design. An increase in thrust fluctuation can lead to higher vibrations within the system. These vibrations may transmit aerodynamic effects to mechanical components and structures, potentially causing damage or wear. Additionally, fluctuation can complicate flight control, especially if the fluctuation frequency approaches the natural frequencies of the aircraft or rotor system, leading to resonance effects that may affect the control capabilities.

Both thrust and fluctuation show significant changes after the 0.5D distance, becoming less impactful. Considering the limited wing span in the VTOL design, the tip separation distance between 0.5D and 1D provides us with the optimum values.

In the velocity contours shown in **Figure 4.35** for different Tip Separation distances, it is clearly observed that the flows generated by the propellers do not significantly interfere with each other.



(a)

(b)

(c)

**Figure 4.35.** Velocity contour at (a) 0.05D (b) 0.1D (c) 0.5D

#### 4.5.4.3 Three Propeller Case

If three propellers are used instead of two on a wing, and the velocity inlet speed of the aircraft, or as referred to in the analysis, "velocity inlet," is assumed to be 12 m/s, then running the propellers at 6000 rpm would be sufficient for our purposes. When conducting a single propeller analysis at this speed, we obtain a thrust of 3.13 N, which will serve as our reference thrust value.

Due to the limitation in wing span, three propellers cannot be aligned on the same axis along the wing. Therefore, in this case, downstream separation will be used to conduct the analyses. For the horizontal axis, the distance between the hub centers of two propellers will be adjusted. The domain and mesh view created for this case are shown in **Figure 4.36**. As the number of rotating domains increased to three, the mesh count also increased to approximately three times the mesh count of the single propeller case. Additionally, the element size in the created refine region was reduced to achieve a finer mesh.

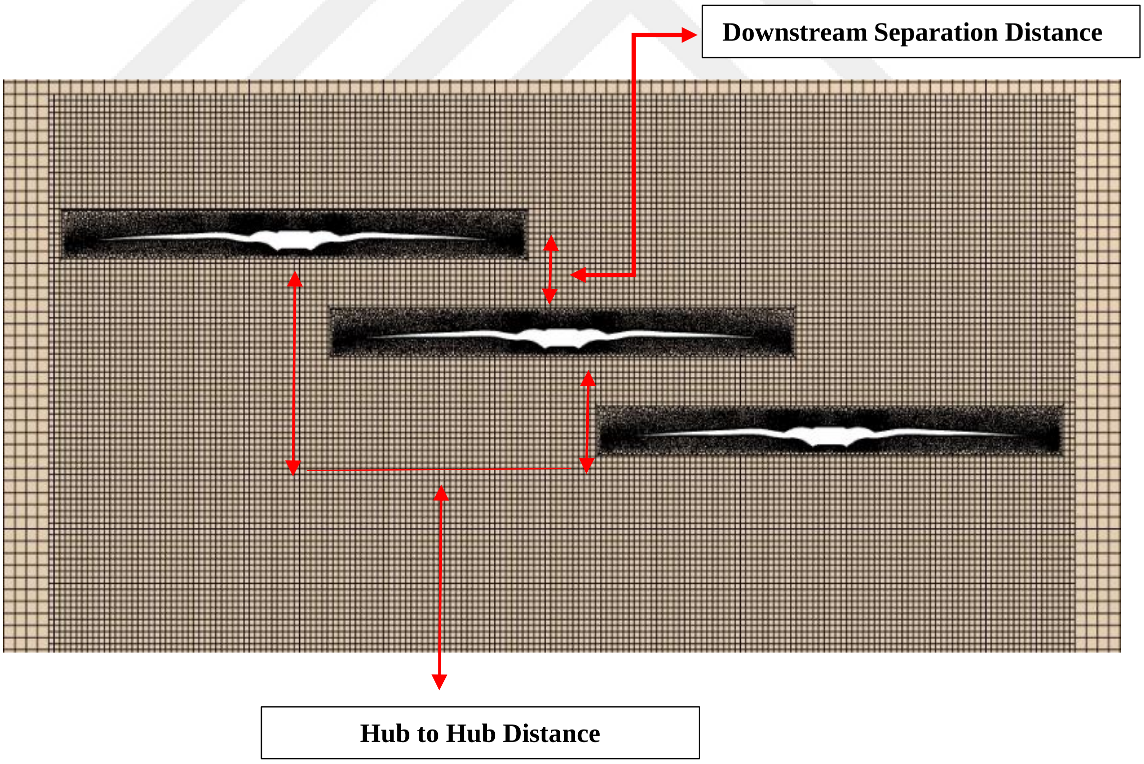


**Figure 4.36.** Mesh View for the Three-Rotor Analysis

Analyses were conducted at hub to hub distances of 0.15m, 0.20m, and 0.25m, with downstream distances of 0.1D, 0.2D, 0.3D, and 0.4D. As seen in **Figure 4.37** and **Figure 4.38**, when the hub to hub distance was set to 0.15m, the downstream distances had little effect on both thrust and fluctuation especially for propeller 2. However, as this distance increases, the changes of other propellers become more evident. Similar observations were made for other hub distances as well. The top propeller is referred to as propeller 1, the middle one as propeller 2, and the bottom one as propeller 3.

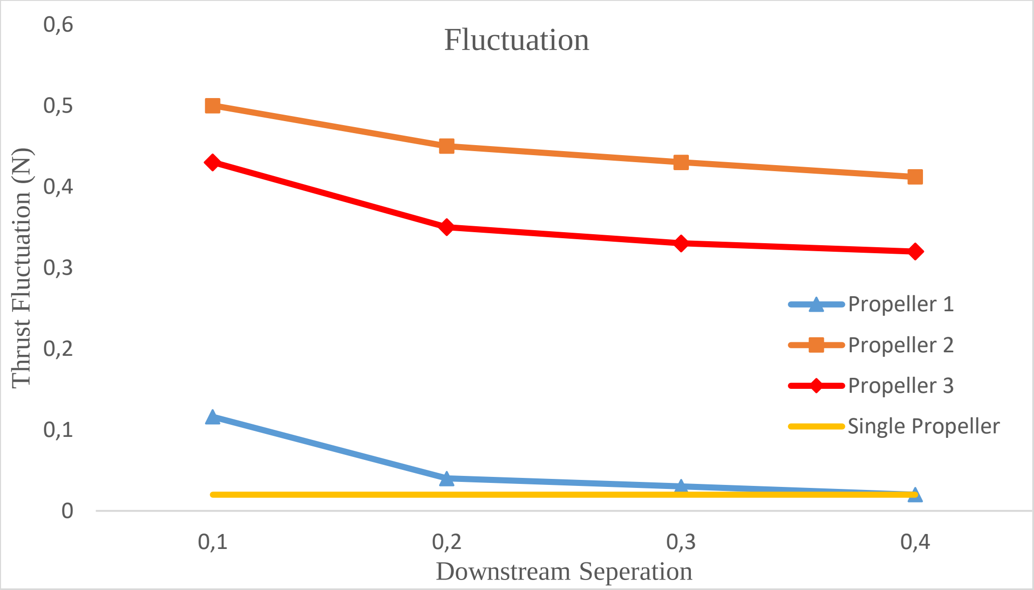


**Figure 4.37.** Effect of Downstream Separation Distance on Thrust Fluctuation

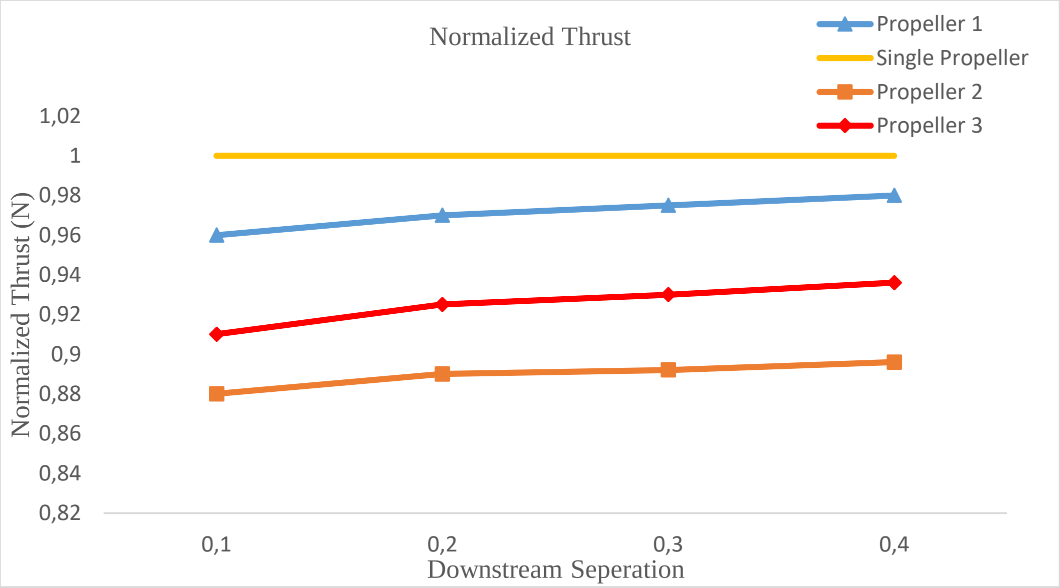


**Figure 4.38.** Effect of Downstream Separation Distance on Thrust

However, at the same downstream distance, variations were more pronounced for different hub to hub distances, as depicted in **Figure 4.39** and **Figure 4.40**.

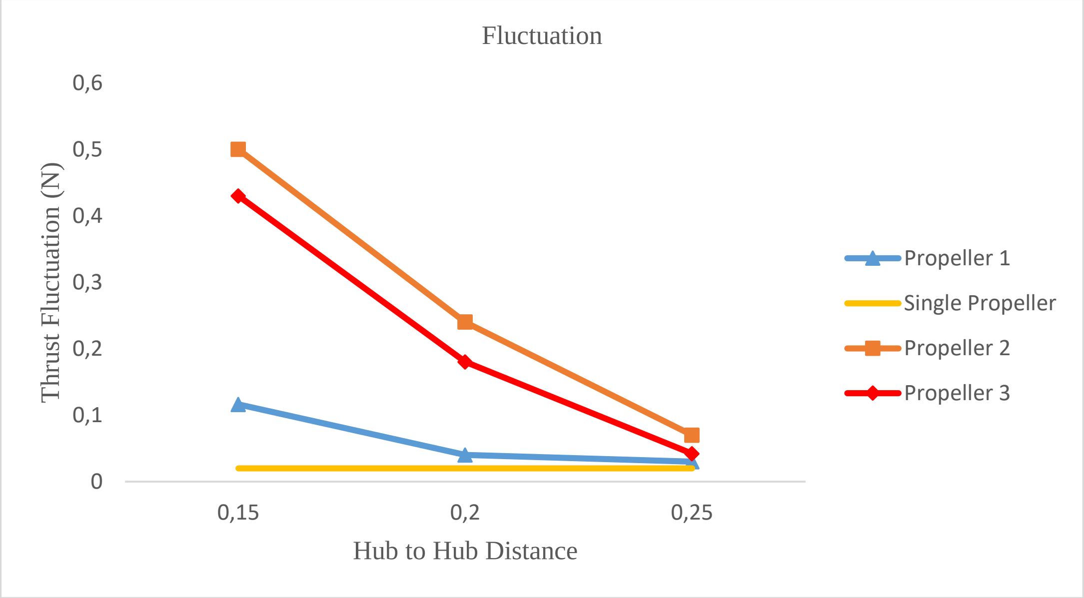


**Figure 4.39.** Effect of Hub to Hub Distance on Thrust Fluctuation

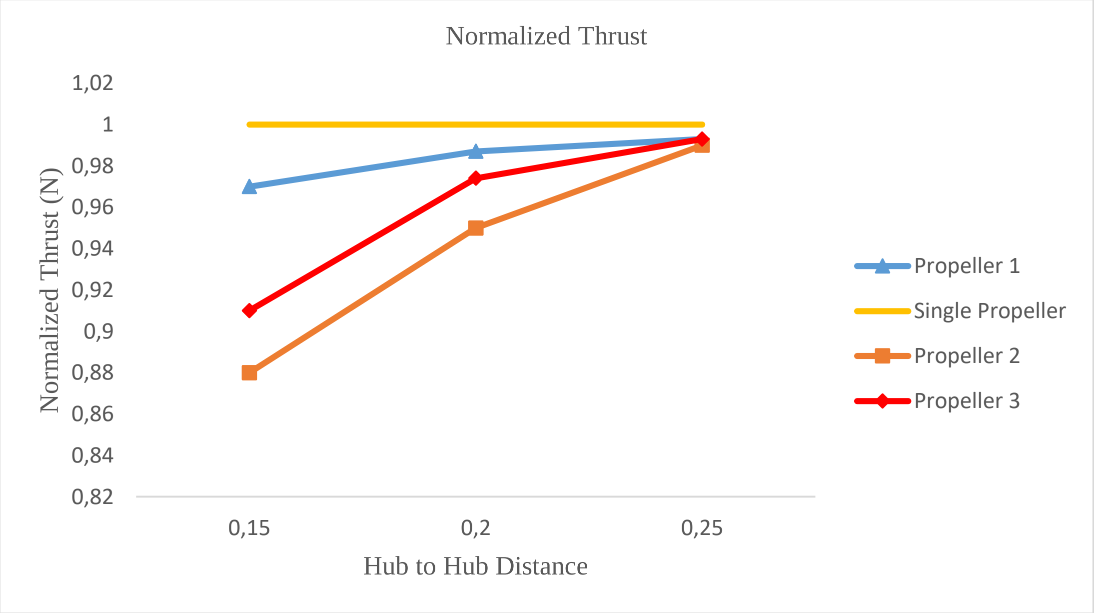


**Figure 4.40.** Effect of Hub to Hub Distance on Thrust

In addition, the total thrust graph resulting from the use of three propellers is provided in **Figure 4.41**.

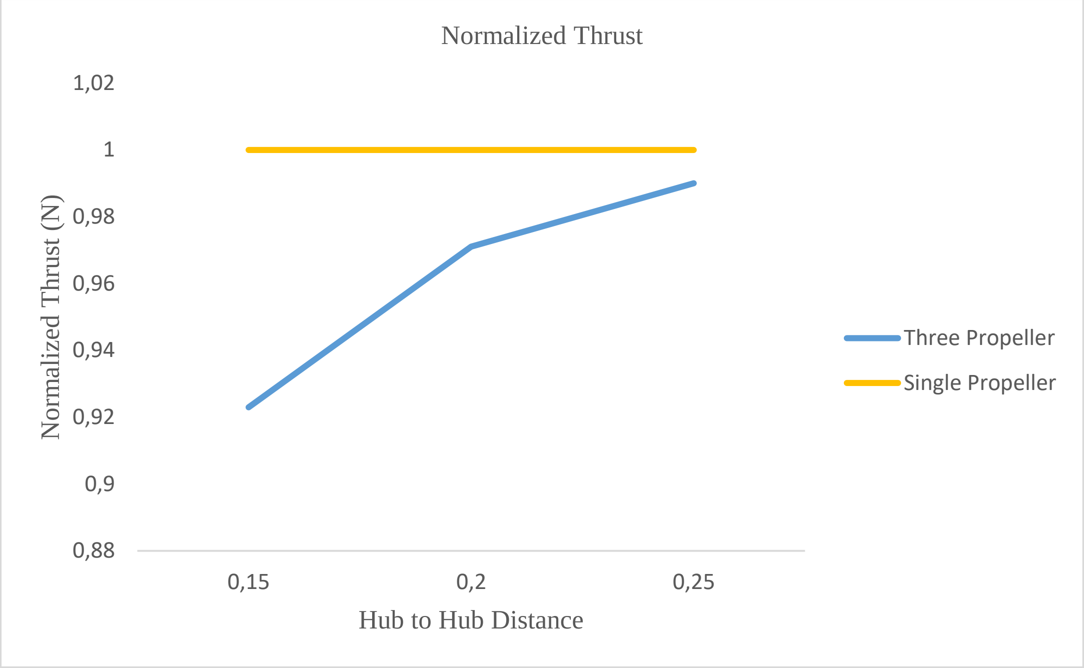
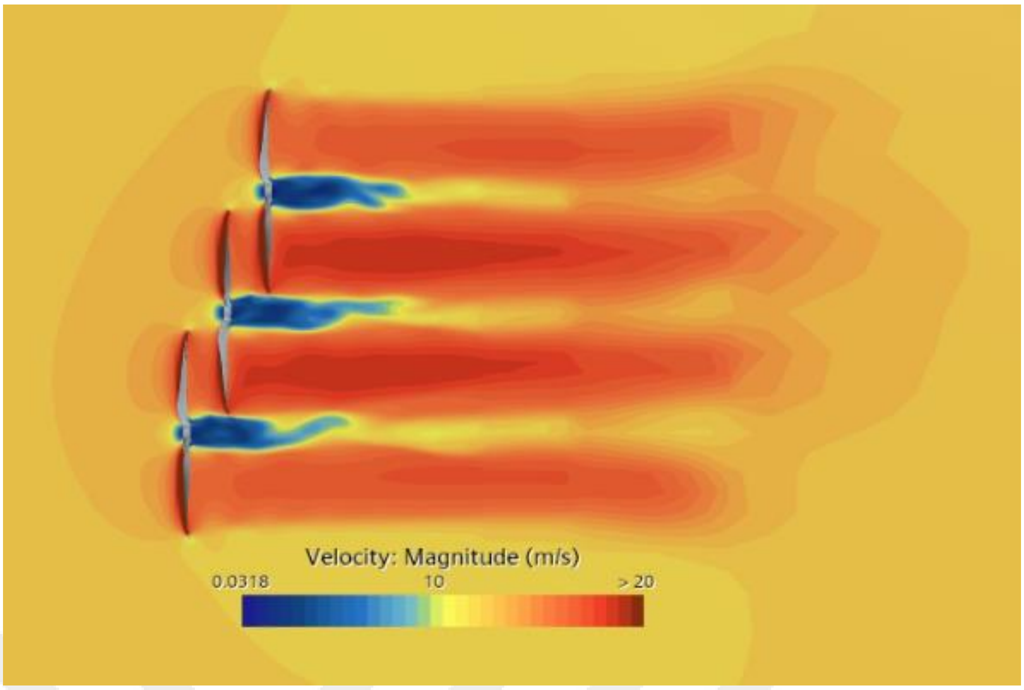


**Figure 4.41.** Effect of Hub to Hub Distance on Total Thrust

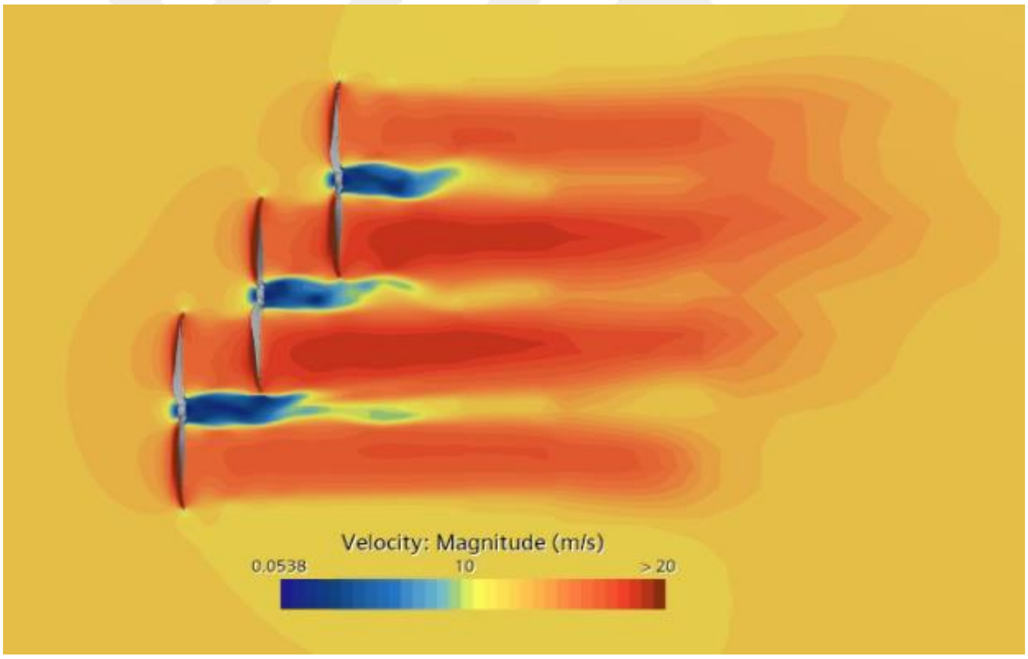
As observed from the results, as the distance between hubs decreases, their mutual interaction increases, leading to both an increase in fluctuation and a significant decrease in thrust.

When the distance between hubs remains the same, the effect of downstream separation changes at most %2 to %3 percent in thrust, while it has great effect in fluctuation, especially in propeller 2. This is due to the fact that the airflow produced by the upper propeller remains relatively consistent for a certain distance and equally affects the lower propellers. In all cases, the highest fluctuation is observed in the middle propeller. Generally, the closest distance results in an approximate 8% thrust loss, while the farthest distance reduces this rate to nearly 1%. Due to the limitation of our wing span, considering these results, the optimum condition is determined to be in the range of 0.20 to 0.25 for the hub distance.

Velocity contour graphs for all cases are presented in **Figure 4.42**, **Figure 4.43** and **Figure 4.44**.

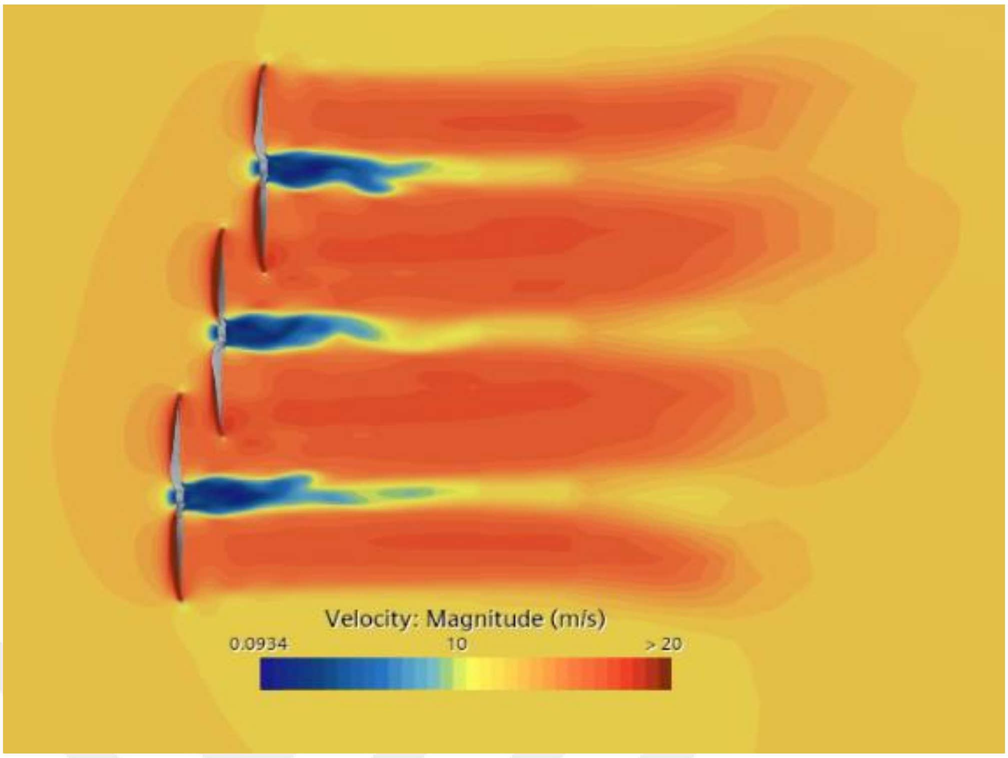


(a)

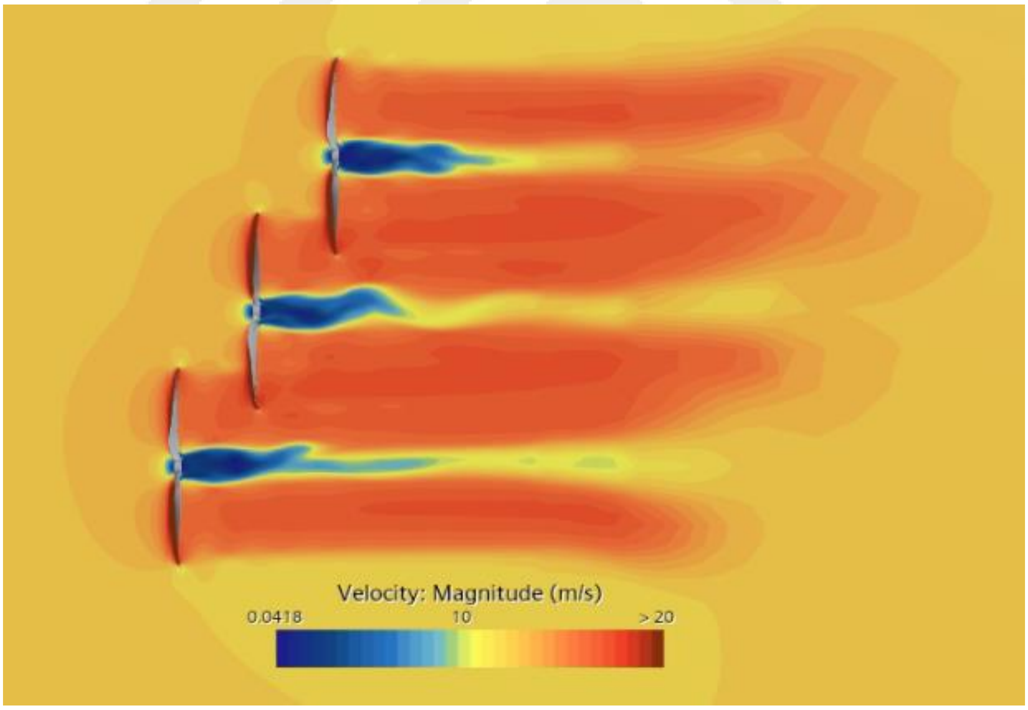


(b)

**Figure 4.42.** Velocity contour for 0.15m Hub to Hub Distance at (a) 0.2D and (b) 0.4D Downstream Distance

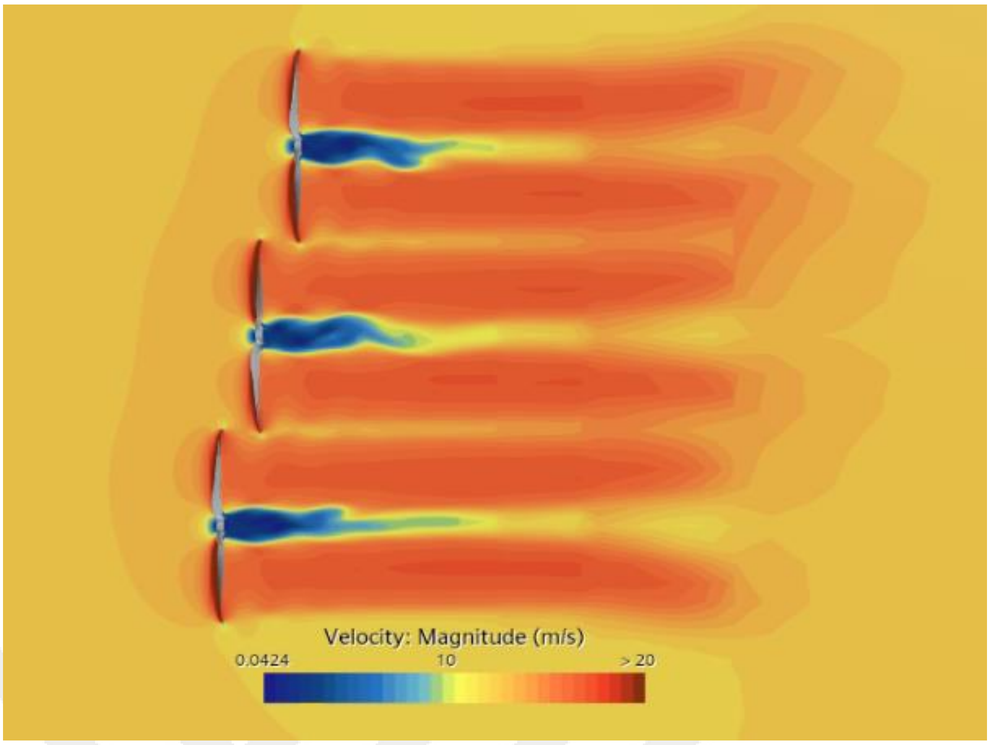


(a)

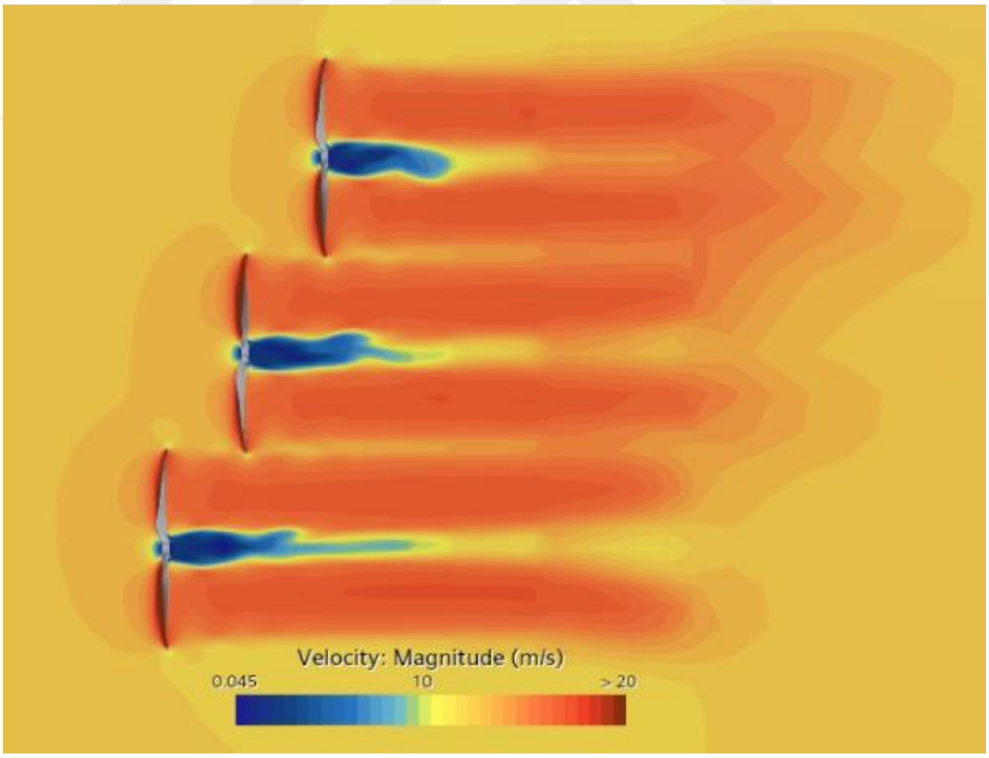


(b)

**Figure 4.43.** Velocity contour for 0.20m Hub to Hub Distance at (a) 0.2D and (b) 0.4D Downstream Distance



(a)



(b)

**Figure 4.44.** Velocity contour for 0.25m Hub to Hub Distance at (a) 0.2D and (b) 0.4D Downstream Distance

# CHAPTER 5
# CONCLUSION

In this thesis, a comprehensive and detailed literature review was conducted to explore tilt wing VTOL aircraft design and propeller analysis. Various VTOL applications and related studies in the literature were examined, and their advantages and disadvantages were compared to achieve an optimal design. Efficiency was taken into consideration for each designed and selected component, and lightweight materials were chosen to ensure a lightweight design. The body and wing design were based on the principle of minimum drag and maximum lift. Among different tilt mechanism options, the worm drive mechanism was preferred, emphasizing its positive effects on the aircraft's performance and stability.

By using different types of propellers on the wings and the rear part of the aircraft, both the required thrust force was achieved, and particularly during vertical takeoff and landing, the issue of moment imbalance was effectively addressed.

The propeller analyses were conducted with optimized speeds and different tip separation distance, providing a significant roadmap for the energy consumption and performance of the VTOL aircraft. These analyses played a critical role in the design of the aircraft, tailored for forward flight and takeoff conditions, and established a solid foundation for validating the aerodynamic performance of the aircraft. As a result of these analyses, the following conclusions have been reached.

- In the single propeller case analyses, the error rate was compared with experimental results, and the error rate was found to be a maximum of 6% for static thrust and a maximum of 10% for velocity inlet.
- The error rate in single propeller case analysis decreases as the advance ratio increases, and in some values, it even matches with the experimental data on

the graphs. This is because as the velocity inlet increases, the velocity variables in the flow field become more prominent.

- In two-propeller analyses, when the tip separation distance was reduced from 1D to 0.05D, the obtained thrust showed approximately %2 decrease.
- Although the thrust loss in the tip separation distance analysis may seem insignificant, the generated thrust fluctuation is 20 times greater compared to the single propeller case.
- In three-propeller analyses, it has been observed that the downstream distance has a negligible effect on the results for thrust value for three different hub-to-hub distances, which are 0.15 m, 0.20 m, and 0.25 m. The thrust value remains relatively close across 0.1D, 0.2D, 0.3D, 0.4D downstream distances but the fluctuation value is high for propeller 2 and 3, also this value decreased by 15-20% as the distance increases. This finding indicates that variations in the hub-to-hub distance have a more significant impact in thrust variation on the analysis compared to changes in the downstream distance.
- In the three-propeller analysis, a thrust variation of approximately 8% was observed for hub-to-hub distances between 0.15 m and 0.25 m, while keeping the downstream distance constant.
- For the designed VTOL aircraft, the optimal distances can be determined based on the number of propellers used. If two propellers are preferred, the optimal tip separation distance can be set between 0.5D and 1D. On the other hand, if three propellers are chosen, the optimal hub-to-hub distance can be selected between 0.20 m and 0.25 m for APC 10x7E propeller.

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