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Structural Design and Analysis of Wind Turbine

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Abstract- This thesis presents a comprehensive exploration into the design, modeling, and analysis of a wind turbine, employing a multidisciplinary approach to optimize its performance. The blade geometry was generated using QBlade software, a robust tool for blade design in wind turbine applications. The 3D model was then meticulously crafted using SolidWorks, integrating aerodynamic principles and structural considerations. The heart of this project lies in the utilization of SolidWorks Flow Simulation for a detailed analysis of the aerodynamic characteristics of the designed wind turbine. The simulation facilitated a thorough examination of airflow patterns, turbulence effects, and pressure distributions around the blades, offering valuable insights into the efficiency and energy-capturing potential of the turbine under various wind conditions.

Index Terms- Wind Turbine; Design; Simulation; QBlade: SolidWorks; CFD; Flow Simulation; NACA4412, Renewable Ener

I. INTRODUCTION

At the end of the 20th century, the inert wind turbine technology awoke to a world of new opportunities. The resurgence has been accelerated by technological advancements in several other fields that were applied to wind turbines. The current generation of wind turbines has been influenced by several fields, including material science, computer science, aerodynamics, testing, analytical techniques, and power electronics. New alloys and composites for metal parts and blades have been made possible by material science. Computer science advancements make design, monitoring, analysis, and control easier. Originally created for the aerospace field, aerodynamics design techniques are now used to wind turbines. The state of analytical approaches has advanced to the point where it is now feasible to grasp how a new design should function far more clearly than it was in the past. Through testing with the wide range of commercially accessible sensors and data gathering and analysis tools, designers are able to gain a deeper understanding of the real performance of the new turbines.

Wind turbines are a very new and somewhat growing fast method of producing electricity. Power electronic devices can transmit energy to and from storage, permit small-scale isolated network operation, and allows the turbine to run at a variable speed, increasing energy production, decreasing fatigue of damage, and benefits the usefulness in the process. They can also assist in easily integrating the turbine's generator into the electrical system. The patterns of wind turbines have altered dramatically in the last 25 years. They are quieter, more affordable, and more dependable. However, the end of the evolutionary epoch cannot be declared. At locations with lesser wind speeds, it ought to still be feasible to cut the cost of electricity. It still has to be economically feasible to create turbines for usage in isolated settlements. Offshore wind energy is still in its early phases of development. Offshore areas provide amazing prospects, but there are also a lot of challenges to face. Intermittency transmission and storage concerns need to be taken up again as wind energy becomes a bigger source of electricity globally. The need on designers to increase wind turbines' cost-effectiveness across the board will not go away. It will be necessary to use better engineering techniques for mass-produced production, design, and analysis. There are also chances for the creation of novel materials to lengthen the lifespan of wind turbines. It will be necessary to pay more attention to the specifications of special applications. In any situation, the development of the wind business poses both a problem and an opportunity for a variety of fields, including computer science, mechanical, electrical, materials, aerospace, controls, and civil engineering.

1. Motivation

Wind power has become a viable option as people's awareness of the need for sustainable energy grows. The large, revolving structures known as wind turbines are essential to using wind power to create energy. We may frequently see them on the horizon. The idea behind this thesis is that a cleaner, more sustainable energy future can be greatly aided by comprehending and improving the architecture of these turbines. This research is driven by the straightforward idea that the world needs greener energy sources, and wind power is one of them. As the effects of utilizing fossil fuels weigh heavily on us, it is becoming more and more important to switch to greener options. A future when our energy comes from a source as natural as the wind is promised by wind turbines, which are a concrete step in that direction.

However, this drive extends beyond merely advancing technology. It's about making a contribution to the wider discussion on renewable energy. Despite their magnificent appearance, wind turbines are not without problems. These include wear and tear and changes in the wind. In order to address these issues head-on, this thesis offers suggestions that can strengthen and improve the resilience of wind turbines. The way the world produces energy needs to change, and it needs to happen quickly. This transition is even more critical in light of climate change and environmental issues. With its unrealized potential and sustainability, wind energy is urging us to move towards a greener future. By examining the design and optimization of wind turbines, this thesis hopes to contribute to this significant shift, which will not only enhance wind energy but also move us closer to a future in which we coexist peacefully with the natural world. The wind turbine's blades represent our dedication to a more sustainable and environmentally friendly future as we move closer to a new era of renewable energy.

2. Objective of the Thesis

This thesis's main goal is to thoroughly design and assess the performance of a new type of wind turbine blade. The goal is to make a useful contribution to the arena of wind energy by a combination of theoretical research, computational modelling, and hands-on experimentation. The particular goals consist of: Create a thorough and well-thought-out design for a wind turbine blade, taking structural integrity, materials, and aerodynamics into account. This entails putting existing blade design ideas to use while incorporating cutting-edge technologies to improve performance.

Aerodynamic Analysis

To simulate and examine the intended wind blade's aerodynamic behavior, use CFD computational tools. This involves determining the best possible energy collection under varied wind conditions by evaluating lift and drag forces, flow patterns, and turbulence effects. Performance Optimization: Apply the insights from the structural and aerodynamic evaluations to iteratively improve the design. A balanced and effective performance that maximizes energy extraction while upholding durability and safety is the aim. Comparative Analysis: Evaluate the new blade's performance against that of the current standard designs. This comparison analysis sheds light on the possible gains in cost-effectiveness, environmental impact, and energy efficiency that the suggested design may bring.

II. LITERATURE REVIEW

Wind energy has emerged as a vital renewable power source, contributing significantly to the global energy landscape. Continuous advancements in design, materials, and analysis methodologies have marked the evolution of wind turbine technology. This literature review explores fundamental studies and developments in wind turbine design, focusing on aerodynamics, structural integrity, and innovative solutions.

1. Historical Evolution

The use of wind energy dates back centuries, with early windmills serving mechanical purposes. The first electricity-generating wind turbine was installed by the Austrian Josef Friedländer at the Vienna International Electrical Exhibition in 1883, followed by wind generators, e.g., in Scotland in July 1887 by Prof James Blyth of Anderson's College, Glasgow (the precursor of Strathclyde University).Blyth's 10 metres (33 ft) high cloth-sailed wind turbine was installed in the garden of his holiday cottage at Marykirk in Kincardineshire, and was used to charge accumulators developed by the Frenchman Camille Alphonse Faure to power the lighting in the cottage, thus making it the first house in the world to have its electric power supplied by wind power.[1]

Wind turbines are essential for clean energy generation. Optimizing blade design improves efficiency and performance. Researchers used QBlade software to analyze and optimize a small horizontal axis wind turbine blade. The study focused on design parameters like twist angle and chord length using the SG6043 airfoil. High accuracy results were obtained, demonstrating QBlade's reliability. The optimum rotor performance occurred at a tip speed ratio of 8. QBlade is valuable for wind turbine development due to its reliable analysis capabilities. Understanding blade behavior is crucial for improving energy efficiency. This study demonstrates the use of blade element momentum theory (BEM) to the design and optimization of a horizontal axis wind turbine blade's rotor at lower operating wind speeds using QBlade software. Using the results of the blade's twist angle and chord length optimization, ten different sections totaling 1.17 meters in length were used. To illustrate the computing methods and outcomes, the SG6043 airfoil shape was used. It was discovered that an angle of attack (α) of 2° can yield the highest value of (CL/CD). Additionally, it was discovered that the rotor operated at its best when the tip speed ratio was eight.

2.CFD Analysis

The use of CFD analysis has become essential for evaluating wind turbine aerodynamic performance. Research like the ones by Mittal and Kumar (2019) demonstrate how CFD is used to assess turbine wakes and optimize blade designs for higher efficiency [9]. A thorough grasp of pressure distributions, turbulence effects, and airflow patterns is made easier with the use of CFD models, which is essential for optimizing design parameters [10]. Wind energy is more important than ever due to the depletion of fossil fuels and the rise in environmental consciousness. Wind farms and wind turbines are getting bigger as the market for wind energy expands. I still have a lot to learn about this technology, though. Present utility-scale turbines, for instance, reach a considerable depth into the air boundary layer. Consequently, the way the turbines and the air boundary layer interact and more needs to be learned about their wakes. The flow field of the upstream turbines is impacted by the turbulent wakes of the turbines in their wake, resulting in a decrease in power generation and an increase in mechanical loading. With more understanding wind farm developers might design wind farms that operate better and require less maintenance if they have this kind of flow. Using computational fluid dynamics (CFD) to simulate this flow is a crucial step in better understanding wind farm currents. This study examines how well actuator disc and actuator line models perform in terms of generating wakes from wind turbines and the interplay between wakes from several turbines. We also look at variables that factors, such grid resolution, and the application of a tip-loss correction. Onto the flow field is projected the turbine force. We see that the expected power drops with grid coarsening.

3. Innovations in Wind Turbine Technology

Innovative solutions have emerged to address various challenges in the designing of the wind turbine. The concept of floating wind turbines, pioneered by Jonkman et al. (2009), opened new avenues for offshore wind farms in deeper waters, expanding the geographical scope of wind energy generation (Jonkman et al., 2009) [15] Moreover, research by Martinez-Tossas et al. (2020) explored multi-rotor configurations, aiming to enhance energy capture efficiency by reducing wake interference (Martinez-Tossas et al.,2020). [16]

4. Environmental Impact and Community Engagement

There are concerns about the environmental impact and social acceptance of wind energy projects. Research conducted by Devine-Wright in 2005 [21]. Explored the psychological and social factors that influence public attitudes towards wind energy, providing helpful information for community engagement strategies. Molina and colleagues demonstrated in 2018 [22] that environmental impact assessments are crucial, taking into account factors like wildlife conservation and landscape preservation.

5. Conclusion

Through the literature review, it becomes evident that wind turbine design has undergone significant advancements in research and innovation.

From basic aerodynamic principles to state-of-the-art technologies, researchers have consistently pushed the limits in utilizing wind energy. Overcoming obstacles related to aerodynamics, structural integrity, and environmental issues has resulted in a wide range of solutions, paving the way for a sustainable future of wind energy.

6. Renewable Energy Market Share and Growth

Renewables, which include solar, wind, hydropower, biofuels, and other energy sources, are at the forefront of the shift to less carbon-intensive and more sustainable energy systems. Recent years have seen a sharp rise in generation capacity because of regulatory support and large cost reductions for renewable energy sources, particularly wind and solar photo voltaics.

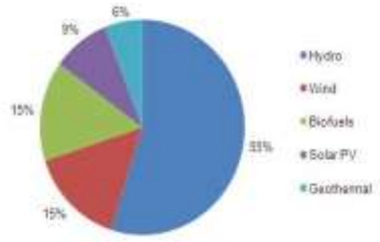


Fig 1: Market share of renewable power sector

The usage of renewable energy sources in the power, heat, and transportation sectors is one of the main things keeping the rise in average global temperatures from going above 1.5 degrees Celsius. In the Net Zero Emissions by 2050 scenario, renewable energy sources allow for practically 100% decarbonization of electricity generation. Meanwhile, transportation fuels and renewable heat sources provide significant emissions reductions in buildings, industries, and transportation.

In 2022, wind power generation surpassed 2,100 TWh, a record 265 TWh (up 14%) more than in the previous year. This was the renewable power technology with the second-highest growth, after solar photovoltaics. To stay up with the Net Zero Emissions by 2050 Scenario, which requires the generation of about 7,400 TWh of wind electricity in 2030, the average annual generation growth rate must increase to nearly 17%. To do this, capacity must rise steadily each year, from about 75 GW in 2022 to 350 GW in 2030. Far more comprehensive regulatory and private sector initiatives are needed to achieve this level of capacity development; the two most important areas for improvement are the ease of obtaining onshore wind permits and the reduction of offshore wind prices.

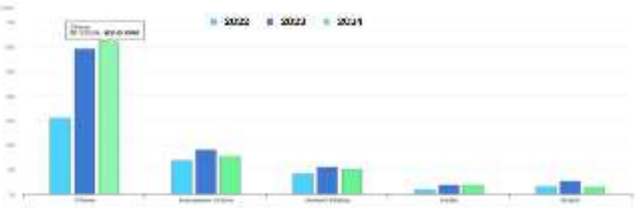


Fig 2:.Net Onshore Wind Power Generation by country.

The graph shows the net onshore wind power generation by country in GW from 2022 to 2024.China is the top country in terms of net onshore wind power generation, with a total of 62 GW in 2024. This is followed by the European Union with 57 GW, the United States with 37 GW India with 26 GW, and Brazil with 25 GW. The graph indicates that net onshore wind power generation has increased significantly globally in the last several years. The entire amount of net onshore wind power generated in 2022 was 175 GW. It is anticipated that this would rise to 225 GW in 2024 from 200 GW in 2023.

III. WIND TURBINES

1. VAWT/HAWT

Horizontal-axis wind turbines (HAWT) and vertical-axis wind turbines (VAWT) are the two different types of wind turbines from a physical configuration perspective. Vertical axis designs were initially considered because to the expected advantages of being omnidirectional and having gear and generator equipment at the tower base.

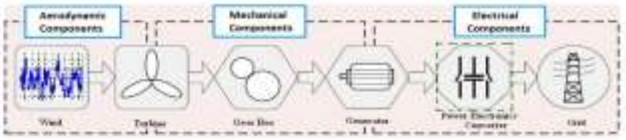


Fig 3: Block Diagram of the components of Wind Turbine.

To capture as much wind energy as feasible, the blades should interact as much as possible with the wind blowing inside the swept region. A wind turbine must ideally be more effective the more blades it has. In actuality, however, there will be greater inter-blade interference as the number of blades increases. It is therefore more likely that the blade will travel through the area of disturbed, weaker wind flow. In order to ensure structural stability, the number of blades on the HAWT should be at least three. If this is the case, the turbine rotor's dynamic features resemble those of a disc. Thus, the majority of modern wind turbines that are sold commercially have three blades. [28]

The Betz Limit: The Betz Limit refers to the German physicist Albert Betz's 1919 conclusion that a wind turbine cannot transform more than 59.3% of the kinetic energy of the wind into mechanical energy to turn a rotor. 22 A wind turbine may extract up to 59% of the energy passed by the wind; this is known as the "power coefficient" and is described as

2. Components of Wind Turbines

The rotor hub, the turbine, and the connecting parts are made of blades. The drive train is made up of the generator rotating mass, gearbox, high-speed shaft, and turbine rotating mass, low-speed shaft. It moves the mechanical output power of the turbine up to the generator rotor, where it is transformed into electrical power. The horizontal-axis turbine's rotor spins when wind strikes it. The gear box receives energy from the low-speed shaft and uses it to increase speed in order to rotate the high-speed shaft. Figure 3.4 displays the key parts of a wind turbine system.

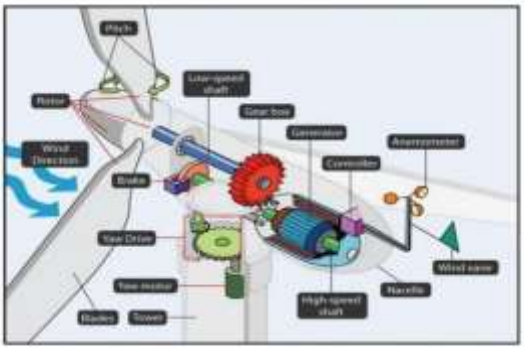


Fig 4: HAWT displaying control, electrical, and mechanical parts

The aerodynamic brake is run by the shaft that houses the hydraulic system's pipes. An emergency mechanical brake on the high-speed shaft is utilized in the event that the aerodynamic brake fails. Typically, a gearbox connects the turbine to the generator shaft, speeding up the blades' sluggish spinning so that it can power an electrical generator more effectively.

HAWTs are three types:

- Dutch windmills.
- Multi blade Water pumping Windmills.
- High speed propeller type wind machines.

Dutch Windmills: Grain grinding was a common application for them. Dutch windmills employed wooden slats or sails to industrialize their blades, which were typically angled toward the wind to produce rotation.

3. Horizontal Axis Wind Turbine (HAWT) Parts

As illustrated in figure 1.3 above, the HAWT is made up of multiple mechanical elements. Parts for safeguarding the turbine and parts for producing electricity are both in operation.

The components are:

The Rotor: The rotor's function is to gather wind energy and transform it into rotating mechanical power through the use of its blades. Two or more metal, fiberglass, or wooden blades make up the rotor. The rotor blade design benefits from advances in airplane wind technology; it operates by the use of Bernoulli's equation of aerodynamic lift and drag force, as will be discussed subsequently. The rotor blade's shape and angle of attack in relation to the wind direction have an impact on the blade's performance. The rotor assembly can be arranged in one of two ways (see image 3 below):

Upwind Rotor: This sort of turbine has its blades facing the wind; gigantic turbines on wind farms, on the other hand, have a motor drive to compel the turbine to face the wind. Despite this, the turbine runs far better smoothly and produces more electricity.

Downwind Rotor: the wind directs the yaw, or left-to-right motion, and it aligns itself according to the direction of the wind. The tower's shadowing causes the blade to bend, which in turn causes weariness, noise, and a decrease in power production. Figure 3: Rotors oriented upwind and downwind. (Source 3) The usable service lifetime of the rotor is influenced by its design and intrinsic mechanical qualities. The rotors of high-speed wind machines typically feature sixteen blades with an airfoils cross section. The blades are composed of metal, fiberglass, or dirty laminated wood.

The Blades: The wind-generated kinetic energy is transformed into mechanical energy via aerodynamic design, which uses the principles of lift and drag to transport the energy through the main shaft and ultimately transform it into electrical energy through the generator. Variables in the rotor blades include length, pitch, number of blades, and material. [31]

Effect on Number of Blades: Aerodynamic efficiency rises with an increase in a wind turbine's blade count. However, the efficiency increases by 3% when we go from two to three blades, but the efficiency improvement is negligible when we go from three to four blades. [34] Furthermore, the cost of the system rises as the number of blades does. To increase aerodynamic efficiency, we should use thinner blades while using more of them. However, if the blade has a thinner section at the root, it might not be able to withstand bending stress brought on by axial wind pressures.

Fig 5: Efficiency increases by number of blades.

The stability of the turbine is a key factor in the odd number blades used in modern wind turbine construction. When determining the machine's dynamic qualities, a rotor of odd number blades can be compared to a disk.

The angle of the attack: It is located between the airfoil's chord line and the flight direction. As the angle of attack increases, more lift is produced; however, when the angle of attack exceeds կı, the life of the airfoil decreases and this is referred to as the stall position. When a wind turbine's blades are in the stall position, their flat side faces the direction of the wind and they are not spinning. Conversely, furling reduces the angle of attack while simultaneously slowing down the blades' spin.

Number of Blades	Optimum TSR
2	Around 6
3	Around 4-5
4	Around 3
6	Around 2

The Length of Blade: The wind turbine's performance is influenced by the length of the blades; a longer blade will maximize power extraction. However, the deflection of the blade tip caused by axial wind force also rises with blade length. Therefore, failing to take into account the increased blade length could result in a dangerous tower and blade collision. [39]

The Hub: The hub is the part that connects the rotor and the nacelle, transmitting motion and the loads produced by the blades. Steel is typically used to make hubs, which can be cast or welded. Three primary types of hubs have been used in HAWTs.

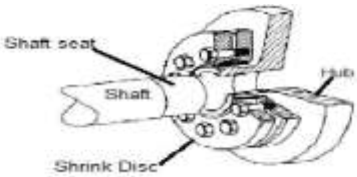


Fig 6: A Rigid Hub.

In addition, the Shrink Disc is made up of two discs and a ring, the outside of which is sharpened in both axial directions and whose interior surface glides over the hub projection's exterior. The two discs are fastened to one another with bolts after being positioned on opposite sides of the taper. The ring compresses as they approach one another, which further compresses the hub projection, which is then crushed and fastened to the hub. The hub is fastened to the permanent flange at the end of the shaft using bolts in the second technique. The flange may be integrated or added to the shaft.
Additionally, the teetering hubs need two different kinds of bearings: a thrust bearing and a cylindrical, radially loaded bearing. Each form of bearing is needed for every pin. For the pin axis, there are two cases: the first one is the first is that the cylindrical bearings will support the entire load when the pin axis is horizontal; in the second case, an axial component is present, mostly because of the weight of the rotor. That portion of the load will thus be supported by one of the thrust bearings. During usual operation, a teetering hub moves only

a few degrees back and forth. However, high winds or high yaw rates can cause greater teeter excursions. To control impact damage caused by these conditions, compliant stops, teeter dampers, and the hub's opposite-side dampers, with a maximum allowed choice of ± 7 degrees, are provided. [40]

Nacelle: This enclosure, which is especially crucial for the wind's electric systems, shields both the prime frame and the components that are fastened to it. On the other hand, the nacelle, which is attached to the rotor and resides at the summit of the tower, houses the gearbox, primary frame, and generator, among other essential parts of the wind turbine. The fiberglass nacelle shields the internal parts from the outside elements. The nacelle's cover is secured to the main frame, which holds up every other component inside the nacelle. The main frames are substantial metal constructions that have to be strong enough to resist the heavy fatigue loads.

Yaw Drive: Using a rotary actuator that engages on a gear ring beneath the nacelle, it rotates the nacelle with the rotor in accordance with the direction of the wind. Nonetheless, making sure the wind turbine is consistently providing the most electricity possible is a crucial part of the HAWT. The yaw drive comes in two primary varieties: 1. The Electric Yaw Drive: This is a standard component of all contemporary wind turbines. 2. Less often than not, new wind turbines use the hydraulic yaw drive.

Gearbox: The gearbox increases speed in accordance with the demands of the electric generator. Nonetheless, high speed shaft and the low-speed shaft were joined by gears, resulting in an increase in rotational speed from roughly 30 to 60 revolutions per minute (rpm) to roughly 1000 to 1800 rpm. This rotational speed is necessary for the majority of generators to generate energy.

Induction Generators: The induction generator is the most popular choice for wind energy system applications because of its longevity of over 50 years, ease of operation, and durability. In addition, the machine has a high-power output per unit mass of materials, flexibility in its operating speed range, and can function as both a generator and a motor without any modifications. The induction generator's primary disadvantages are its lower efficiency and the requirement for reactive power to raise the terminal voltage. Nonetheless, the contemporary design can increase the 28 efficiency, and solid-stat converters can be employed to provide the necessary reactive power. [41]

4. Operating Region of Wind Turbine

A variable-speed and variable-pitch wind turbine's power curve, which displays the projected power output as a function of wind speed as seen in Figure 3.11, can be used to depict the operational zone of the machine. This power curve displays three separate wind speed points:

5. Control of the Wind Turbine System

As wind turbines grow in size and capacity, their control system becomes increasingly important in keeping them operating in safe areas and enhancing their energy conversion efficiency and output power quality. A wind turbine control structure's primary goals are: - Energy capture: Taking into account safety constraints such as rated power and rated speed, the wind turbine is operated to harvest the most wind energy possible. - Power quality: Complying with grid connections regulations while conditioning generated power.

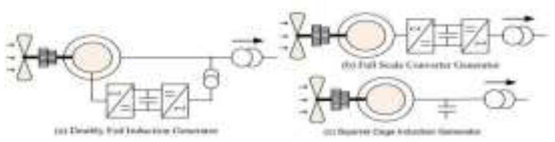


Fig 7: Electrical generators used in wind turbines.

Pitch control, stall control and yaw control are the three different control methods utilized in wind turbines. Pitch control, however, is the most widely used control technique in contemporary variable speed-variable pitch wind turbines. The horizontal axis wind turbine blades in this control method are oriented whichever upwind or downwind by rotating around the tower of the turbine. [43]

IV. AERODYNAMICS OF WIND TURBINE

The way that wind and rotor interact is what powers wind turbines to produce energy. One way to conceptualize wind is as a blend of turbulent variations surrounding the mean flow and the mean wind itself. The mean loading and power generation of wind turbines are primarily influenced by the aerodynamic forces produced by the mean wind, according to past observations. Elements such as off-axis winds, periodic aerodynamic forces resulting from wind shear, rotor rotation, randomly fluctuating forces due to turbulence, and dynamic effects influence the peak loads of a wind turbine. These are important, of course, but they also require knowledge of aerodynamics in steady-state operating. Thus, the focus of this chapter is mostly on steady-state aerodynamics. [44]

1. General Momentum Theory

The General Momentum Theory (GMT) of wind turbines, a fundamental concept in wind energy engineering, provides a theoretical framework for understanding the aerodynamic principles governing wind turbine operation. Developed in the early 20th century and refined over the years, this theory is based on the law of conservation of mass and momentum.

According to GMT, as wind flows through a wind turbine rotor, it experiences a decrease in velocity and an increase in pressure. This change in air velocity and pressure results in the extraction of kinetic energy from the wind, converting it into mechanical energy to drive the turbine's generator. The theory takes into account factors like blade geometry, airfoil design, and the overall turbine configuration to predict power output and efficiency. GMT forms the basis for modern wind turbine design and optimization. Engineers and researchers use it to develop advanced turbine models, ensuring maximum energy capture from the wind while decreasing structural loads and aerodynamic losses. Through GMT, the wind energy industry continues to innovate, driving the development of efficient, sustainable, and environmentally friendly power generation systems.

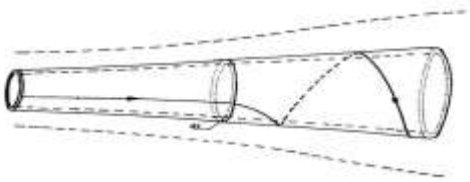


Fig 8: Streamtube model of flow behind rotating wind turbine blade

A key idea in wind energy engineering is the General Momentum Theory (GMT) of wind turbines, which offers a mathematical foundation for comprehending the aerodynamics of wind turbine operation. By taking into account the conservation of mass and momentum, GMT, which is based on the concepts of fluid dynamics, enables engineers to forecast the operation of wind turbines. One of the key equations in GMT is the momentum balance equation:

$$\rho\,{}^{2}{}_{1} = \rho\,{}^{2}{}_{2} + 2({}_{1} - {}_{2}) \qquad (4.1)$$

where p is the air density, A is the swept area of the rotor, V_1 and V_2 are the wind velocities before and after passing through the rotor, r is the radial distance from the rotor hub, dr is an infinitesimal radial thickness of the rotor, and P_1 and P_2 are the pressures on the upstream and downstream sides of the rotor.

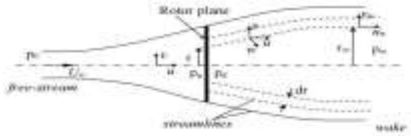


Fig 9: Geometry of the stream tube model of flow through a HAWT rotor

2. Blade Element Moment Theory

The general momentum hypothesis concentrated primarily on the forces acting on the blades and the motion of the fluid. The general momentum hypothesis was flawed in that it did not identify the kind of blade required to produce the reactions that were being studied. The basic tenet of the blade element theory was to consider the forces that the rotor's blades encountered throughout their motion through the air; hence, the geometry of the blade was a key component of this theory

Momentum Theory

The actuator disc theory can be applied when an axisymmetric, constant, and incompressible inflow of an inviscid fluid is assumed. By functioning as an actuator disc, the rotor plane maintains a constant flow velocity across the disc and reduces pressure equitably throughout the rotor region. The actuator disc theory, in its most basic form, posits that the velocity through the rotor plane does not possess a tangential component. Additionally, it asserts that the pressures immediately preceding and following the rotor are equivalent to the ambient pressure.

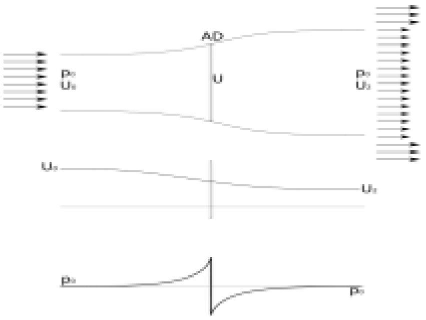


Fig 10: Blade momentum theory, pressure and velocity evolution.

3. Blade Element Theory

The loads operating on a rotor can be calculated by using the blade element theory by taking into account the geometric and aerodynamic characteristics of each span wise blade section. The blade is separated into portions that are dispersed radially in a discrete number. Assuming that the flow is locally two-dimensional and in the plane of the airfoil section, the stresses on each section are computed. This makes it possible to calculate sectional airfoil forces using two-dimensional lift, drag, and moment coefficients in addition to the relative flow velocity.

V. WIND TURBINE DESIGN

The complex process of designing wind turbine blades is explained in this chapter, which is an important aspect of the effort to maximize the extraction of wind energy. The methodological strategy used in this project makes use of QBlade, an open-source program known for its versatility and computing efficiency in enabling aerodynamic study. This chapter will carefully outline the stages involved in designing wind turbine blades via the lens of QBlade, with an emphasis on attaining the best possible performance metrics. The choice of an airfoil a crucial part of blade design will be the main focus. This chapter explores the careful procedure of selecting an airfoil and provides detailed graphical explanations to clarify the reasoning behind the choice. The benefits that come with the selected airfoil will be discussed in detail, giving readers a more sophisticated knowledge of the aerodynamic properties that lead to increased turbine stability and efficiency. [47]

1. Wind Blade Rotor Size

Wind turbines take the kinetic energy of moving air to generate electricity, and the length of their blades plays a crucial role in determining their power output. The relationship of power (*P*), air density (ρ), swept area (*A*), and wind speed (*V*) is encapsulated in the simple yet powerful equation:

In this equation, *P* represents the power output of the wind turbine, ρ is the air density, *A* is the swept area of the turbine blades, *V* is the wind speed, is the efficiency and Cp is the efficiency. To delve into the specifics of wind turbine design, understanding the swept area is essential. The swept area (*A*) is influenced by the rotor diameter (*D*), the circular area covered by the rotating blades. By employing the formula for the area of a circle, $A=\pi*(D/2)^2$, we can establish a connection between the rotor diameter and the swept area. Once armed with the swept area, the next step is to determine the length of the wind turbine blades. The blade length (*L*) is intrinsic to the efficiency and overall performance of the turbine. The relationship between swept area and blade length is encapsulated in the formula:

2. Selection of Airfoil

HAWT blades use airfoils to provide mechanical power. The cross-sections of HAWT blades are shaped like airfoils. The width and length of the blade are determined by the intended aerodynamic performance, the maximum planned rotor power, the projected airfoil characteristics, and strength estimates. Thus, creating HAWT blades requires an understanding of airfoil properties.

Selecting Greatness - The NACA 4412 Airfoil in Highlights: The choice of airfoil is crucial in the complex field of aerospace engineering since it affects an aircraft's efficiency and performance.

One specific airfoil in particular, the NACA 4412, stands out as a beacon of accuracy and adaptability in this quest for the best aerodynamic design. The NACA 4412 was selected over its competitors due to its unique geometric features and superior aerodynamic performance, which provide a pleasing balance that makes it stand out among the large selection of airfoils.

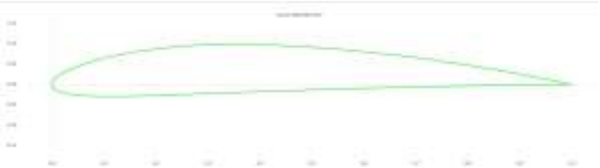
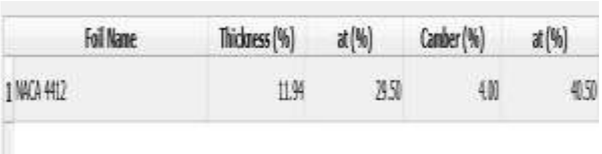


Fig 11: Airfoil Profile of NACA 4412

Detail in Design: The NACA 4412 airfoil represents a precisely designed geometry that has been refined via rigorous testing and study, not just a designation based on numbers. Careful engineering was used in selecting a 4% maximum camber that is positioned at 40% of the chord length and a 12% maximum thickness. The remarkable performance of the airfoil under a variety of flight situations is a result of its precise design.



	Foil Name	Thickness (%)	at (%)	Camber (%)	at (%)
1	NACA 4412	11.94	29.50	4.00	40.50

Fig 12: NACA 4412 airfoil data

Benefits Compared to Other Airfoils: In the aerospace industry, several airfoils compete for attention, but the NACA 4412 stands out because to a number of unique benefits. Because of its 4% camber, which effectively generates lift, it is appropriate for applications requiring exceptional low-speed performance. Maximum camber is placed strategically to improve control and stability, two essential components of an aircraft's safety and maneuverability.

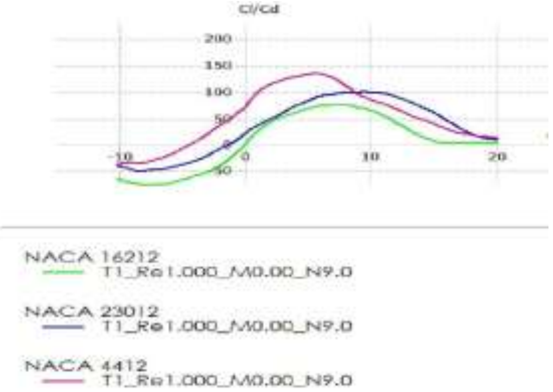


Fig 13: Comparison of different airfoil

According to the following simulation results, the NACA 4412 airfoil has the best lifting efficiency, making it easier for the windmill to revolve when used as a blade airfoil than the NACA 23012 and NACA 16-212 airfoils. [48]

3. Aerodynamic Data of NACA 4412

Reynolds Number: The choice of Reynolds number in aerodynamics and airfoil analysis is frequently impacted by practical factors and the intended use of the data. The Reynolds number, which is defined as the ratio of inertial forces to viscous forces, is a dimensionless quantity that describes the flow regime surrounding an airfoil. [49]

Polar Name
○ Set Automatic ● User Defined
NACA_4412_Re1.000_M0.00_N9.0
Reynolds and Mach
Reynolds 1000000 Mach 0
Transition Settings
N-Crit (e^N) 9
Forced top transition 1
Forced bottom transition 1

Fig 14: Chosen Reynolds number

Lift Coefficient CI: Like the NACA 4412, an airfoil's lift coefficient is a dimensionless coefficient that links the lift force the airfoil generates to its geometric and flow characteristics. Plotting the lift coefficient versus the angle of attack (α) yields a lift curve, which illustrates how lift changes with changes in the angle of attack.

Fig 15: Lift coefficient to angle of attack graph

The graph shows how the lift coefficient of a NACA 4412 airfoil increases as the angle of attack increases. The reason is when the angle of attack increases, the airfoil deflects the airflow more, creating lift. However, at a specific angle of attack known as the stall angle, the airflow over the airfoil separates from the airfoil surface, and the lift coefficient rapidly decreases.

Drag Coefficient Cd: Like the lift coefficient, the drag coefficient of an airfoil, such as the NACA 4412, is a dimensionless number that connects the airfoil's drag force to its geometric properties and flow circumstances. Usually, the drag coefficient is graphed against the angle of attack (α) to produce a drag curve that shows how drag varies with angle of attack

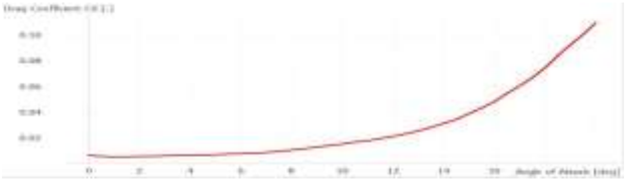


Fig 16: Drag coefficient to angle of attack graph

The graph shows the drag coefficient of the NACA 4412 airfoil against angle of attack. The graph shows how the drag coefficient of a NACA 4412 airfoil increases as the angle of attack increases. This is due to the fact that when the angle of attack increases, the airfoil deflects the airflow more, creating drag.

Pressure Distribution: The air pressure variations over the upper and lower surfaces of an airfoil at different sites are described by the pressure distribution surrounding the airfoil, like the NACA 4412. Understanding the distribution of pressure is essential to comprehending lift generation and aerodynamic performance. [50]

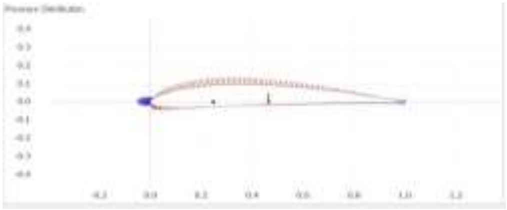


Fig 17: Pressure Distribution graph

Generating the Blade Design : To generate the blade geometry by QBlade, Tip speed ratio of 5 is selected to achieve the maximum result. [51]

	Pos [m]	Chord [m]	Twist [deg]	Foil
1	0	3.27674	49.05	NACA 4412
2	0.08789	3.51354	48.62	NACA 4412
3	0.17578	3.74253	48.19	NACA 4412
4	0.35156	4.17759	47.33	NACA 4412
5	0.70313	4.95952	45.65	NACA 4412
6	5.62500	8.09400	26.78	NACA 4412
7	22.50000	3.96997	6.05	NACA 4412
8	33.75000	2.78881	2.29	NACA 4412
9	45.00000	2.13694	0.31	NACA 4412

Fig 18: The length of the blade, chord length and twist angle is generated.

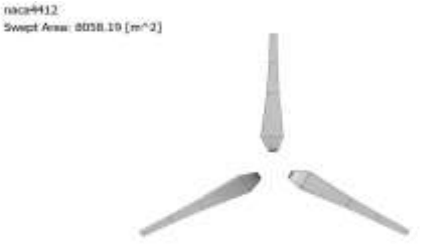


Fig 19: Model generated in QBlade.

3D Model Design in SolidWorks

Blade and Rotor: After generating the required data by QBlade, now proceeding to design the Blade in SolidWorks.

Fig 20:.3d model of wind blade

By importing the NACA 4412 airfoil data into SolidWorks and converting the curve line entities to different plane according to the data generated in QBlade, by using the loft command the generation of blade is done. The by circular pattern mirror two other blade is generated.

Nacelle: Nacelle is a crucial component of a wind turbine to house the rotor hub, the generator and the other components. The design has to be spacious and optimized to hold all the components.

Fig 21: Model of Nacelle

Max Length of the nacelle = 10m
Max Width = 9.5m
Max Height = 7.5m
Volume = 88.77 cubic meters

Wind Turbine Tower: Given that winds tend to rise with altitude, turbine towers are growing in height in order to harness more energy. Wind shear is the term for the difference in wind speed with altitude. Wind can flow more easily and with less resistance from surface-level obstructions like trees and other vegetation, structures, and mountains at higher altitudes.

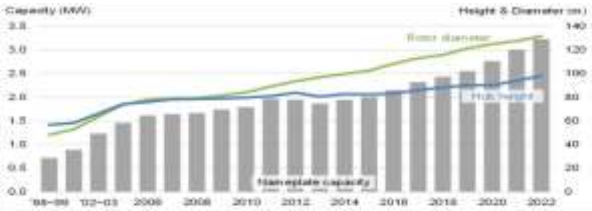


Fig 22: .Relation of height of tower and Capacity

The wind resource at a particular location is a primary factor influencing tower height. Taller towers can access stronger and more consistent wind speeds at higher altitudes. By choosing an 85-meter tower height, developers may be targeting specific wind regimes that are optimal for energy production.[52]

Fig 22: .Model of Tower

Tower Height = 85m
Top radius = 9m
Bottom radius = 10m
Inner top wall radius = 7m
Inner bottom wall radius = 8m
Volume = 2269.80 cubic meters

Generator: The generator is an essential component of a wind turbine. The wind turbine generator produces electrical energy by converting mechanical energy into motion as the blades spin. Compared to other producing units that are normally connected to the electrical grid, wind turbine generators are a little different. One explanation is that the wind turbine rotor, which provides the generator with its power, is a very variable source of mechanical power (torque).

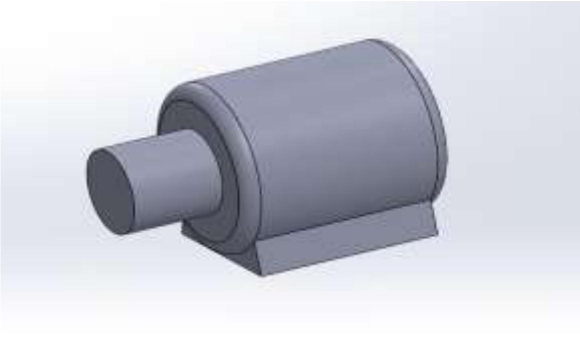


Fig 23: Model of Generator Parameters of the.

Generator modeled in SolidWorks.
Shaft length: 8m
Diameter of the generator body: 6m

Base Foundation: The foundation of a wind turbine is a critical element that provides essential support and stability to the entire structure. It serves as the anchor that bears the weight of the tower, nacelle, and blades, ensuring that the wind turbine remains securely in place. Beyond its primary function of structural support, the foundation plays a pivotal role in absorbing and distributing the various forces and loads exerted on the turbine, both statically and dynamically. A well-designed foundation is instrumental in preventing excessive vibrations, managing wind-induced stresses, and enhancing the overall structural integrity of the turbine. Furthermore, the foundation must be tailored to the specific characteristics of the site, considering soil conditions, geological factors, and environmental requirements. In essence, the foundation is a cornerstone of wind turbine construction, contributing significantly to the reliability, safety, and longevity of the entire system.

Fig 24: Model of Base Foundation

Simulation and Analysis

Introduction: Computational fluid dynamics, or CFD, is the process of using computer power to solve the governing equations and forecast physical fluid flow numerically. When an engineer has to develop a new product, like a race vehicle that will win the upcoming race season, aerodynamics plays a critical role in the overall performance of the design. However, measuring aerodynamic performance is challenging at the concept stage. Traditionally, the only method for an engineer to optimize his or her design is to test actual product prototypes. Moore's law has allowed computers to grow in power, which has led to a rise in the use of computational fluid dynamics (CFD) as a technique for predicting physical occurrences.

Computational Fluid Dynamics (CFD) History:

The human race has long been keen to explain its observations of fluid flow. In that case, how old is CFD? A significant limitation of CFD is its high computational cost, which hindered progress in the field until significant improvements in processing power resulted in cost and performance reductions. Until now, scientists and engineers had concentrated mostly on creating mathematical models and numerical approaches to reduce the cost of computation.

CFD Governing Equations:

The governing equations for thermo-fluids examination are extracted from the conservation law of the physical properties of the fluid. The three conservation laws are the fundamental equations.

- Continuity Equation for Conservation of Mass
- The Second Law of Newton: Conservation of Momentum
- Energy Conservation: The Energy Equation or First Law of Thermodynamics Continuity Equation The equation for the Conservation of Mass is stated as:

$$\frac{D\rho}{Dt} + \rho(\nabla \cdot \vec{v}) = 0$$

Where ρ is the density, $\vec{v}$ the velocity and ∇ the gradient operator.

$$\vec{\nabla} = \vec{i}\frac{\partial}{\partial x} + \vec{j}\frac{\partial}{\partial y} + \vec{k}\frac{\partial}{\partial z} \tag{6.2}$$

If the density is constant, the flow is expected to be incompressible and the continuity equation shrinks to:

$$\frac{D\rho}{Dt} = 0 \rightarrow \nabla \cdot \vec{v} = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{6.3}$$

The Navier-Stokes Equations' Ascent: The basic mathematical basis for all theoretical fluid dynamics models is provided by the Navier-Stokes equations, which characterize the motion of viscous fluid domains. The story of their discovery is an intriguing one. The famous Navier-Stokes equation was developed by two men who had never met, Sir George Gabriel Stokes (1819–1903) and Claude-Louis Navier (1785–1836). What an odd coincidence this is. Claude-Louis Navier's work was restricted to a subset of equations until 1822. Sir George Gabriel Stokes later improved and concluded the equations in 1845.

6.3.2 Navier-Stokes Equation: Conservation of Momentum which can be denoted to as the Navier-Stokes Equation is specified by:

$$\overbrace{\frac{\partial}{\partial t}(\rho\vec{v})}^{I}+\overbrace{\nabla\cdot(\rho\vec{v}\vec{v})}^{II}=\overbrace{-\nabla p}^{III}+\overbrace{\nabla\cdot\left(\bar{\bar{\tau}}\right)}^{IV}+\overbrace{\rho\vec{g}}^{V} \quad (6.4)$$

Where p is static pressure, τ ̅is viscous stress tensor and ρg ⃗ is the gravitational force per unit volume.

Here, it denote:

- I: Local change with time
- II: Momentum convection
- III: Surface force
- IV: Diffusion term
- V: Mass force

Viscous stress tensor τ ̅can be specified as below in accord with Stoke's Hypothesis:

(6.5)

If the fluid is expected to be incompressible with constant viscosity coefficient μ the Navier-Stokes equation simplifies to:

$$\tau_{ij}=\mu\frac{\partial v_i}{\partial x_j}+\frac{\partial v_j}{\partial x_i}-\frac{2}{3}(\nabla\cdot\vec{v})\delta_{ij}$$

$$\rho\frac{D\vec{v}}{Dt}=-\nabla p+\mu\nabla^2\vec{v}+\rho\vec{g} \quad (6.7)$$

Newton's First Law of Thermodynamics: The principle of energy conservation, which is the first law of thermodynamics, posits that any increase in heat or work applied to a system will lead to an equal and opposite increase in energy within the system:

$$dE_t=dQ+dW$$

where dQ is the heat added to the system, dW is the work done on the system and dEt is the increase in the total energy of the system. One of the common kinds of an energy equation is:

$$\rho\left[\overbrace{\frac{\partial h}{\partial t}}^{I}+\overbrace{\nabla\cdot(h\vec{v})}^{II}\right]=\overbrace{-\frac{\partial p}{\partial t}}^{III}+\overbrace{\nabla\cdot(k\nabla T)}^{IV}+\overbrace{\phi}^{V} \quad (6.9)$$

- I: Local change with time
- II: Convective term
- III: Pressure work
- IV: Heat flux
- V: Source term

Equations with partial differentials (PDEs): The relationship between the transport constraints that are involved in the entire activity, either directly or indirectly, is all that the mathematical model offers. Although each term in those equations has a unique effect on the physical phenomenon, parameter modifications must be considered in tandem with the numerical solution, which employs vector and tensor notations in addition to differential equations.

$$\frac{d^2x}{dt^2}=x\rightarrow x(t)$$

Where T is the single variable
Example of PDE:

$$\frac{\partial f}{\partial x}+\frac{\partial f}{\partial y}=5\rightarrow f(x,y)$$

Where both x and y are the variables
(6.11)

Discretization: A discretization-based technique called the numerical solution is used to get approximations for complex problems that analytical approaches are unable to solve. As demonstrated in Figure 4, discretization-free solution techniques only produce a precise but straightforward analytical answer. Furthermore, the quality of the discretization has a significant influence on the numerical solution's correctness. It is possible to specify widely used discretization techniques such boundary element, spectral (element) approaches, finite element, finite difference, and finite volume.

Mesh Convergence: Multitasking is one of the modern illnesses that frequently leads to failure or postponement. Thus, in order to accomplish goals, it is far more appropriate to have jobs that are scheduled, separated, and sequenced; this has also worked well for CFD. To make analysis easier, the solution domain is separated into a number of sub-domains, or cells. The configuration of these cells inside the computational framework is referred to as a mesh.

(6.8)

4. CFD analysis of the Wind Turbine in SolidWorks: Engineering simulation has advanced significantly with the ability to do Computational Fluid Dynamics (CFD) investigations within the SolidWorks platform. Renowned for its expertise in computer-aided design (CAD), SolidWorks smoothly incorporates computational fluid dynamics (CFD) capabilities, giving designers and engineers an extensive toolkit for assessing fluid dynamics in 3D models. The combination of CAD with CFD enables users to investigate the complex behaviors of heat transfer, fluid flow, and other important phenomena in addition to producing precise geometric representations.

Initialization for the Simulation: To initialize the simulation of the wind turbine first need to setup the computational domain. The specification of a computational domain is a critical aspect of setting up a Computational Fluid Dynamics (CFD) simulation. In this case the computational domain is defined as a cube with dimensions of 100m×100m×100m. This three-dimensional space encompasses the entire region in which the fluid flow or other phenomena of interest will be simulated

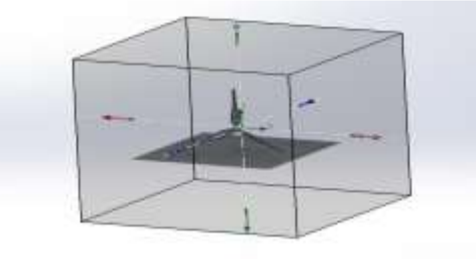


Fig 25: computational domain for the simulation

Boundary Conditions

Inlet Boundary Condition:

- **Type:** Velocity Inlet
- **Velocity:** 12 m/s in Z direction
- **Temperature:** normal temperature of the air (for example, 298 K298K or 25 °C25°C) Density: 1.225kg/m3

Outlet Boundary Condition:
Type: Pressure Outlet or Outflow

Wall Boundary Conditions:

- **Type:** No-slip Wall
- **Temperature:** adiabatic wall condition

Goals

- Average Velocity
- Total Pressure
- Force
- Torque

Meshing

Global Meshing is applied with uniform meshing.

Fig 26: Meshing of the model

Results and Analysis

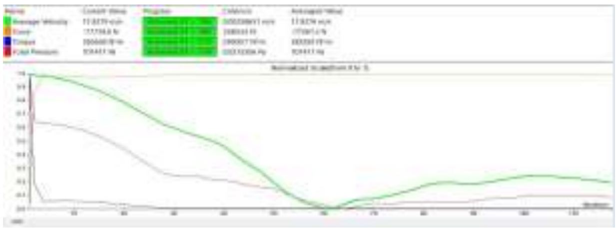


Fig 27: Iteration result of the simulation

The number of iterations the solvent completed is displayed in the figure. It comes out that the solution has converged in 120 iterations, but the solvent specifies 150 iterations to reach convergence. Velocity and pressure contours are visible once they have converged.

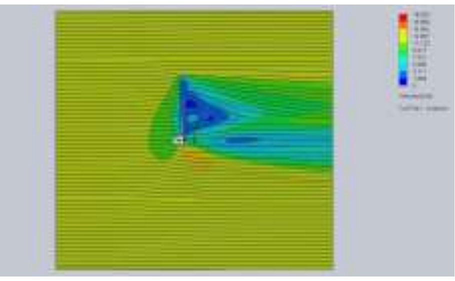


Fig 28: velocity contours

The color map shows that the velocity of the fluid is highest in the center of the flow field and decreases towards the edges of the flow field. The highest velocity in the flow field is approximately 18.553 m/s. The lowest velocity in the flow field is approximately 0 m/s.

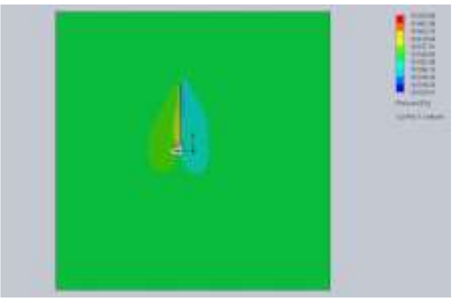


Fig 29: Pressure contour

The color map shows that the pressure of the fluid is highest in the stagnation region, which is the region of the flow field where the fluid is brought to rest. The stagnation region is located at the front of the flow field, just below the upper surface of the object. The pressure of the fluid decreases rapidly along the upper surface of the object, reaching a minimum at the trailing edge. The pressure of the fluid is lowest on the lower surface of the object. The pressure of the fluid increases along the lower surface of the object, reaching a maximum value at the trailing edge.

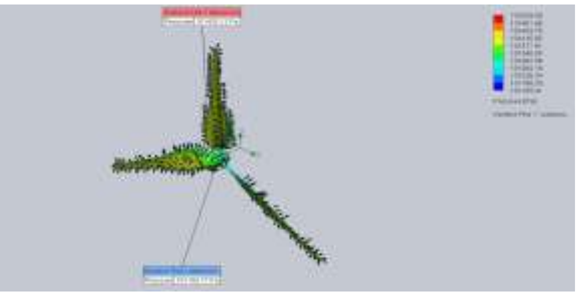


Fig 30: Pressure plot on blade surface.

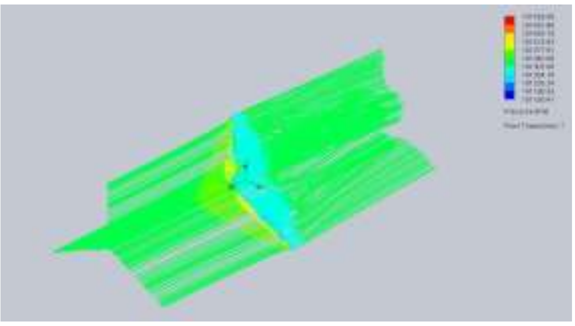


Fig 31:.Flow trajectory

A wind turbine blade's pressure distribution is significant because it influences the lift and drag forces acting on the blade. The force that propels the blade forward and starts the wind turbine's rotation is known as the lift force. The force that prevents the blade from moving is known as the drag force.

VI. CONCLUSION

In the realm of renewable energy, this thesis marks a significant stride forward by delving into the intricate design and computational fluid dynamics (CFD) analysis of a novel wind turbine. As we stand at the precipice of a pivotal era in energy evolution, the importance of renewable sources cannot be overstated. This research, focused on harnessing the inexhaustible potential of the wind, contributes to the broader narrative of transitioning towards sustainable and cleaner power solutions. The synthesis of innovative blade design and meticulous CFD analysis has provided valuable insights into the complex interplay of aerodynamics that govern the performance of wind turbines. Beyond the intricacies of the simulation models, this study underscores the broader significance of renewable energy in shaping our collective future. The global imperative to mitigate climate change and reduce dependence on finite fossil fuel resources propels renewable energy to the forefront of the energy landscape. Wind energy, in particular, emerges as a beacon of hope a source that not only capitalizes on the Earth's natural rhythms but also aligns seamlessly with the ethos of sustainability.

As we navigate towards a future where the demand for energy surges alongside our commitment to environmental stewardship, wind energy stands poised as a key player in the global energy portfolio. The designed wind turbine, with its optimized blade and validated CFD analyses, contributes not just to the academic discourse but holds practical promise for a world hungry for clean and efficient power solutions.

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