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NUST COLLEGE OF ELECTRICAL & MECHANICAL ENGINEERING

DESIGN, ANALYSIS AND FABRICATION OF LEADING EDGE TUBERCLES (LET) ON VERTICAL AXIS WIND TURBINE BLADE

A PROJECT REPORT

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Submitted by

HAROON UMER ABDULLAH

AHSAN SAEED

BACHELORS IN MECHANICAL ENGINEERING

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DR. TARIQ TALHA

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DECLARATION

- We hereby declare that this project titled "**Design, analysis and fabrication of Leading Edge Tubercles (LET) on the Vertical Axis Wind Turbine blade**" is solely done by our group under the supervision of Project Supervisor Dr. Tariq Talha.
- No portion of the work referred to in this Project Thesis has been submitted in support of an application for another degree or qualification of this of any other university or other institute of learning.
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Acknowledgement

We are very grateful to Almighty Allah that we are able to complete our Final Year Project along with the Thesis Report on the assigned time. The support of our parents and teachers was very helpful during the entire crucial period of struggles. Our sincere gratitude is to our supervisor Dr. Tariq Talha for his valuable guidance, direction and encouragement throughout the progress of this project and his precious time to help us achieve the goals of this project. We are grateful to all of those with whom, we have had the pleasure to work during this project.

ABSTRACT

The project analyzes the effect of Leading Edge Tubercle (LET) on a vertical-axis wind turbine. The Leading Edge Tubercles tend to decrease the wake region in a stream- lined body, resulting in reduced drag and avoid stall at higher angles of attack. First, NACA 0018 profile is selected. CFD analysis is done on simple NACA 0018 without tubercles on its leading edges. The results are validated. Then, Tubercles are made on the blade and CFD analysis is done. The results show a significant increase in lift to drag ratio of turbine blade with tubercles. To further increase the lift and reduce the drag cambered airfoil is used. For this purpose, unsymmetric airfoil DU06W200 is selected and its CFD analysis shows improved Lift and Drag coefficients compared to NACA0018. Then, in order to enhance the performance, different parameters of tubercles like wavelength, amplitude, angle of attack, altering span wise length of tubercles portions on the blade and camber of the airfoil are changed to study their effect on performance. The results suggest that LET enhances turbine performance by reducing vortex generation, wake region and increasing lift to drag ratio.

Key points:

Leading edge tubercles (LET), CFD, lift-drag ratio, NACA 0018, DU06W200, Vertical Axis Wind Turbine.

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P	Pressure
C_L	Coefficient of Lift
C_D	Coefficient of Drag
F_L	Lift Force
F_D	Drag Force
AOA	Angle of attack
CFD	Computational Fluid Dynamics

Chapter# 1

Introduction

The continuous improvement of this world is based on technological advancement which is directly related to the utilization of energy. The demand of energy is creeping up every day due to the increase of population, industrial and agricultural advancement. But the conventional energy sources are becoming limited which is ultimately making them more expensive.

Cleaner and more abundant alternative energy sources are needed. In addition to this, everyone is concerned about global climate change. This whole scenario is pushing the world to find alternative sources of energy. One such energy source is wind.

Harvesting wind energy is a socially responsible alternative to fossil fuels, but key challenges remain that must be overcome in order to access its full potential. One such challenge is the mitigation of performance losses within a wind farm due to turbulent wake interactions among individual wind turbines.

1.1 Sources of Energy Production

Energy production has always been on the agenda of all the countries, since each of them tries to develop new and efficient ways of energy production. Some of them use traditional energy generation techniques while most of them are shifting towards the latest green energy sources.

Coal, oil, and natural gas are the most common fossil fuels burned in power plants to produce electricity[1]. These fuels burn, producing carbon dioxide and other greenhouse gases that aid in climate change. On the other hand, clean energy sources like hydro, wind, and solar produce electricity without releasing greenhouse gases into the atmosphere.

1.2 Traditional Energy Sources

The traditional energy production techniques include following:

1. Nuclear Power Plants
2. Coal Power Plants
3. Gas Power Plants

1.2.1 Nuclear Power Plants

Nuclear energy is a type of energy that is generated through nuclear reactions[2], which release a significant amount of energy in the form of heat.

Because of worries about safety, waste management, and the possibility for nuclear accidents, nuclear energy is a contentious subject. Although not releasing greenhouse gases into the atmosphere, nuclear energy does produce radioactive waste that can be hazardous for thousands of years. Nuclear accidents might also happen at any time, which would be extremely dangerous for both the environment and human health.

While there are certain advantages to nuclear energy. The main disadvantage is that it has cost a lot of lives as a result of nuclear accidents, among those Chernobyl is the most prominent, while in terms of reducing greenhouse gas emissions and ensuring energy security, it is also a very contentious and dangerous technology

Fig 1. Nuclear Power Plant

1.2.2 Coal Power Plants

Two of the most popular designs of thermal power plants used to produce electricity are coal and gas-fired facilities. Fossil fuels, usually coal or natural gas, are used in these power plants to create heat, which is subsequently converted into electricity.

One of the most prevalent and accessible fossil fuels, coal has long been a significant source of energy. Being a major source of greenhouse gas emissions, coal power stations are responsible for about one-third of the world's carbon dioxide emissions. Other air pollutants released by coal burning include particulate matter, Sulphur dioxide, nitrogen oxides, and mercury, all of which can have detrimental effects on both human health and the environment[3].

1.2.3 Gas Power Plants

A cleaner substitute for coal, natural gas is a fossil fuel that has grown in popularity recently. Natural gas generates less greenhouse gas emissions and air pollutants per unit of energy than coal does. So, Natural gas is a comparatively clean-burning fossil fuel, generating fewer greenhouse gases and pollutants than coal or oil, which makes gas power plants attractive.

Gas power plants may also be constructed quite fast and readily scaled up or down to suit changing electrical demand. The utilization of natural gas as a fuel source, however, is still debatable because of worries about methane leakage during extraction, transportation, and storage. Natural gas is still a fossil fuel [4] and its use has an environmental impact in addition to contributing to climate change. However, building and maintaining gas power plants requires a large infrastructural investment.

1.3 Renewable Energy Sources

Although coal and gas power plants have played a significant part in providing for our energy needs, there is growing interest in switching to cleaner and more sustainable energy sources, such as renewable energy sources like solar and wind power[5]. The potential for these technologies to lessen the effects of burning fossil fuels on the environment, including greenhouse gas emissions, is very high.

To ensure a sustainable and dependable energy future, it is crucial to carefully weigh the advantages and disadvantages of these technologies and investigate alternatives, such as renewable energy sources. Renewable energy sources are in high demand not just only because of high carbon emissions but also due to the reason that there is a gradual hike in the prices of hydrocarbon fuels each year. So, there is a demand of cheap energy sources. These demands can be fulfilled by the following types of renewable resources.

The main types of renewable energy sources are:

1. Wind Energy
2. Solar Power
3. Hydro Power
4. Geothermal Energy
5. Biogas Energy

1.3.1 Wind Energy

Wind energy is the type of energy harvested from the moving wind. It is an appealing replacement for energy sources based on fossil fuels because it is a clean, sustainable energy source that doesn't emit greenhouse gases or other air pollutants. Wind turbines are used to generate wind energy. The rotor shaft of the turbine spins because of the wind's effect on the blades, which revolve.

Depending on the availability of wind resources, as well as other criteria like environmental effect and closeness to the grid, wind turbines may be built on land or offshore. When compared to offshore turbines, which can benefit from stronger and more reliable wind resources, onshore wind turbines are often less expensive to construct and maintain. On the other hand, offshore wind turbines are normally more expensive to install and maintain.

Fig 2. Wind Turbines

In order to produce wind energy as efficiently as possible, wind turbines are often constructed in wind farms, which are sizable clusters of turbines placed in strategic locations with abundant wind resources. Many utilities or independent power producers may own and operate wind farms, which can range in size from a few to several hundred turbines.

1.3.2 Solar Power

Solar power works by converting energy from the sun into power[6]. It is a source of energy that is renewable and may be used in a variety of ways. The energy that the sun emits towards the earth after millions of years of illumination is thought to be sufficient to power the entire planet for a year. The difficulty has been in finding a cost- and energy-effective approach to harness and use this energy.

Solar panels are the most popular means of capturing solar energy. Photovoltaic cells, which are used in these panels, turn sunlight into electricity. The panels are set up on rooftops or in open spaces so that they can maximize solar energy.

Homes, companies, and even entire cities can be powered by the electricity produced by the solar panels.

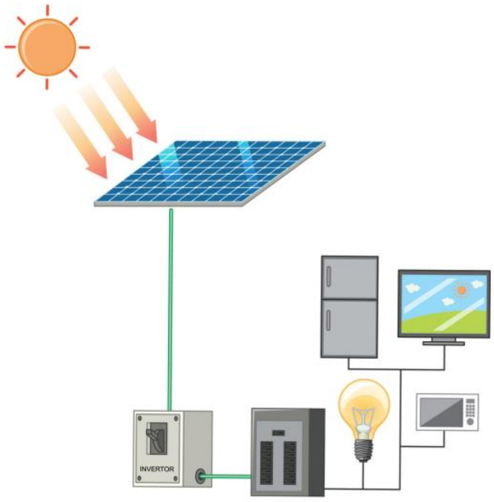


Fig 3. Solar Power

Solar Energy is a promising renewable energy source that has the potential to completely change how we produce and consume electricity. It seems expected that solar energy will play an increasingly significant part in supplying our energy demands in the future as technology advances and costs decline.

1.3.3 Hydro Power

Hydro Power is the most versatile method of energy production used worldwide for massive scale energy production. Hydroelectric power plants utilize the kinetic energy

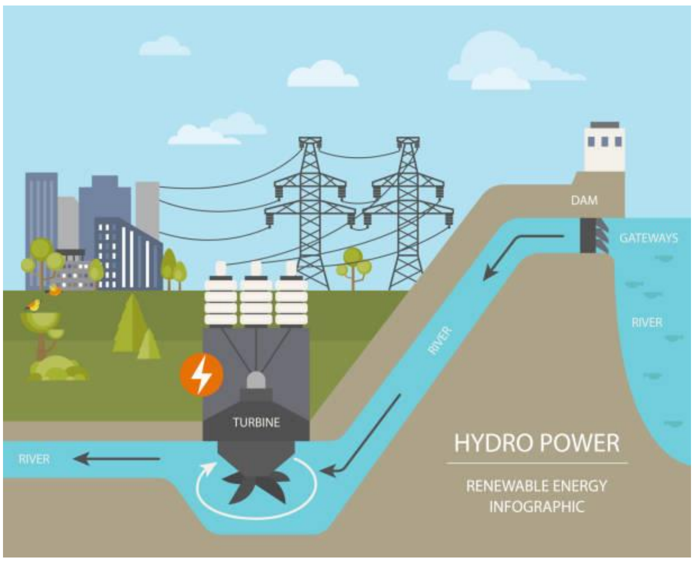


Fig 4. Hydro Power

of moving water to generate electricity. The water rotates the turbines as it passes through them, producing power.

Being a clean and renewable energy source is one of the benefits of hydropower. Hydro energy doesn't produce any emissions or waste materials that can affect the environment, in contrast to fossil fuels, which emit dangerous toxins when burned. Due to the water cycle's consistency and predictability, hydro energy is another dependable source of power. This means that hydroelectric power facilities can produce electricity continuously regardless of the weather or other variables.

Hydro electricity is not only safe and dependable, but also economical. The cost of producing electricity from hydroelectric power plants is very low, even though their original construction might be expensive. In the long run, hydroelectric power plants are a cost-effective alternative for producing electricity since they are long-lasting and require little maintenance.

1.3.4 Geothermal Energy

Geothermal energy is the thermal energy in the Earth's crust which originates from the formation of the planet and from radioactive decay of materials[7]. Geothermal power stations use geothermal resources with high temperatures to produce electricity.

The high temperature and pressure in Earth's interior cause some rock to melt and solid mantle to behave plastically[8]. The Earth's subsurface contains heat that can be captured using a variety of technological methods to produce electricity or heat structures. Geothermal energy is a clean, long-lasting energy source that can help lessen reliance on fossil fuels and greenhouse gas emissions[9]. In depths of 3-5 km, high-temperature resources can be found that are hotter than 150°C. Resources with a temperature range of 100 to 150 °C are found at depths of 1-3 km. Resources with low temperatures are those that can be discovered in depths less than one kilometer.

It is a clean, renewable energy source that doesn't release any greenhouse gases or other pollutants, so that's the first advantage[10]. Unlike fossil fuels, geothermal energy is a reliable energy source.

Drilling for and building geothermal power facilities can be expensive and necessitate a sizable initial outlay. Finally, although this danger can be reduced via careful site selection and monitoring, geothermal power plants can occasionally result in earthquakes.

1.3.5 Biogas Energy

Biogas energy is a type of renewable energy that is produced by the process of anerobic digestion of organic wastes. It is a flexible source of energy that may be used for cooking, heating, and producing power. Methane (CH_4) and carbon dioxide (CO_2) make up the majority of biogas, with small amounts of other gases like hydrogen (H_2), nitrogen (N_2), and hydrogen sulfide (H_2S). It can be created from a number of organic waste products, including wastewater, food waste, municipal trash, and agricultural waste.

The use of biogas energy has several benefits. Firstly, biogas is a form of renewable energy that is produced from organic waste. It lessens the amount of waste that is dumped in landfills, which lessens the smells and release of greenhouse gases. Secondly, biogas energy is a constant energy source that may be generated all year round. Finally, biogas energy is a flexible energy source that may be applied to a range of tasks, including the production of power, heating, and cooking. In vehicles powered by compressed natural gas (CNG), it can also be used as fuel.

1.4 Energy Harvesting Techniques

Energy harvesting techniques are the strategies to collect and transform minute amounts of energy from numerous environmental sources into useful electrical energy. Low-power electronic gadgets can be powered using these methods without a constant source of electricity.

Techniques for harvesting renewable energy are comprised of taking advantage of energy from natural sources including sunlight, wind, and temperature variations.

1. Wind Turbines
2. Solar Panels
3. Tidal Turbines

Solar energy harvesting contains the procedure and apparatus to utilize solar panels or photovoltaic cells to collect and transform solar energy into electrical energy. Wind energy harvesting entails utilizing wind turbines to capture the kinetic energy of the wind and transform it into electrical energy.

1.5 Wind Turbines

Wind turbines are devices used to harvest the kinetic energy of the wind to produce electricity. They consist of a rotor connected to a generator by a set of blades.

The rotor is spun to produce electricity as the wind blows, which rotates the blades. Either houses and businesses can be directly powered by the energy produced by the turbine, or it can be put into the electrical grid for distribution to a larger area. To produce power without pollution, wind turbines are a source of renewable energy.

1.6 Types of Wind Turbines

Wind turbines can be classified in several ways, on the basis of following categories:

1. Axis of the turbine
2. Impact of air on the blades
3. Direction of wind

1.6.1 Axis of Wind Turbine

Based upon the axis, following are the most common types of wind turbines.

1. Horizontal Axis Wind Turbine
2. Vertical Axis wind turbine

1.6.1.1 Horizontal Axis wind turbines

Horizontal Axis wind turbines are the most common type of wind turbines. Horizontal axis wind turbines utilize the aerodynamic lift force to rotate the rotor blade similar as an airplane flies[11]. Generally, the aerodynamic lift force works once they exposed to winds around both the higher and lower segments of a blade. The pressure difference which is formed between the top & bottom faces of the blade generates a force in the top direction of the blade. The horizontal axis wind turbine line diagram is shown below[12].

Fig 5. Horizontal Axis Wind Turbine

1.6.1.2 Vertical Axis Wind Turbine

Vertical axis wind turbines (VAWT) are one of the types of wind turbines for which rotors rotate a shaft that is installed vertically[13]. No matter what direction the wind blows, the blades would still move and rotate the shaft to produce power.

They are less susceptible to variations in wind direction, which is one benefit that VAWTs have over conventional horizontal axis wind turbines (HAWTs). For best effectiveness, HAWTs are often required to face straight into the wind. This calls for a sophisticated yaw system that monitors wind direction and modifies the turbine's orientation as necessary.

The low noise profile of VAWTs is an additional benefit. Due to the rapid speed of their blades, HAWTs make a lot of noise, which can be an issue in residential areas. VAWTs, in contrast, are quieter because their blades move more slowly and are located closer to the ground, which lessens the noise they make.

1.7 Types of Horizontal Axis Wind Turbines

Horizontal axis wind turbines can be further classified as

1. Upwind Turbine
2. Downwind Turbine

1.7.1 Upwind Turbine

An upwind turbine is a type of wind turbine where the rotor is positioned in front of the unit. These are the turbines which produce energy by rotating when air strikes their blades from front. The position is similar to that of propellers used in airplanes. Most of the wind turbines used commercially are upwind turbines.

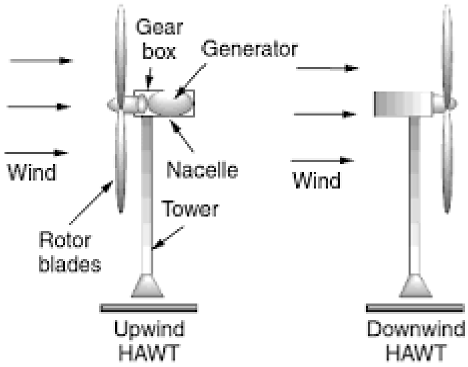


Fig 6. Upwind and Downwind Turbines

1.7.2 Downwind Turbine

The downwind turbine has its rotor on the back of the turbine. The nacelle is typically designed to seek the wind, thus negating the need for a separate yaw mechanism[14]. In this type of wind turbine, air usually strikes the blades from back direction.The figure shows a comparison of upwind and downwind turbine.

1.8 Types of Vertical Axis Wind Turbines

Vertical axis wind turbines can be further classified as

1. Darrieus Turbines
2. Savonius Turbine
3. Helical Blade Darrieus Turbine
4. H- Rotor Darrieus Turbine
5. Squirrel Cage Darrieus Turbine

1.8.1 Darrieus Turbine

Darrieus wind turbines in contrary to the Savonius wind turbines are of the lift-type VAWTs, in which the idea of lift production of airfoils has been implemented. These types of wind turbines are the most widely used type of vertical axis wind turbines for power generation with curved blades, C-shaped, that go from the top of tower to the bottom where it is connected to the generator shaft. They have good efficiency because they rotate at higher speeds that could generate more power.

Fig 7. Darrieus Wind Turbine

1.8.2 Savonius Turbine

The force that makes Savonius turbines turn is drag, which makes them drag-type VAWTs. The idea of their design is pretty much like cup anemometers. In cup anemometers, such as the one below, there is always a cup facing the wind experiencing the most drag exerted on its surface, while other cups have their other round-shaped and hence drag-lowering surfaces facing the wind.

Fig 8. Savonius Wind Turbine

1.8.3 Helical Blade Darrieus Turbine

The helical blade Darrieus turbine is a type of vertical-axis wind turbine (VAWT) that is based on the Darrieus turbine design. Yet unlike a conventional Darrieus turbine, which has straight airfoil blades, the helical blade Darrieus turbine features curving blades that are fashioned like a helix or twisted ribbon.

Fig 9. Helical Darrieus Wind Turbine

Several of the drawbacks of conventional Darrieus turbines, such as their low efficiency and high levels of vibration and noise, are expected to be addressed by the helical blade design. The helical blade Darrieus turbine's curved blades are made to generate a more effective lift and decrease drag, increasing overall efficiency and power output.

Due to less vortex shedding and turbulence than with straight blades, the helical blade design contributes to a reduction in vibration and noise. Since noise and vibration levels must be kept to a minimum, the helical blade Darrieus turbine is more suited for usage in residential areas and other settings.

1.8.4 H-Rotor Darrieus Turbine

The Darrieus turbine that has straight blades is called H-rotor Darrieus turbine. The H-rotor system has straight and vertical blades instead of standard shapes that have curved blades of the Darrieus turbine.

The H-Darrieus turbine is more durable and less prone to damage than other kinds of wind turbines since it can function effectively in turbulent and gusty wind conditions. The H-Darrieus turbine's modest size also enables installation in confined areas like roofs and small wind farms. Due to its ability to produce power at low wind speeds, the turbine is appropriate for usage in residential and urban locations where wind speeds are often lower.

Fig 10. H-Rotor Darrieus Wind Turbine

1.8.5 Squirrel Cage Darrieus Turbine

The main advantage of Squirrel cage wind turbine is that it can be operated at low wind conditions. Unlike conventional horizontal axis wind turbines (HAWT), which need winds of at least 10 miles per hour to begin producing electricity, the Squirrel Cage Darrieus VAWT can produce power in winds as low as 4 miles per hour. Because of this, it is the perfect option for places with modest wind speeds, like cities or places with erratic wind patterns.

The Squirrel Cage Darrieus VAWT's small size is another benefit. It has a smaller footprint than HAWTs, which need wide open spaces because it is installed vertically. In urban or suburban settings with limited space, this makes installation simpler.

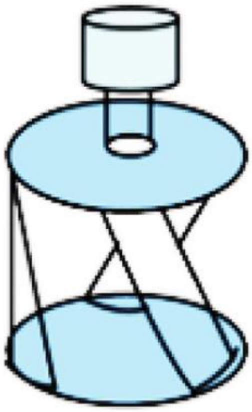


Fig 11. Squirrel Cage Turbine

Some other concepts are also gaining momentum, such as SheerWind's INVELOX that first collects air from different directions, funnels it to a section that reaches a Venturi, inwhich a turbine with a higher frequency than conventional HAWTs is placed.

Fig 12. Sheerwind's Invelox

1.9 Contribution of Different Energy Production Sources

Depending on the place, nation, and historical period, different energy production sources make up varied portions of the overall energy production. The International Energy Agency (IEA) projects the following breakdown of energy production sources for 2021, however, on a worldwide scale:

Until 2021, almost 84% of the world's energy was produced from fossil fuels (Oil, Coal, and Natural Gas). The largest contributor is oil, accounting for 33%, followed by coal (27%), and natural gas (24%). Till 2021, renewable energy sources (which include Solar, Wind, Hydro, Geothermal, and Biomass) made up around 11% of the world's energy output. The largest contributor, at 6%, is hydroelectric power, which is then followed by wind and solar energy. As of 2021, nuclear energy accounts for about 4% of the world's energy generation.

1.10 Motivation

Wind energy has the potential to resolve the power demand of the entire world if it can be converted into electricity efficiently. Wind is going to be the most popular alternative energy source, because of its availability throughout place and time. As a pollution free and sustainable source, wind is getting importance in energy policy too. The disadvantages are its lower efficiency and high installation cost. But the ultimate cost would be lowered if it operates continuously and small-scale turbines can be installed in any corner of the world. As a result, they can now be put in areas that were previously inappropriate for wind turbines, including cities or places with little wind.

Reduced environmental effect of energy production is another reason for studying tubercle turbines. Production of energy using fossil fuels plays a significant role in greenhouse gas emissions and climate change. Alternatives to fossil fuels that are cleaner include renewable energy sources like wind power. Traditional wind turbines, however, have the potential to harm the environment by destroying habitat and killing off birds and bats. These effects can be lessened and the shift to a low-carbon energy future sped up with the development of more effective and environmentally responsible wind turbines, like tubercle turbines.

Fig 13. Humpback Whale flippers with Tubercles

Furthermore, applying biomimetic design concepts may lead to wind turbines that are more efficient and quieter, easing concerns about noise pollution and the aesthetic impact of wind farms.

Recently, the Tubercles on the Leading Edges of humpback whale flippers have drawn the attention of researchers working in the field of tidal energy and wind energy, as these round protuberances along the leading edges have the ability to delay the stall and improve the lift-to-drag ratio of blades. The figure above shows the humpback whale flippers.

Some other applications of leading edge tubercles include Compressor blades, fan blades of laptop cooling systems etc.

1.11 Research Gap

The world is running out of resources. There is a high demand to shift towards renewable energy sources. Fossils fuels are not only decreasing on daily basis, but they are also a massive source of emission of carbon and other harmful gases. These gases are causing global warming. Due to which the temperature of the earth is rising gradually. The purpose of this project is to optimize the design of wind turbines for maximum output. Critical parameters for the VAWT with tubercles would be analyzed in this project.

Use of leading edge tubercles, which have shown promise in raising the efficiency of horizontal axis turbines, is one potential remedy. Even though research on adding tubercles to VAWTs has been done, more work has to be done to understand how tubercles affect VAWT performance and how to best use them in particular applications.

Little research has been done on applying tubercles to VAWTs, but there have been some encouraging outcomes. For instance, according to a study [15] by Chang and Kang (2014), adding tubercles to a VAWT boosted power production by 5.5% when compared to a design with a plain blade. Similar findings were made by Syed Saddam ul Hassan (2023), who discovered that a VAWT with tubercles performed better at startup than a VAWT with a smooth blade. One area of study is the ideal design of tubercle for VAWTs. Although studies have demonstrated that tubercles can improve performance, it is still unclear what the ideal tubercle size and shape should be for various VAWT setups. For instance, the Reynolds number, blade shape, and attack angle can all have an impact on the ideal tubercle design. To find the ideal design parameters for tubercles on VAWTs, more investigation is required.

Chapter#2

Leading Edge Tubercle on Turbines

In order to understand the concept of leading edge tubercles, first there is a need to know about the edge of airfoil. Some basic terminologies to understand the concept are below.

2.1 Leading and Trailing Edge

The airfoil of a wind turbine has two type of edges named as Leading edge and Trailing edge. The front edge of the airfoil is basically termed as leading edge, while the rear edge where the flow separates from the body is known as trailing edge. The shapes of leading and trailing edges of the airfoils play a significant role in the generation of lift and drag forces.

2.2 Chord

The straight line between leading edge and trailing edge of blade is called chord. Chord length plays an important role in improving the aerodynamic characteristics of airfoil.

2.3 Span

The maximum length of turbine blade is called Span.

2.4 Camber Line

A curved line drawn exactly in the center of upper and lower surfaces of airfoil or blade is called mean camber line.

2.5 Camber

The distance between chord line and mean camber line is called camber.

Camber may be either zero, positive or negative. All the symmetric airfoils have zero camber.

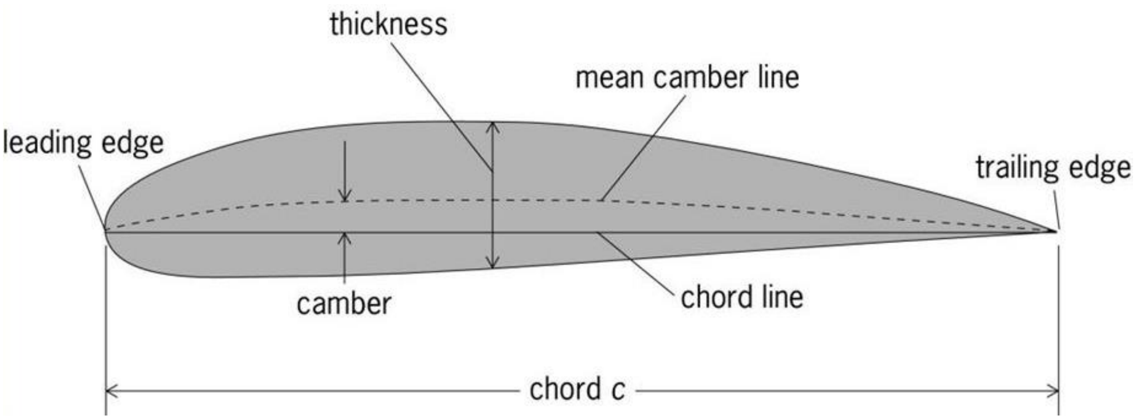


Fig 14. Airfoil Description

2.6 Stall

The sudden decrease in the lift force or lift of airfoil is called Stall. It occurs when the drag is increased or when the flow separation causes an induced wake region behind the airfoil. It reduces the lift to drag ratio and causes loss in efficiency of airfoil.

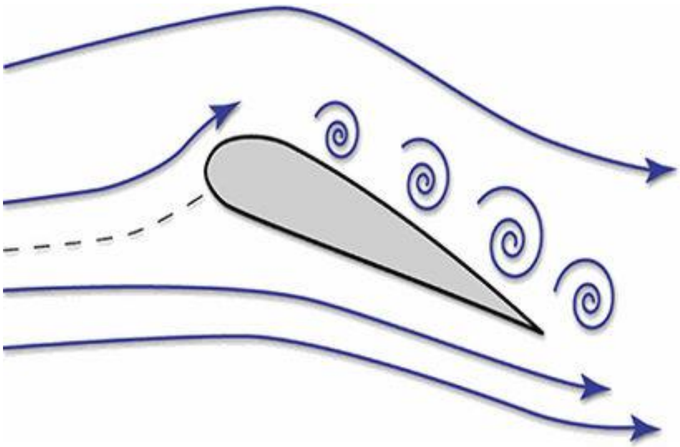


Fig 15. Stall

2.7 Wake Region

The region behind the airfoil where vortices are produced is known as wake region. It is the region of disturbed flow (often turbulent) downstream of a solid body moving through a fluid, caused by the flow of the fluid around the body.

2.8 Angle of Attack

The Angle of Attack is the angle at which relative wind meets an Aero foil. It is the angle formed by the Chord of the aero foil and the direction of the relative wind or the vector representing the relative motion between the aircraft and the atmosphere.

2.9 Stagnation Point

The point on the leading edges of airfoils where flow streamlines start separating above and below the aero foil is called Stagnation Point.

2.10 Flow separation and Lift to Drag Ratio

Flow separation generally occurs, when the airflow over an aerofoil separates from the airfoil's surface and forms a low-pressure area behind it. This low pressure region lessens the lift produced by the airfoil and raises the drag, or airflow resistance.

In case of wind turbines, flow separation occurs, when the angle of attack of the blade is too high, which can happen when the blade is rotating too fast or when the wind speed is too high.

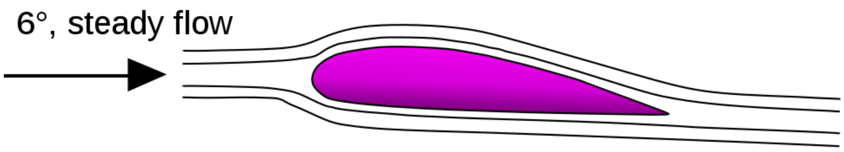


Fig 16. No flow separation at less angle of attack

When the angle of attack increases, the airflow over the airfoil adjacent to the airfoil starts separates from the surface. At this point aerofoil has the maximum lift and least drag.

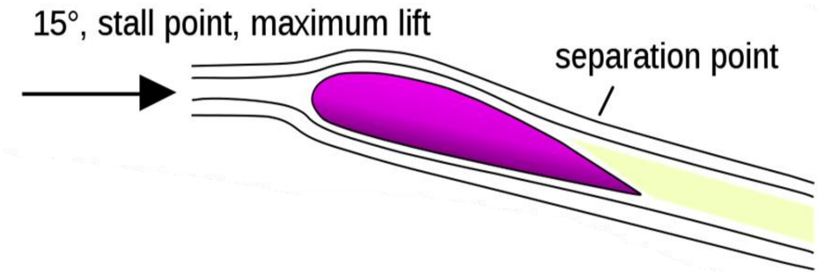


Fig 17. Standard angle of attack for maximum Lift

When the angle of attack is too high, the airflow over the airfoil becomes turbulent and the boundary layer of air adjacent to the airfoil separates from the surface.

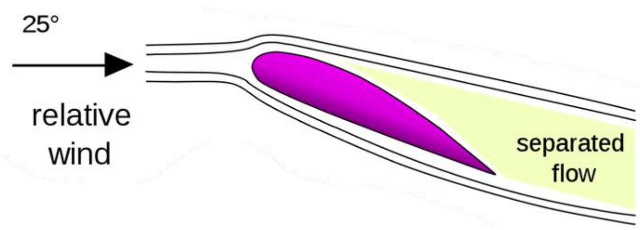


Fig 18. Increased Angle of attack with Flow separation

This Flow Separation creates a low pressure region behind the airfoil, which reduces the lift generated by the airfoil and increases the drag.

Flow Separation is undesirable in wind turbines because it lowers the efficiency of turbines and may potentially harm the blades. By delaying flow separation with the help of Leading edge tubercles, there may be an improved lift and decreased drag of airfoil, resulting in a higher power output and longer blade lifespan.

2.11 Leading Edges Tubercles

Leading edge tubercles are small bumps or protrusions found on the leading edges of some wings and fins. They can also be defined as triangular patterns made on the leading edge of aerofoil. They appear as sawtooth blades and are named after the tubercles found on the leading edges of humpback whale flippers, which are thought to improve their maneuverability and agility in the water.

In aerodynamics, leading edge tubercles are believed to enhance the lift and stability of wings and fins. They disrupt the formation of turbulent airflow over the surface of the wing or fin, allowing for smoother, more efficient airflow and reducing drag. This can improve the performance of aircraft, wind turbines, and other systems that rely on lift and propulsion.

With the depletion of the traditional fossil energy sources, protection of energy reserves has been high on the agenda of many governments. Massive investment has been made in the renewable energy field to exploit sustainable energy resources.

Leading edge tubercles have been studied extensively in recent years, and researchers are still exploring their potential applications and benefits. Some of the most promising areas of research include using tubercles to reduce the noise and vibration produced by wind turbines. They are used to improve the efficiency of turbines.

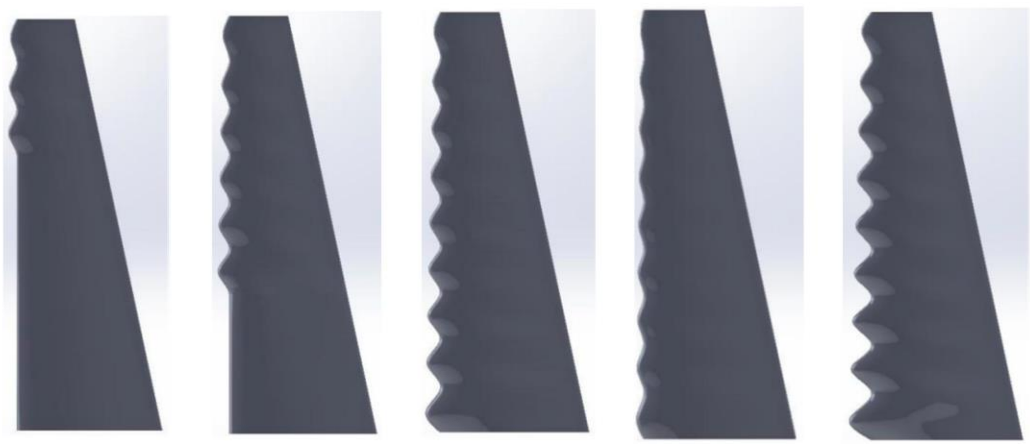


Fig 19. Wind Turbine Blades with Tubercles

There are different parameters of Tubercles which can be changed to improve the performance of wind turbines. Some of the important parameters are listed below.

1. Wavelength of Tubercles
2. Amplitude of Tubercles
3. Chord Length of blades
4. Angle of attack of turbines
5. Span Length of turbine etc.

The following figure shows these characteristics of an aerofoil, which can be altered to increase the performance of these turbines.

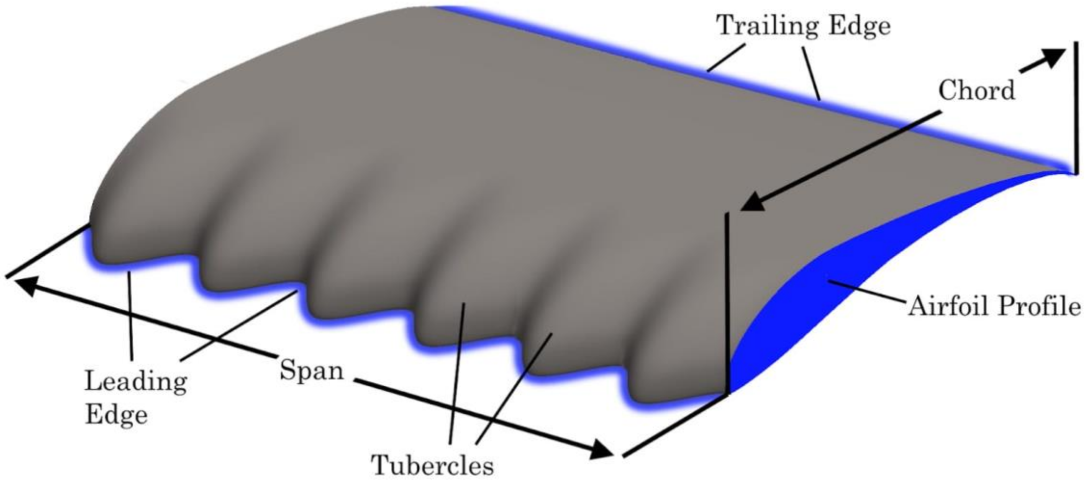


Fig 20. Tubercle Characteristics

2.12 Why VAWT for this Project

The basic purpose of this project is to apply tubercles on leading edges of a wind turbine blade. There was an option to select horizontal or vertical axis wind turbine. We had done literature review and studied about leading edges on HAWTs and VAWTs. The studies showed that there is lot of work done on applying leading edges to HAWTs. There was a need to do research in applying this concept to VAWTs. Therefore, we selected vertical axis H-Darrieus wind turbine and applied tubercles on it.

In VAWTs, the blades rotate around a vertical axis, while in HAWTs, the blades rotate around a horizontal axis. Leading edge tubercles have been found to be more effective in VAWTs because they help to increase the blade's angle of attack and maintain it at higher wind speeds. This results in better lift generation and higher power output. On the other hand, in HAWTs, the blades rotate in a plane perpendicular to the wind direction, which makes the application of leading edge tubercles less effective.

Additionally, the complex motion of the blades in HAWTs makes the implementation of leading edge tubercles more difficult and may not be worth the effort.

In contrast to HAWTs, VAWTs have a different aerodynamic profile. VAWTs operate in a three-dimensional flow environment with a changing angle of attack, whereas HAWTs work in a two-dimensional flow regime with a largely constant angle of attack. The risk of flow separation and stalling in VAWTs arises from the varying angle of attack, which can diminish lift and increase drag. But, by giving the blades leading edge tubercles, the flow separation can be postponed and the lift increased, leading to a greater output of power.

Moreover, VAWTs are frequently utilized in urban and residential areas where buildings and other barriers can cause the wind speed and direction changeable after some time. The VAWTs can generate power at lower wind speeds and keep their high power output even when the wind is often changing directions because to the usage of leading edge tubercles.

2.13 How is a lift produced?

A VAWT generates lift when the wind passes over its airfoil-shaped blades. A low pressure zone is created on the upper surface of the blade and a higher pressure region is created on the lower surface of the blade when the wind passes over the curved surface of the blade. A lift force that acts perpendicular to the direction of the wind is produced by this pressure difference. The blades revolve around the vertical axis due to the lift force they provide.

As the fluid flows around, the airfoil experiences two types of stresses i.e., Wall shear stresses and Pressure distribution shear stresses.

a) Shear Stresses

They act tangential to the airfoil surface and are caused be the viscosity of the fluid and friction between fluid and airfoil surface.

b) Pressure Stresses

They act perpendicular to the object surface.

Lift is created by the help of both shear and pressure distribution stresses around the airfoil. It can be found by

1. Bernoulli’s Principle
2. Newton’s Third Law

2.13.1 Bernoulli’s Principle

Bernoulli’s Principle explains that there is stagnation point at the leading edge of airfoil which experiences maximum air pressure, here the velocity of fluid reaches to zero and causes flow separation. The fluid passing on the above surface of the airfoil has higher speed while o the lower speed it has lesser speed. According to the Bernoulli’s Principle, where the speed is high pressure will be low and vice versa. Thus, the pressure on the upper surface of the airfoil is minimum and pressure below is higher. This pressure difference helps in creating an increased Lift Force.

There may be a situation when the flow above and below the surface of airfoil is parallel while leaving the trailing edge of blade. This condition is known as Kutta Condition.

2.13.2 Newton’s Third Law

Newton’s Third Law explains that the lower surface of airfoil creates downwash. So, in reaction to this, airfoil produces an opposite force in upward direction. Many research works have proved that increasing the camber of airfoil helps in increasing the lift to drag ratio. There may be another option of increasing the angle of attack. But there are some restrictions to this concept, because if the angle of attack increases a certain limit, the boundary layer doesn’t remain further attached to the surface, causing separation of flow and produces a wake region behind the airfoil to reduce lift and increase the drag. there may be decrease in the lift force which will directly impact the coefficient of performance of turbines.

Generally, Lift force can be find by using the following equation,

$$F_L = \frac{1}{2} C_L \rho A V^2 \qquad \text{Eq 2.1}$$

2.14 Recent Theories about Lift

There have been some other recent theories which explain that the action reaction concept of newton, pressure difference effect of Bernoulli’s Principle and viscosity effects are not solid enough to explain the cause of lift. Several recent theories with good results have shown that there is a need to modify the curriculum. Some of the most prominent among these theories are:

1. Variational Theory of Lift by Haithem E. Taha [16]
2. NASA theory of lift

2.15 Power Calculations of Turbines

Power of turbines converted from mechanical energy of air to electrical energy can be found by several ways. One of these methods is as blade element moment theory.

2.15.1 Blade Element Moment Theory

It is a 2D analysis approach which can be used to find the power of turbines with lesser blades. The air used by each of these blades is assumed to be unaffected by other blades. If we increase the number of blades, then all blades become less effective due to the wake region created by each of the blade moving ahead of the previous. Therefore, BEMT becomes unable to find the loss of performance by crowded rotor. BEMT helps in preliminary design of turbine blades. It can be used to find the optimum number of blades for turbines, twist in horizontal axis wind turbine blade and chord length.

The turbine rotates due to resultant of two components, Thrust and Torque. These can be found by following equations:

$$\delta Q = (\delta L\ Sin\phi - \delta D\ Cos\ \phi)r \qquad \text{Eq 2.2}$$

$$\delta T = (\delta L\ Cos\phi + \delta D\ Sin\ \phi)r \qquad \text{Eq 2.3}$$

When,

Q represents Torque

T represents Thrust

L is Lift Force

D is Drag Force

The total power can be found by using the relation:

$$P = QN \qquad \text{Eq 2.4}$$

When,

P is Power

Q is Total Torque

N is Rotational speed

2.16 Velocity Triangles of Aero Foil

Since, we have selected vertical axis wind turbine, so following diagram shows all the incident and resultant forces on the aero foil.

Where: from [17]

a = interference factor

R* = Resultant Consequential Force

R = Radius of Turbine

α = Angle of attack

ωR = Tangential Velocity

w = Resultant applied force

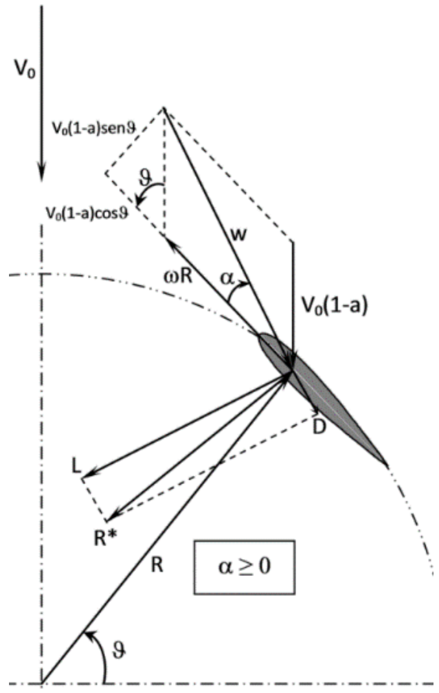


Fig 21. Velocity Triangles of airfoil

2.17 Results Extracted from Literature Review

So, far the literature review suggests that there is a high potential to decrease flow separation and drag at higher angles of attack using tubercles on the leading edges of blades. Leading edge tubercles avoid stall at higher angles of attack and thus Increasing Lift to Drag ratio. Moreover, Camber and Angle of attack are the main parameters to increase the lift generated by an airfoil having tubercles.

During this project, we followed a research article and validated its results. Therefore design parameters like chord length, span, angle of attack are taken from that research article, attached in the reference[], and then we applied different changes to its parameters and obtained optimized results.

Chapter#3

CAD Modelling

This chapter explains the CAD Model and different types of analysis done during the progress of project. Design parameters, Finite element analysis and CFD analysis done in the project are discussed briefly in this chapter. Airfoil selection, Model preparation, and result contours of all these analysis are shown graphically.

NACA four digit series airfoils are most commonly used to make blades of H-Darrieus VAWT.

3.1 NACA 0018

The NACA 0018 is symmetrical airfoil, which means that both of its upper and lower surfaces have the same shape. During this project, the design of turbine blade was started from simple NACA 0018 airfoil.

3.2 Software used in Designing

Since the project is related to design and analysis of leading edge tubercles, we needed designing and simulation software.

3.2.1 SOLIDWORKS

For the designing of the project, we used SOLIDWORKS. The coordinates of NACA 0018 are inserted in the SOLIDWORKS. And after completing its sketch the geometry is extruded. In order to do some analysis on it, step file is generated and exported in ANSYS WORK bench's FLUENT Module.

3.2.3 KEYSHORT

KEYSHORT is used for getting high quality rendered images. After completing the CAD Designing and CFD analysis, in order to show model for demonstration purposes, KEYSHOT is used to get high quality rendered images of the model.

3.3 Airfoil Design

In the first step of designing, simple NACA airfoil was created, which is shown in the below section:

3.3.1 NACA 0018 Airfoil

After inserting excel file of NACA 0018 coordinates, the model of airfoil is generated. During the first step, simple airfoil without leading edge tubercles is created for which the chord and span length are fixed according to the research article we followed.

Fig 22. NACA 0018 Profile

In order to start the working on project, the first thing required was to design simple Airfoil Blade.

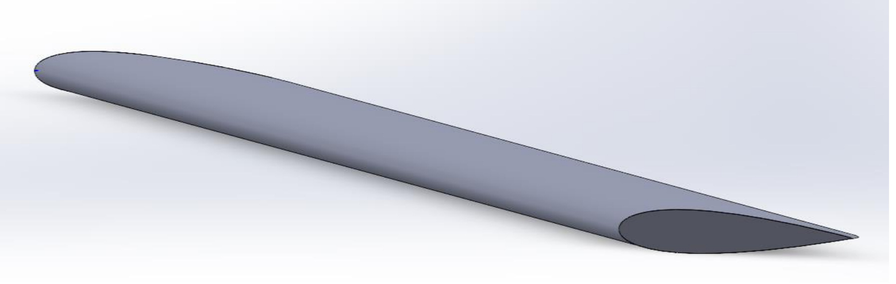


Fig 23. NACA 0018 simple Blade

The above figure shows NACA 0018 symmetric airfoil. The chord length is 150mm. The full length blade of turbine having span length of 750mm is then made using this airfoil.

3.3.2 NACA 0018 with tubercles

After designing simple airfoil, the next step is to design airfoil with tubercles on its leading edges. The tubercles are introduced by applying function driven curves in the SOLIDWORKS. 5*sin(2*t/9.5429)

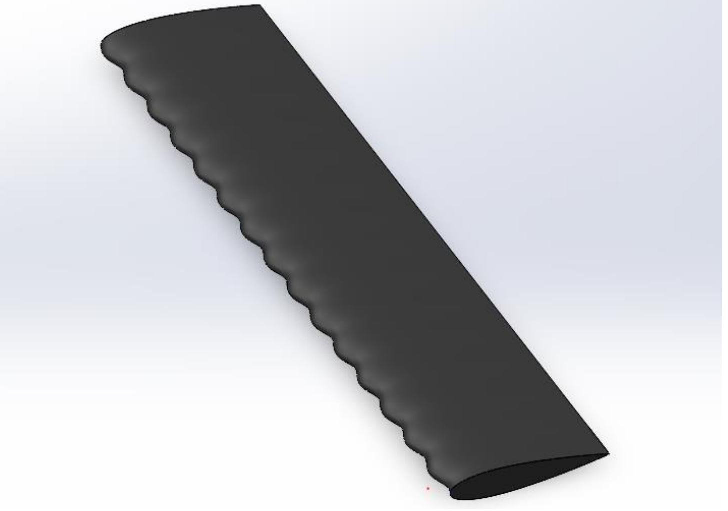


Fig 24. NACA0018 with Tubercles

The parameters like amplitude and wavelength are set by a function values whose value can be changed at later stages of work progress according to the requirements. The airfoil designed with leading edges tubercles having amplitude 5mm and wavelength 20mm is shown as below.

3.4 CAD Modelling of Components

After the designing of airfoils, next step is to design other parts of the vertical axis wind turbine. These parts are shown as below;

3.4.1 Airfoil Coupling Joint

In order to join airfoil with connecting rods, a coupling mechanism is designed. It joins airfoil with connecting rods through tightning nuts. The design is shown as below:

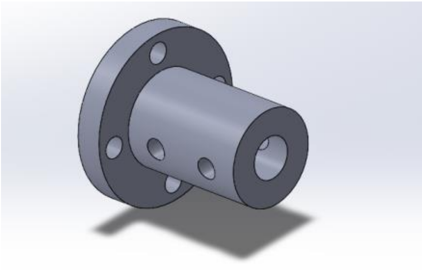


Fig 25. Coupling Joint

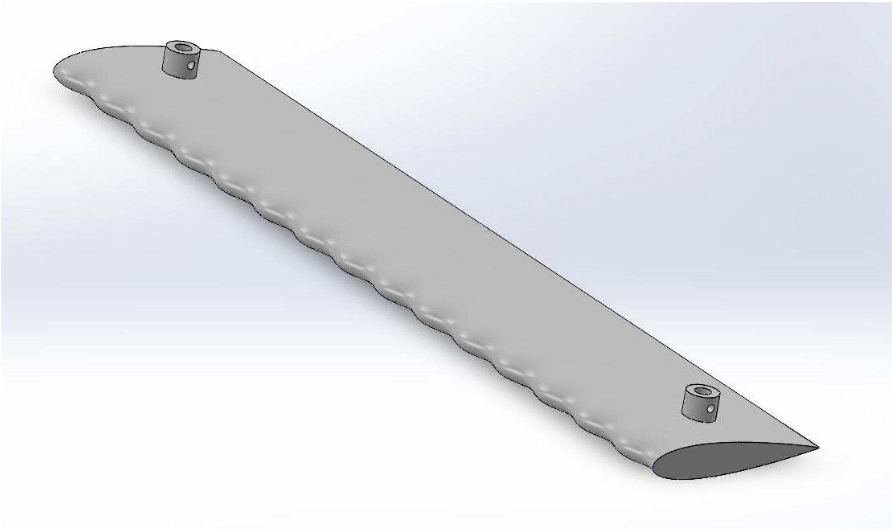


Fig 26. Airfoil with coupling joints

3.4.2 Central axis and Connecting Rods

Connecting rods connect airfoils to central axis with the help of coupling joints. Dimmensions are as follow:

Part	Diameter (mm)	Length (mm)	Material
Central Axis Shaft	19.4	750	Stainless Steel
Connecting rods	7.6	500	Plastic(Fibre Pole)

Table 1. Shaft Parameters

Both selected shafts are hollow to keep the turbine light weight and materials selected are also according to the weight to required stregth ratio. The design is show as follows:

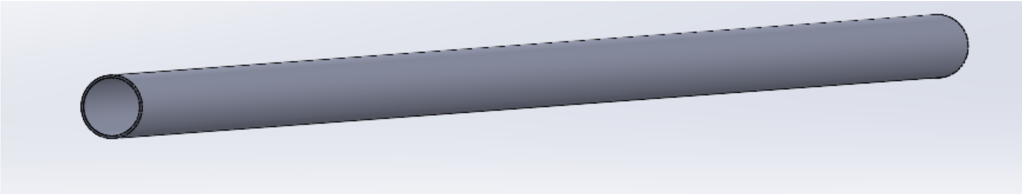


Fig27. Stainless Steel Central Axis Shaft

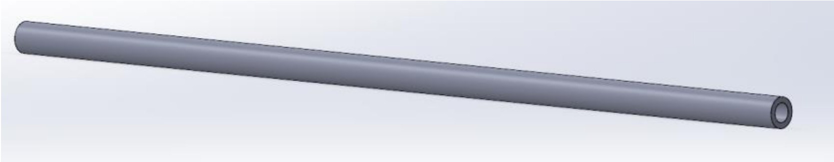


Fig 28. Plastic Connecting rod

3.4.3 Tri-Connection Joint

To join the central shaft with conecting rods a tri-connection joint is designed whose dimensions are 19.4mm for central shaft and 7.6 for three connecting rods. The holes are designed to place bolts and tight them at their places.

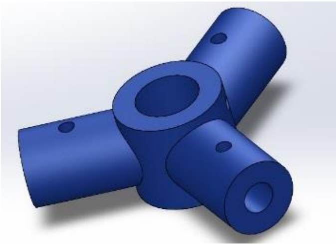


Fig 29. Tri-Connection Joint

3.4.3 Bearing

To hold, rotate symmtircally and prevent the central axis shaft from slipping down, flange bearing is used. Its locking mechanism prevents the shaft from falling down and thus it rotates symmetrically.

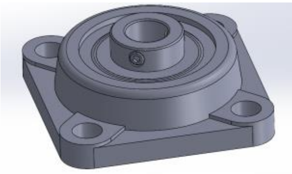


Fig 30. Flange Bearing

3.4.4 Base Stand

The base stand is the main component on which all the assembly parts are fixed. Upper and lower surfaces have housings for bearings.

Fig 31. Base Support

3.4.4 CAD Design Assembly

The base stand is the main component on which all the assembly parts are fixed. Upper and lower surfaces have housings for bearings.

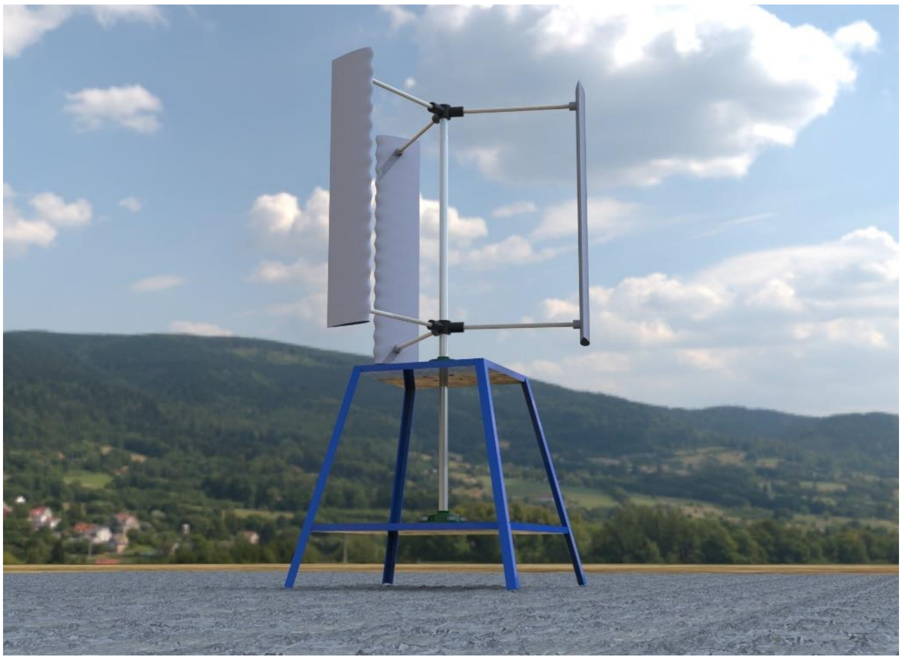


Fig 32. Rendered CAD Design Assembly

Chapter#4

CFD Analysis of NACA 0018 Airfoil

After the design process, the next step is to validate the results of airfoil by CFD analysis. This chapter explains the graphical plots and results obtained by performing CFD analysis on NACA 0018.

4.1 Software used

The software used for CFD analysis is Ansys Fluent.

4.1.1 ANSYS FLUENT

ANSYS FLUENT is a popular computational fluid dynamics (CFD) program. Fluent provides a complete range of tools, such as fluid flow simulation, heat transfer analysis, turbulence modelling, multiphase flow, combustion modelling, and fluid-structure interaction, for the solution of complicated fluid flow issues. For the simulations we used ANSYS FLUENT. These are the steps followed while working.

- Importing geometry
- Setting Rotor and Stator parts.
- Meshing
- Setting the Flow conditions, Boundary conditions and simulation models
- Selecting the output plots required.
- Initialize, run and calculate the setup.

In next step, the solution is analyzed using CFD POST Analysis, a module of FLUET.

4.2Boundary conditions and Models

Following meshing techniques have been applied.

4.2.1 Meshing Approaches

These are further divided as shown below.

4.2.1.1 Non-Conformal Meshing:

Non-conformal meshing is the process of creating a mesh that consists of multiple parts, or zones, that do not share common nodes. This is in contrast to conformal meshing, where the nodes on each part of the mesh align with each other. Non-conformal meshing is often used for complex geometries, such as those with moving parts or interfaces between different materials.

4.2.1.2 Sliding Mesh Approach:

The sliding mesh method is based on the idea that the mesh can be moved along with the moving part. This is done by creating a sliding interface between the two parts of the mesh. The sliding interface is a thin region of cells that are allowed to move with the moving part.

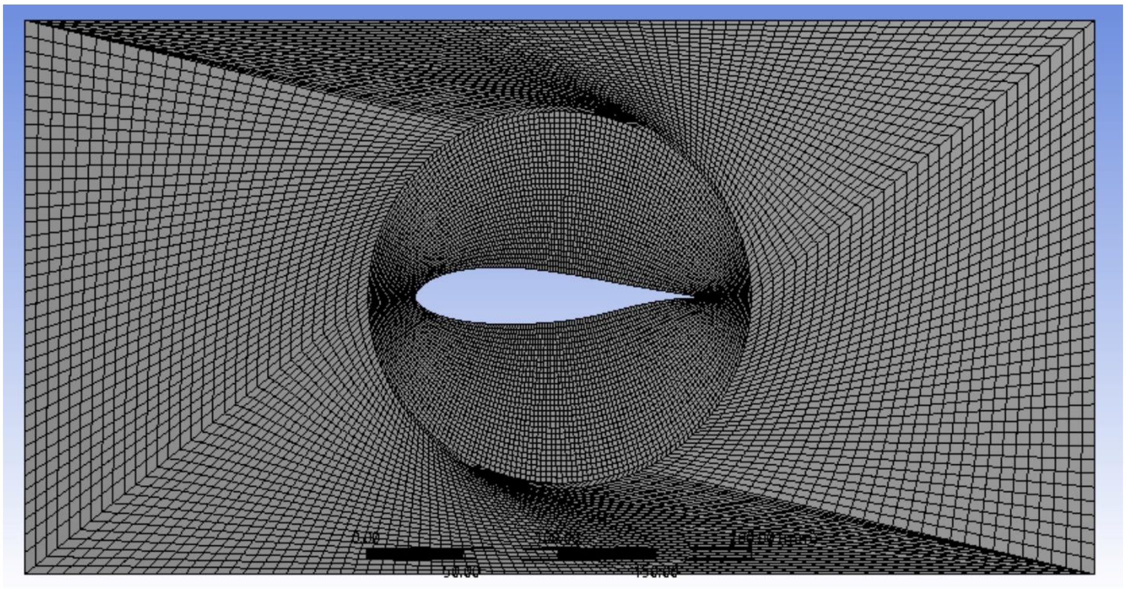


Fig 33. Sliding Mesh between Rotating and Static Domain

4.2.1.3 Dynamic Mesh:

Dynamic meshing is a technique used in computational fluid dynamics (CFD) to create a mesh that can change shape as the flow field changes. This is important for simulating flows that involve moving parts, such as the flow around an Airfoil.

4.3Turbulence Models

Following turbulence modals have been used while doing analysis on Fluent.

4.3.1 Turbulent Kinetic energy:

Turbulent Kinetic Energy (TKE) is a measure of the intensity of turbulence in a fluid flow. It is defined as the mean kinetic energy per unit mass of the fluid associated with turbulent eddies. TKE is typically used to characterize the intensity of turbulence in a variety of applications, including engineering, meteorology, and oceanography.

TKE can be calculated using a variety of methods, including:

Reynolds-averaged Navier-Stokes (RANS) equations: RANS equations are a set of simplified equations that are derived from the Navier-Stokes equations. RANS equations are less accurate than DNS, but they are much less computationally expensive.

4.3.2 K-Epsilon Standard Model:

The K-epsilon standard model is a two-equation turbulence model used in computational fluid dynamics (CFD) to simulate turbulent flow. It is one of the most widely usedturbulence models, and is particularly useful for free-shear layer flows with relatively small pressure gradients.

The model is relatively simple to implement and has good accuracy for a wide range of flow conditions. However, it can be less accurate for flows with strong adverse pressure gradients or complex geometry.

4.3.3 K-Omega SST Model:

The K-omega model solves two transport equations: one for the turbulent kinetic energy (k) and one for the specific dissipation rate (ω). The turbulent kinetic energy is a measure of the intensity of turbulence, while the specific dissipation rate is a measure of the rate at which turbulence is dissipated. The K-omega model is a relatively simple model to implement, but it can be quite accurate for a wide range of flows. It is particularly good at predicting the onset of turbulence and the transition from laminar to turbulent flow. The K-omega model is often used in conjunction with other turbulence models, such as the k-epsilon model, to improve the accuracy of CFD simulations.

4.4 CFD Analysis of NACA

4.4.1 Simple NACA 0018 contours

The streamlines show that there is large wake region at lower angle of attack. The data provided below is at 15 degrees of angle of attack.

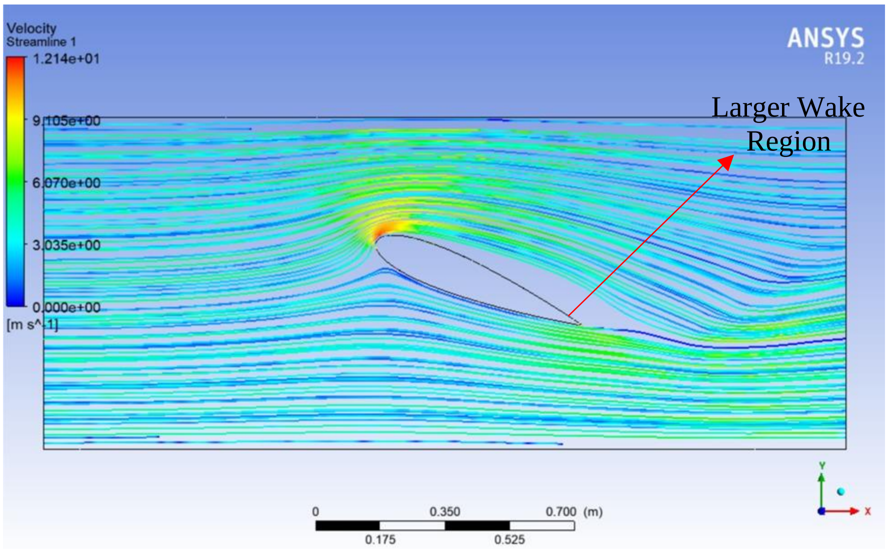


Fig 34. Velocity Streamlines NACA airfoil without Tubercles

The pressure contours show that the maximum pressure applied at the leading edge without tubercle is 20.25Pa.

4.4.2 Contours at NACA 0018 5mm LET Amplitude

The streamlines show that there is a reduction in the wake region at lower angle of attack. The data provided below is at 15 degrees of angle of attack.

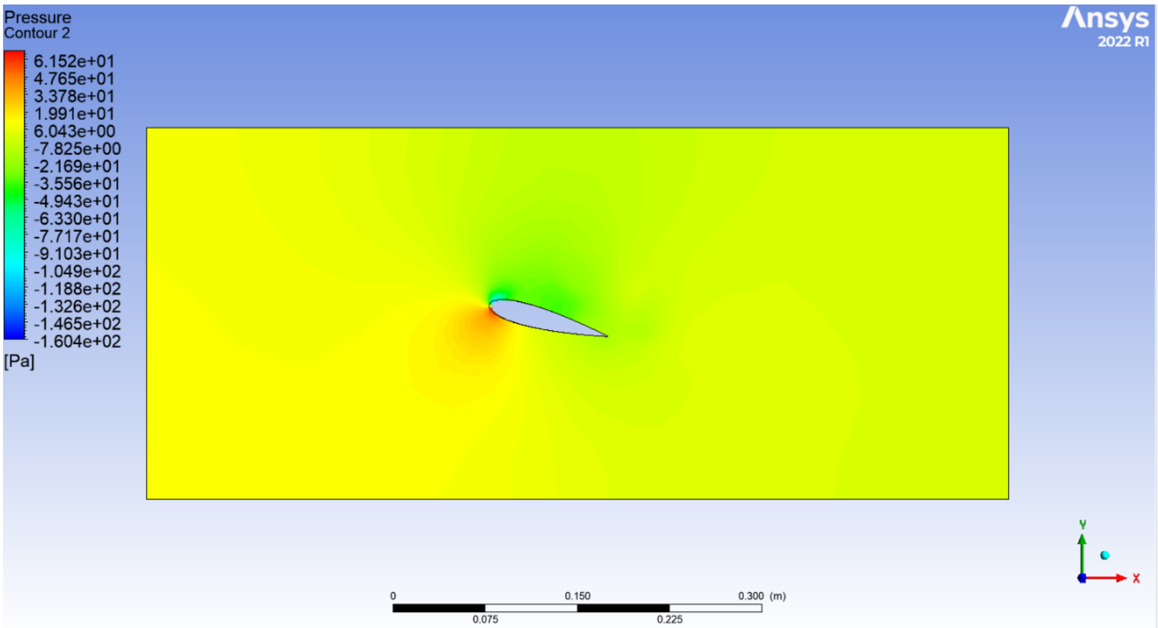


Fig 35. Pressure contours at 5mm LET Amplitude

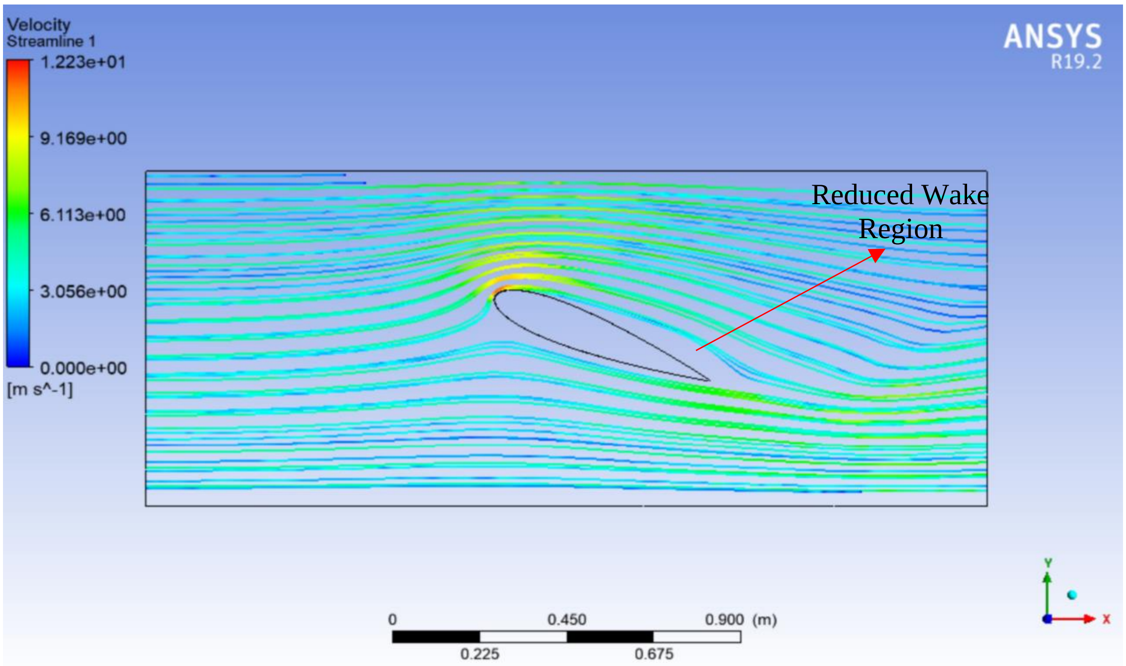


Fig 36. Velocity Streamlines at 5mm LET Amplitude

The pressure is increased with the application of tubercles, thus incraesing the lift coefficient.

4.4.3 Contours at NACA 0018 20mm LET Amplitude

The pressure contours show that the variation in maximum pressure applied at the leading edge is greater than that of airfoil without tubercles. Moreover, a slight decrease in wake region is observed as well, with the tubercles applied. The data provided below is at 15 degrees of angle of attack [18].

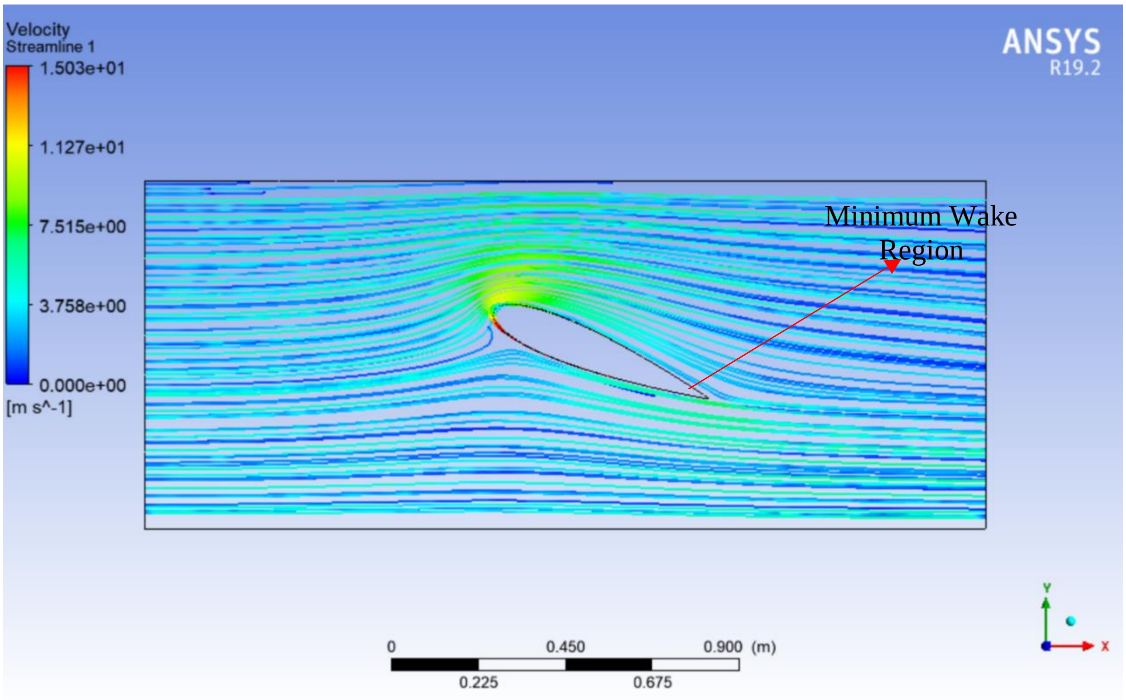


Fig 37. Velocity Streamlines at 20mm LET Amplitude

4.5 Results and Conclusion

After the application of leading edges tubercles on NACA 0018, the improved results have been seen. The application of leading edges tubercles decreases the wake region, delays dynamic stall at higher angles of attack, increases lift coefficient and reduces drag. So, there is new insight to test the results on cambered airfoil. In the next chapter we have selected DU06W200 airfoil which has maximum 6% camber at the point 20% of the total chord length of the airfoil.

Chapter 5

Design Optimization

After the CFD analysis on NACA 0018, results were found impressive. But literature review insists on introducing camber in the airfoil to get more good results [19]. DU06W200 is Dutch series of unsymmetric airfoil. The comparison of these two different types of airfoils and their performance is shown in the next portion of this chapter, there are two designs i.e., NACA 0018 and DU06W200.

5.1 Comparison of NACA0018 and DU06W200

The 2D sketches of both DU06W200 and NACA 0018 are sgown in this section respectively.

Fig 38. DU06W200

Fig 39. NACA 0018

NACA profile can be seen symmetric, while the DU profile has camber. The camber helps in increasing the lift coefficient.

5.2 DU06W200 with Tubercles

In order to introduce the camber in airfoil, DU06W200 is selected. The excel file of its coordinates is inserted in the SOLIDWORKS and sketch is made.

The span and chord are same as that for NACA0018. The next step is to make tubercles. Spline command in the SOLIDWORKS is used to produce sine curve type tubercles. All the parameters like wavelength and amplitude are set. The DU airfoil design is shown as following:

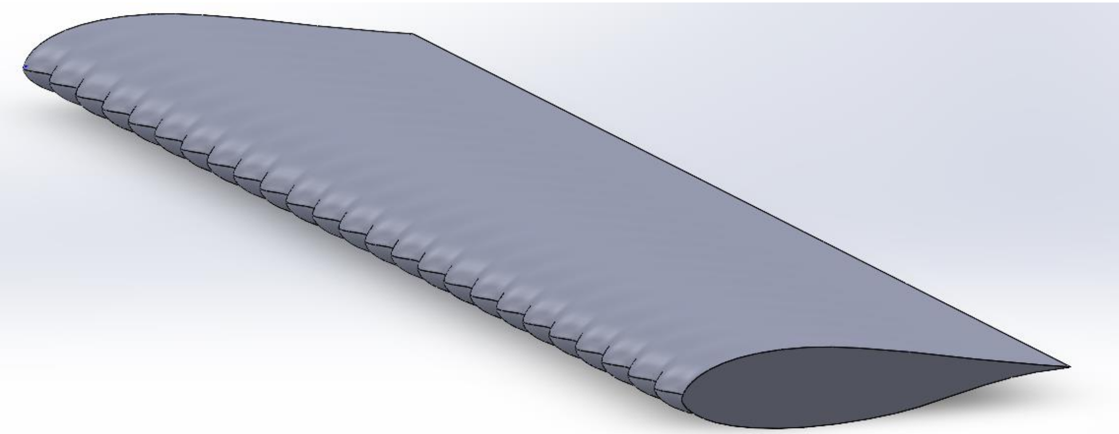


Fig 40. DU06W200 (750mm span and 150mm chord)

Chapter#6

CFD Analysis on DU06W200 Airfoil

The DU06W200 is an airfoil from “Delft University” airfoil series. The Du 06-W-200 airfoil is a laminar, 20% thick airfoil with 0.8% camber. The original NACA 0018 airfoil is a turbulent, symmetric airfoil with 18% thickness.

6.1 DU06W200 Parameters:

The following are the features for which the Du06W200 airfoil gives more better results than a NACA0018:

- Added thickness of 2% add to the blade strength without decreasing performance
- 0.8% camber increases the performance with respect to a symmetric airfoil
- DU06-W-200 performance equals the NACA 0018 for negative angles of attack
- DU06-W-200 has a much higher C_{lmax} for positive angles of attack, resulting in a wider drag bucket
- Deep stall occurs at higher angles of attack with a smaller drop in lift coefficient
- In contrast to the NACA 0018 the DU 06-W-200 does not have laminar separation bubbles which extend over the trailing edge
- The increase in turbine performance at the operating tip speed ratio of A = 3 is 8% in clean conditions and twice as much when dirty

6.2 Result Validation:

In order to match and validate the results of DU06W200 airfoil with reference article, we performed following simulation and results.

6.2.1 Simulation Setup:

The XFLR5 software was used to simulate the flow around the DU06W200 airfoil and to generate the Cl vs Cd and Cl vs Angle of Attack graphs. The simulation was set up with the following parameters:

Reynolds number: 300,000 to 700,000

Mach number: 0 (incompressible flow)

Turbulence model: Tollmien Schlichting

Transition model: Free transition with an amplification factor of 9.0

Angle of attack range: -20 to 20 degrees

Airfoil geometry: DU06W200

The Cl vs Cd and Cl vs Angle of Attack graphs generated by XFLR5 were compared to the experimental data obtained from reference article. The results are summarized below:

6.2.2 Cl vs Cd graph:

The predicted Cl vs Cd graph closely matches the qualitative experimental data for all Reynolds numbers tested. The XFLR5 software accurately predicts the stall behavior of the airfoil, with a sharp increase in Cd and a drop in Cl at higher angles of attack.

6.2.3 Cl vs Angle of Attack graph:

The predicted Cl vs Angle of Attack graph shows good agreement with the experimental data for all Reynolds numbers tested. The XFLR5 software accurately predicts the lift coefficient variation with angle of attack, including the stall behavior of the airfoil.

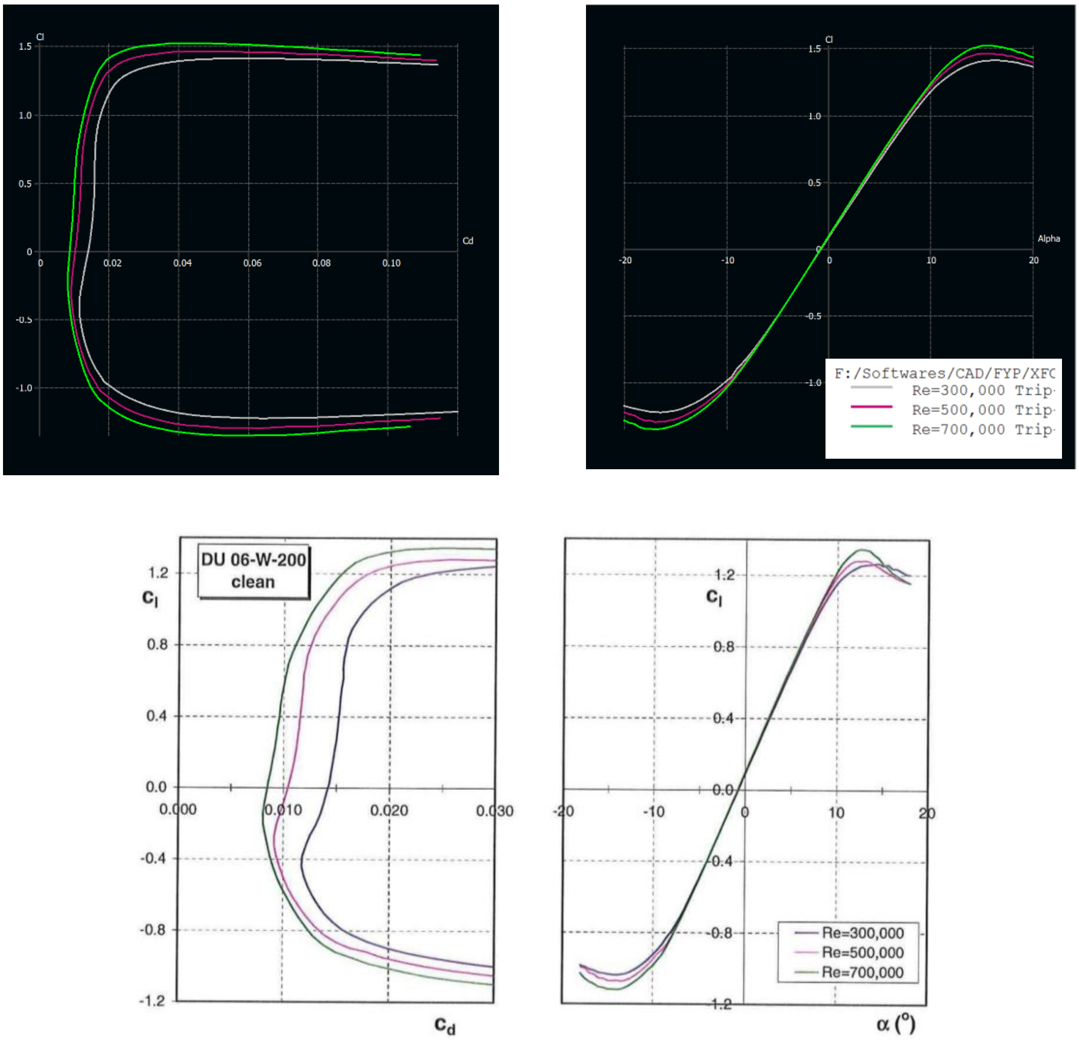


Fig 41. Rfoil Data for free Transition

6.3 C_L/C_D of DU06W200 and NACA 0018

The following results of parametric analysis show that the DU06W200 has greater C_L/C_D than NACA 0018 [20]. This shows that the former has greater effectiveness of lift than the later.

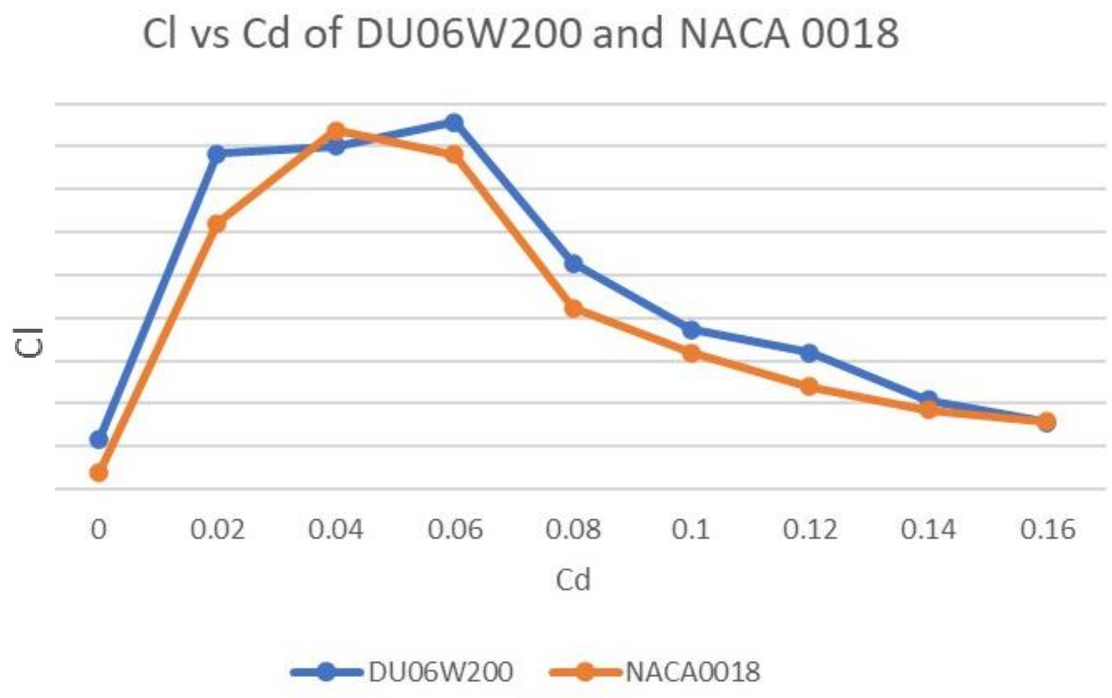


Fig 42. C_L/C_D of DU06W200 and NACA 0018

Chapter 7

Finite Element Analysis

This chapter explains the Mechanical and structural analysis done on the various parts of the turbine, turbine assembly and calculates their stress, strain and fatigue factors of safety.

7.1 FEA Software

The software used for these analyses are mentioned. These are the different modules of ANSYS WORKBENCH.

7.1.1 TRANSIENT STRUCTURAL

ANSYS TRANSIENT STRUCTURAL module helps to find the factor of safety, mode shapes, stress, strain, fatigue failures and optimization of design. The results are useful to find whether the structure has strength to bear high pressure forces so that it does not make our turbines heavy weight. After analyzing the results produced by STATIC STRUCTURAL module, design can be optimized keeping in mind all the factors.

7.1.2 MODAL

The modal analysis tool determines the system's natural frequency, assists in analyzing the mode shapes associated with each natural frequency and performs frequency response analysis to comprehend how the system responds to various excitation frequencies.

7.2 Structural Analysis

To initialize the transient structural analysis, there are some geometric requirements. Material assignment to all parts of the assembly is done first.

The parameters are as following:

- Material of Blades: Thermopore and Veneer sheet
- Material of Joint: PETG (3D Printed)
- Material of Shaft: Steel
- Material of connecting Rods: Plastic
- Pressure of Wind: Through CFD we get 28.01 Pa at Max.
- Weight of Each Blade: 100g with 10% infill
- Weight of Each connecting Rod: 8g

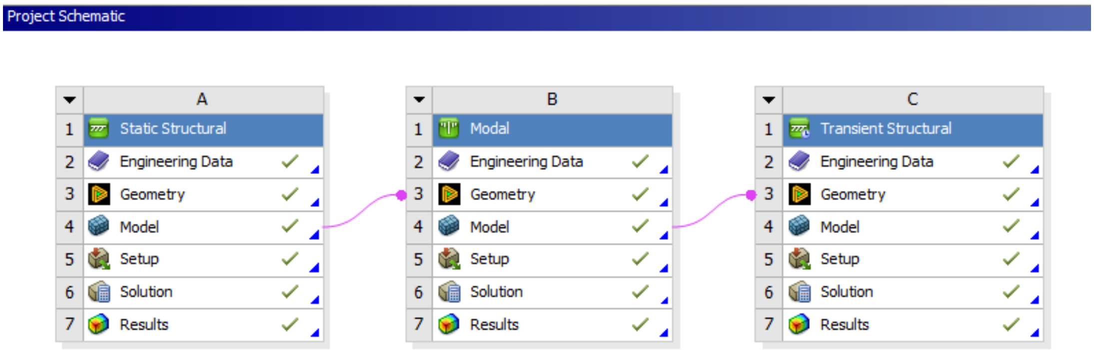


Fig 43. Schematic of Structural and Modal Analysis

7.2.1 Total Deformation

The results show that there is maximum deformation of 27mm at 102kmph which is worst case scenario in case of storms or tornado. On normal air speeds, like 10 to 20 m/s there is very little deformation in the structure.

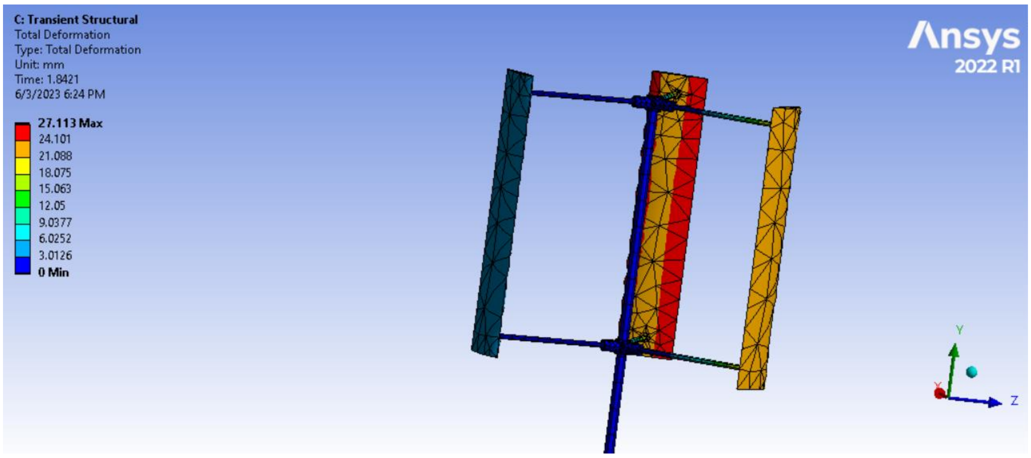
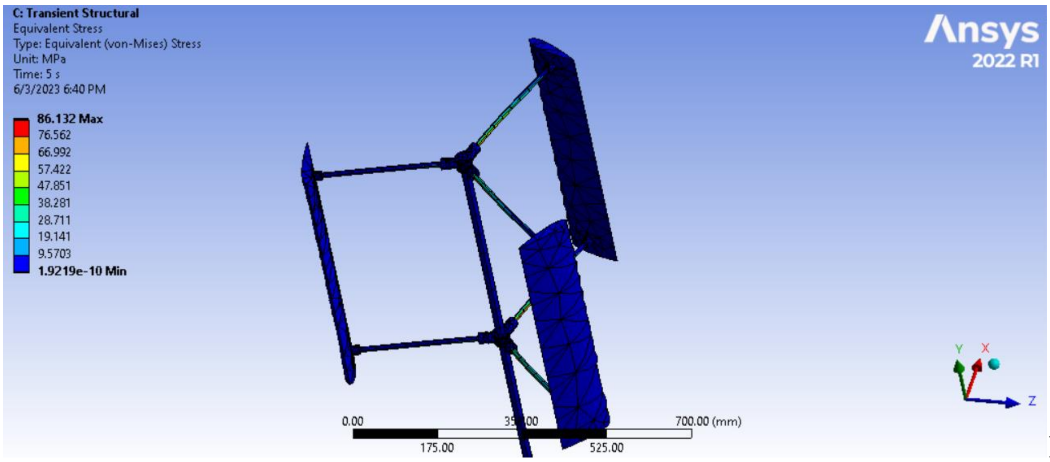


Fig 44. Total Structural Deformation

7.2.2 Equivalent Stress

Equivalent Stress contours show that there is maximum stress of 86.132MPa and minimum stress of $1 \cdot 92 \times 10^{-4}$ Pa. The plots are shown below.



Fig

Fig 45. Equivalent Stress

7.2.3 Equivalent Strain

Equivalent Strain contours show that there is maximum strain of 0.006321 and minimum strain of 5.958×10^{-15} . The plots are shown below

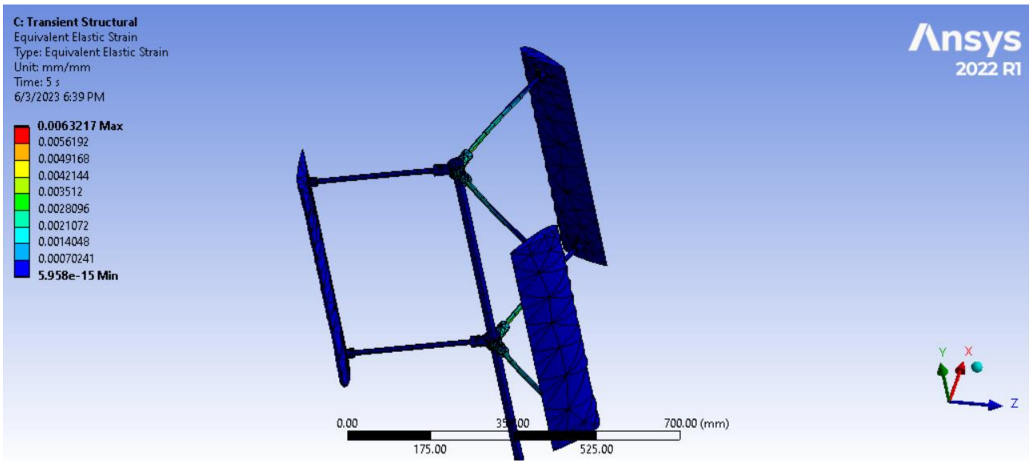


Fig 46. Equivalent Strain

7.2.4 Factor of safety

The analysis shows that the structure is strong enough to bear all the weight and air pressure and forces. The air pressure apllied are 70 Pa and 500 Pa in x and z directions respectively. The analysis shows that the structure can withstand these high pressure upto wind speed of 28m/s or 102kmph. But there is some deformation in connecting rods. The minimum value of factor of safety is nearly 1.5 as shown below:

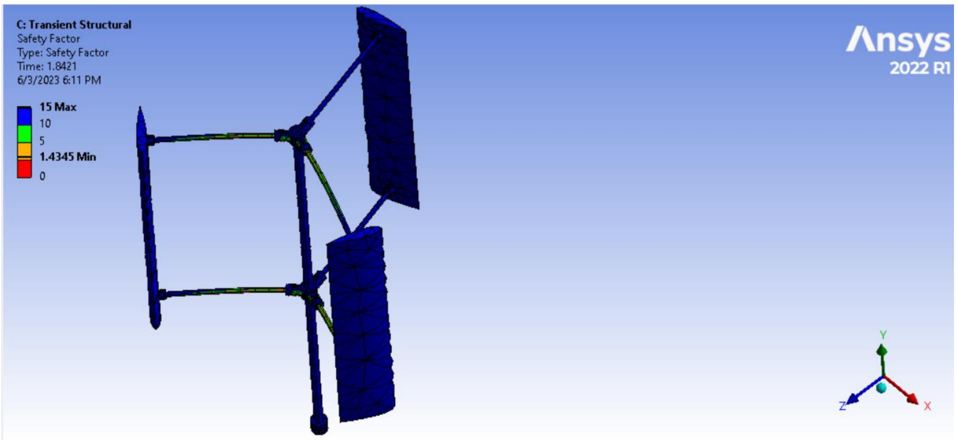


Fig 47. Factor of Safety

The plots below show the regions where there is maximim and minimum factor of safety. Minimum factor of safety is 1.504 and highest factor of safety is found to be 15.

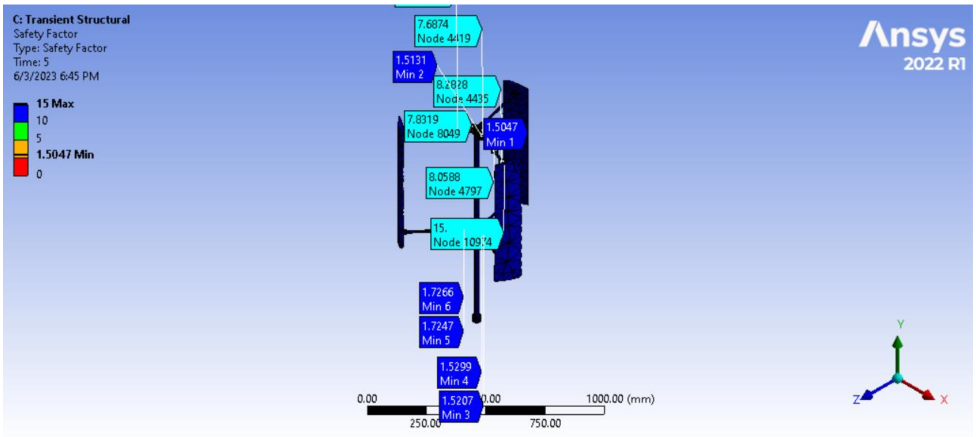


Fig 48. Regions of High and Low Factor of Safety

The plots show that there is minimum factor of safety 1.504 at the connecting rods. Since the material of rods is plastic they have maximum deformation at the high wind speed.

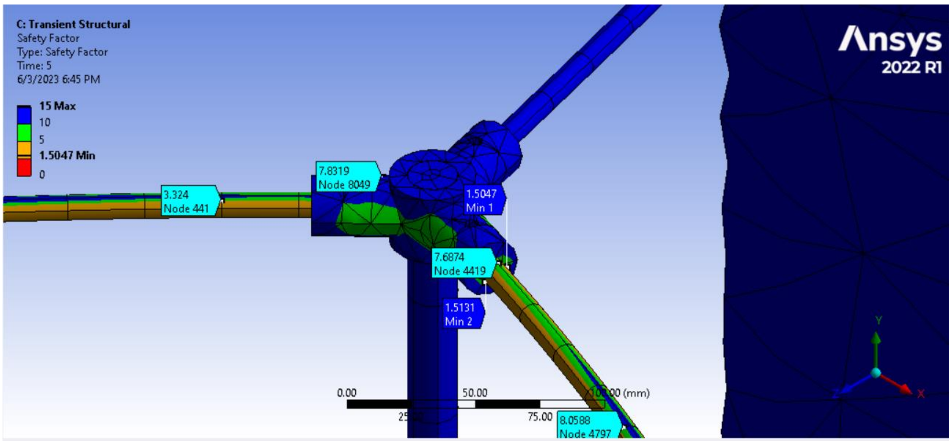


Fig 49. Minimum Fcator of safety at Connecting Rods

7.3 Modal Analysis

After the completion of CAD Designing and CFD Analysis, the next step is to find whether the designed model is capable to bear the loads and forces which act on it. MODAL ANALYSIS USING ANSYS MECHANICAL APDL SOLVER is done to find the Frequency Response System (FRS), Mode shapes and Vibrational Frequencies of the structure.

7.4 Mode Shapes

The mode shapes show the frequency of vibration and magnitude of deformation

Tabular Data

	Mode	Frequency [Hz]
1	1.	6.2771
2	2.	7.16
3	3.	7.1835

Fig 50. Vibrational Frequency of structure

7.4.1 1st Mode Shape

Maximum deformation during 1st mode shape is found to be 28.809 during the Transient Modal Analysis.

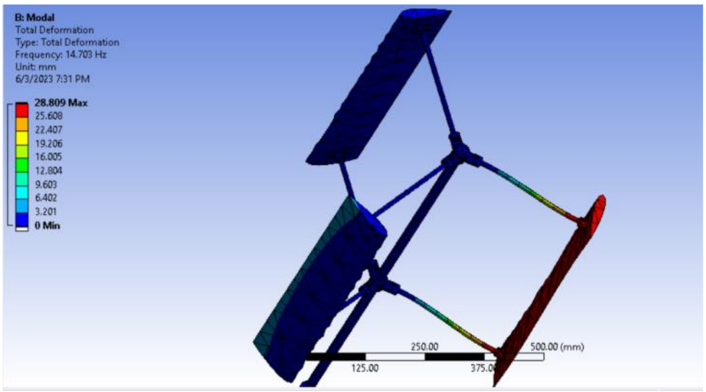


Fig 51. 1st Mode Shape

7.4.2 2nd Mode Shape

Maximum deformation during 2nd mode shape is found to be 18.439 during the Transient Modal Analysis.

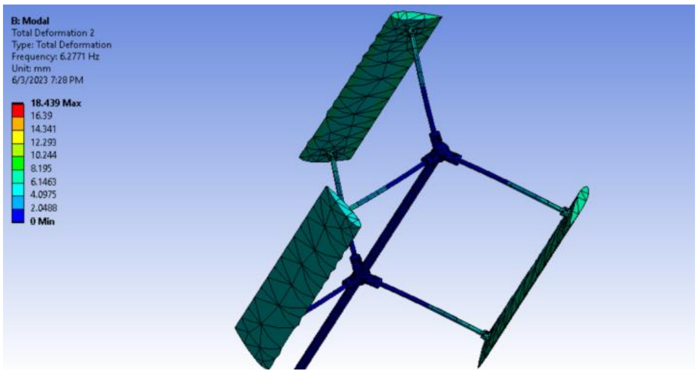


Fig 52. 2nd Mode Shape

7.4.3 3rd Mode Shape

Maximum deformation during 2nd mode shape is found to be 23.954 during the Transient Modal Analysis.

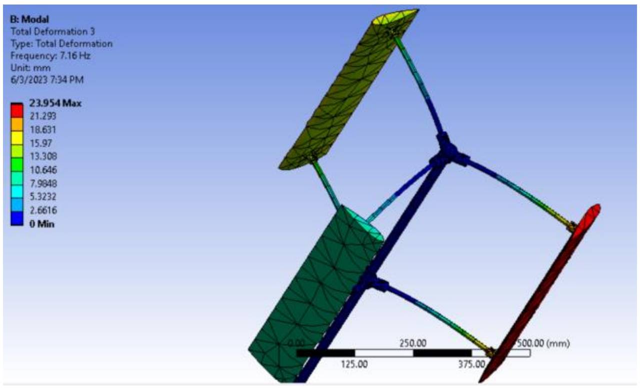


Fig 53. 3rd Mode Shape

Chapter# 8

Fabrication Processes

After the completion of CFD analysis, the design with maximum lift to drag ratio is selected for fabrication.

The table below shows the different materials used for different parts.

Part	Material
Airfoil Profile	Thermopore (Density # 20)
Airfoil Covering	Veneer Sheet (Wood Paper)
Leading Edges	PETG (3D Printed)
Connecting Rod	Plastic
Central Axis Shaft	Stainless Steel
Tri-Connection Joint	PETG (3D Printed)
Airfoil Coupling	PETG (3D Printed)
Base Stand	Sheet Metal(Guage#20 and L-Angle Iron)

Table 2. Material Assignments

The processes involved in the fabrication are mentioned below.

8.1 Airfoil Cutting

Before cutting the thermopore, a plywood sample is required. For this, airfoil is printed on the paper with desired scale ratio. The printed airfoil profile is pasted on plywood and cut in that shape using a Ply wood cutter machine.

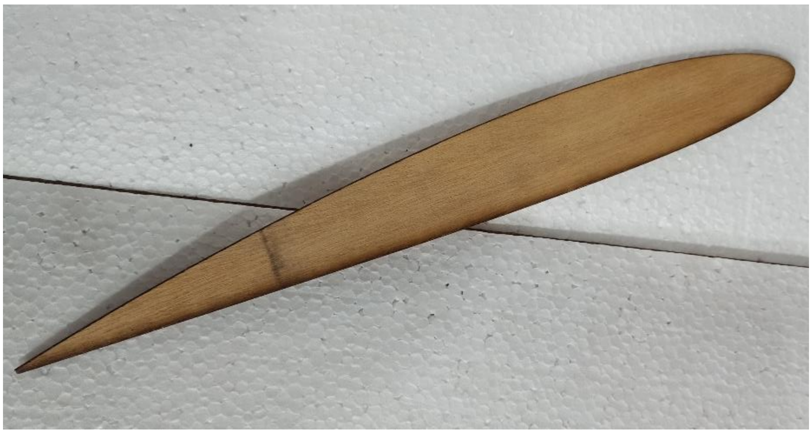


Fig 54. Plywood Airfoil sample

Thermopore with density number 20 is used. Wooden sample of airfoil is fastened on thermopore and hot DC wire cutter is used to cut the airfoils.

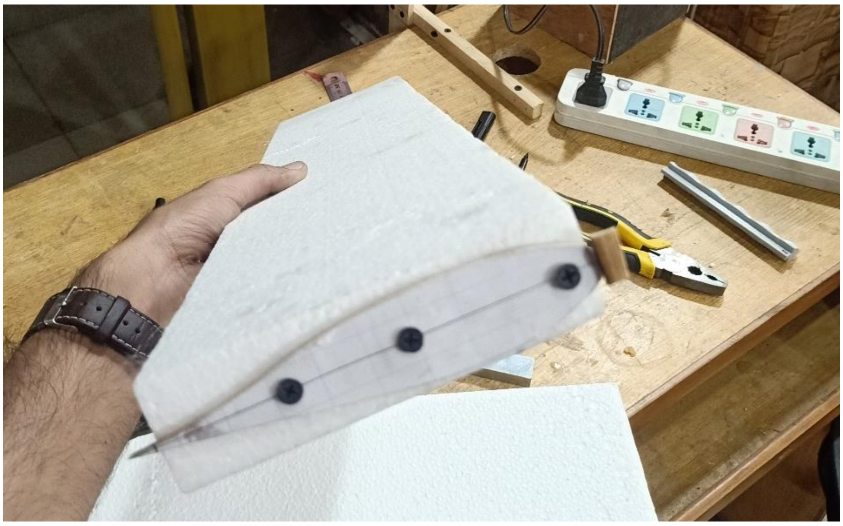


Fig 55. Airfoil Cutting

8.2 3D Printed Leading Edge Tubercles

To cater with the accurate amplitude and wavelength of tubercles the best suitable option was to manufacture them by 3D Printing. The 3D printed leading edge tubercle is show as follows:

Fig 56. 3D Printed Leading Tubercle

8.3 Leading Edge Tubercles Fitting

In order to fit the tubercles in leading edges of blades, rectangular slots are made in thermopore by hot DC wire cutter. Then using resin, the leading edges are fixed in the slots and kept to dry for 12 hours.

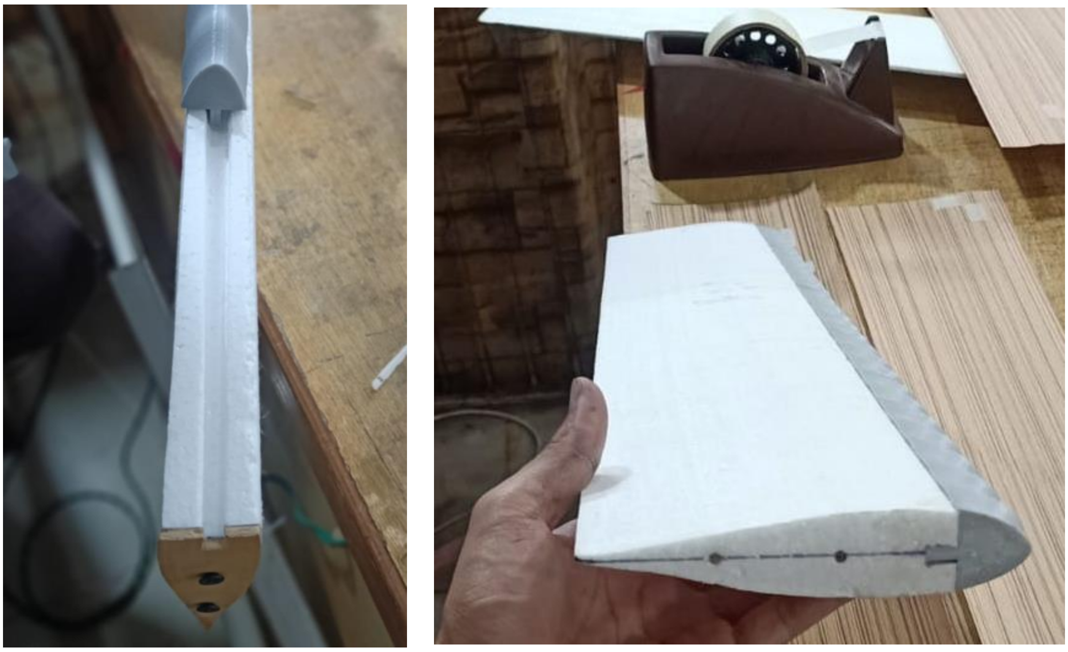


Fig 57. Leading Edge Tubercles Fitting

8.4 Airfoil Surface Covering

The airfoil is made of thermopore and leading edges are 3D printed. To give the thermopore a smooth finishing surface, it is first finished with sand paper. After sanding, glue is applied on thermopore and veneer sheet kept away to dry for 1 hour. After drying veneer sheet is them applied on thermopore airfoil.

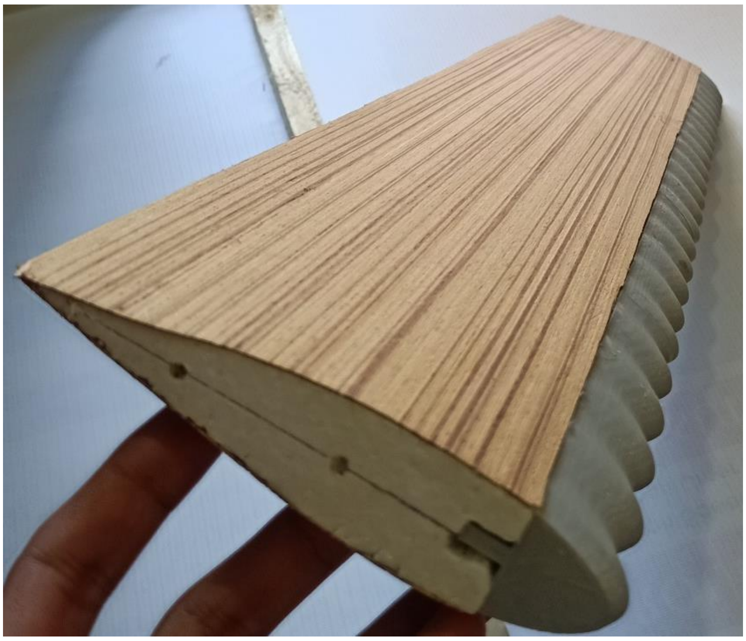


Fig 58. Full Airfoil

8.5 Airfoil Coupling

The connecting rods are coupled with airfoils. They are 3D printed by PETG and coupled by screws.

Fig 59. Airfoil Coupling

8.6 Tri-Connection Joint

Tri-connection joint attaches the central axis with connecting rods and then indirectly to the airfoils. Locking nuts stop shaft from sliding down. All the three airfoils are then connected to joint by rods.

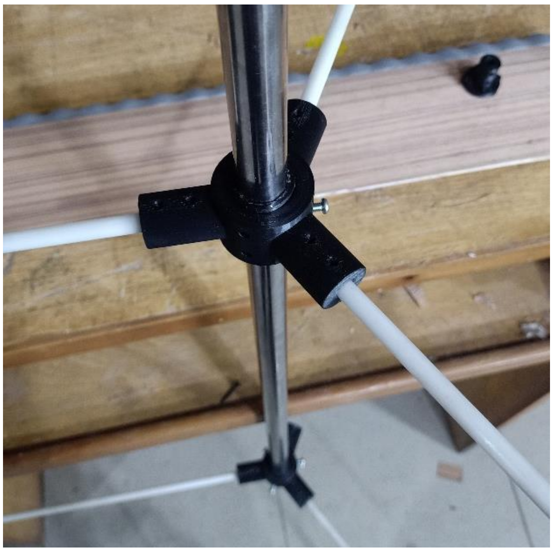


Fig 60. Tri-Connection Joint

8.7 Base Stand

Base stand provides the base to support project assembly. The upper and lower bases are made from mild steel sheet of Gauge# 20. The bearing is a flange bearing with a locking mechanism to prevent shaft from slipping downwards.

The alignment of upper and lower bearings was not correct. There was whirling in the shaft. We balanced it with a Bubble level instrument.

Fig 61. Bubble Level for Shaft and Bearings alignment

After alignment and painting, the base stand is shown as follows:

Fig 62. Base Stand

8.8 Materials Cost

The table below shows the material and manufacturing cost for all the processes of project.

Part	Cost (Rs)
Thermopore (Density # 20)	750
3D Printing Material Spool	3,000
3D Printing Cost	2,180

2x Bearings	1,750
Central Axis Shaft	770
Sheet Metal (Guage#20)	1,100
L-Angle Iron	1,070
Bolts	240
Iron Pipe (Square)	600
Magic Epoxy	250
Paint	350
Total	12,060

Table 3. Materials and Manufacturing Cost

8.9 End Product

The base consists of two bearings aligned for central shaft. The bearings used are flange bearings. The locking nuts help in gripping the shaft. The bearings are bolted on the base plates. The end product after assembling all the components is as shown.

Fig 63 Final Assembly

Chapter 9

Results, Conclusions and Recommendations

The CFD Analysis shows that the leading edge tubercles increase the lift coefficient, decrease the drag coefficient, decreases wake region and stall at higher angles of attack. There is some limit to the amplitude of the tubercles beyond which the tubercles amplitude has negative impact on the lift and drag coefficients. NACA 0018 symmetric airfoil results are somehow acceptable with decent Lift and Drag Coefficients. The literature suggests using the unsymmetric air foil having some camber. The DU06W200 with camber gives improved results. After the parametric studies and analysis during this project, we have found that the maximum lift to drag ratio (C_L / C_D) occurs at the 5mm Tubercles Amplitude. Furthermore, the leading edge tubercles decrease the velocity swirl normal.Z which is helpful in decreasing Blade-Vortex Interaction. The vortex generated by the upstream blades are lower and decrease effect on downstream blades. Thus the lift of downstream blades is less hindered. These results greatly help to validate Blade-Vortex Interaction theory (BVI).

Recommendations

The leading edge tubercles have great potential in decreasing the wake region drag. Further studies can be done on the blades of marine turbines and axial turbo machinery where reduced wake region is required. Such utility is usually required at low Reynold's number and Mach number. Leading edge tubercles make an analogy with the vortex generators. To completely create an increase in utility, a specific amplitude and wavelength is required which varies based upon the scope of studies. Studies can also be done on the profile of protrusions introduced on airfoil. These cases open up a very broad scope of research and development.

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