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Design Optimization for Horizontal Axis Wind Turbine Blades

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Abstract - **This project report is based on methods by which the blade design for a horizontal axis wind turbine can be enhanced. This was conducted by a series of research and CFD simulations of the various improvements devices with was observed by comparing the lift to drag ratios from the baseline model of a simple NACA 4415 blade design. The optimization was conducted by initially setting up a baseline value using a single NACA airfoil. Optimizations such as using multiple airfoils with indues twist in the blade followed by addition of wingtips and surface enhancements with the addition of flaps.**

Keywords – Aerodynamics, CFD, Wind turbine, Blade optimization

I. Introduction

The early invention of horizontal axis wind turbine, people of the past used drag as one of the main factors that caused the turbine blades to rotate. But as technology has advanced, we have learned that the main factor that helps in rotating the turbine blades is pressure difference. These pressure differences are associated with lift and drag forces.

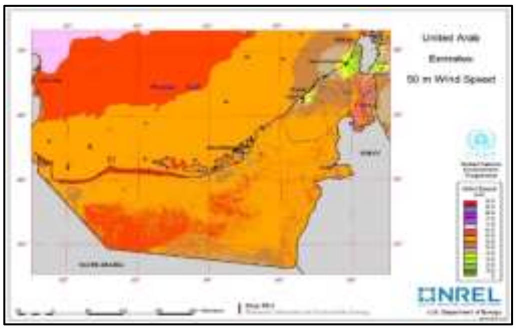


Figure 1: Wind speed distribution map of UAE [1]

The shape of a wing and the devices attached to its tips, known as winglets, significantly influence the reduction of aerodynamic drag [2]. Researchers have focused on learning how lift and drag different winglet designs provide a limited air-plane wing.
Evaluation of such forces and identification of the contribution of each winglet to the overall lift and drag forces of the wing may be achieved via the use of computational fluid dynamic (CFD) simulations and wind tunnel testing of scaled-down 3D-printed models. Using the measured lift and drag forces, the wing's efficiency was calculated.
One of the most crucial factors that influence the performance of a wind turbine is the geographical location at which it is placed. In the UAE, as per research the average wind speed is five meters per second during the summer seasons and can have an average wind speed of 8 to 10 meters per second during the winter season [1].

II. Background Research

A. *Aerodynamic Shape optimized design for wind turbine blade using new airfoil series.*

Wind turbines have evolved significantly since their inception in the early 1980s, increasing in power output from fifty kilowatts (kW) to multiple megawatts (MW). Considerable attention has been given to improving the aerodynamic and structural design of horizontal-axis wind turbine rotors. A new series of airfoil designs, known as the CQU-A series, has been developed to enhance the aerodynamic efficiency of wind turbine blades. Through wind tunnel testing and the use of RFOIL, these airfoils have demonstrated superior performance. One notable implementation of these novel airfoils is found in the Terborg rotor, a 2 MW pitch-controlled wind turbine. The Terborg rotor minimizes blade surface area while maximizing the power coefficient, resulting in increased annual power output. By reducing the surface area, optimized blades can be made thinner and lighter, preserving the internal structure, extending fatigue life, and reducing material costs. This optimization program also manages the blade's root load. However, research on optimal blade designs utilizing entirely new airfoil families remains scarce in the literature. Furthermore, achieving maximum aerodynamic performance while minimizing weight is crucial. Reducing the weight of wind turbine blades can improve fatigue life and lower composite material costs. Previous studies exploring the lightest possible blades have primarily focused on structural aspects, neglecting aerodynamic performance. Developing a mathematical model for blade mass is challenging due to the complex surface flow and varying densities of composite materials throughout the span of MW-size wind turbine blades. Additionally, discussions surrounding wind turbine blade profile optimization entail simplifying the blade mass model. To address these challenges, this study introduces a series of seven newly developed airfoils with a maximum relative thickness ranging from 15% to 40%. The aerodynamic performance of this airfoil series has been validated through wind tunnel testing.

Figure 2: Multiple Airfoil used in a wind turbine blade [2].

B. Multi-dimensional optimization of small wind turbine blades

The higher-performing airfoil resulted in superior blade designs for E-glass and flax, where the minimal shell thickness was enough to preserve structural integrity. The same holds true for the thick, sturdy blades of hoop pine [3]. However, the ABS M-30 benefited from the thicker airfoil, which shifted the shell farther away from the neutral axis and increased stiffness, leading to improved performance. To further optimize power, the SG6043 blades have a negative p at the tip for w = 1. However, as seen in Equation 1, this results in a negative initial torque, which is subsequently removed throughout the optimization process. In this study, we provide a multi-objective optimization method for the blade design of small wind turbines. These objectives might include maximizing power output while minimizing noise, reducing startup time, and strengthening the turbine's overall structure. The beginning time is calculated by modifying the traditional blade element theory, which also provides predictions for the power extraction. The current computations do not include the effect of noise. By selecting one of two load scenarios from the IEC 61400-2 SLM for small wind turbines, the structural strength is determined using simple beam theory with the assumption of isotropic material characteristics. For simplicity, let us suppose the blades are hollow and have a uniform shell thickness.

C. Aerodynamic analysis on wings with and winglets and vortex generators

Most of the electricity we use comes from wind power, and this rapid expansion in usage is justified by the increasing maturity of related technologies as well as the widespread interest and investment from businesses and universities in developing new ways to harness renewable and clean energy sources. With the price of oil dropping, renewable energy sources like solar and wind are the future of clean, reliable power. Wind energy is the most competitive renewable resource because it can generate electricity efficiently and on a huge scale. Wind energy is non-linear; hence optimization methods are essential for constructing a functional wind farm. Soft computing approaches have been widely investigated in the literature and are used for layout improvement. As a result, this article summarizes the most important studies that have been conducted on wind farm modelling using optimization methods. The novel methods of wind farm modelling are also discussed in this paper. In addition, it provides an in-depth analysis of the current research approaches used in the optimization of wind farm architecture. Because of this, our effort aims to aid both established researchers and fresh faces in wind farm modelling and layout optimization. The potential usefulness of wind farms to increase energy production efficiency and their contributions to lowering carbon emissions have increased their profile across the globe [4]. This report provides a thorough evaluation of the primary literature about methods for optimizing the layout of wind farms.

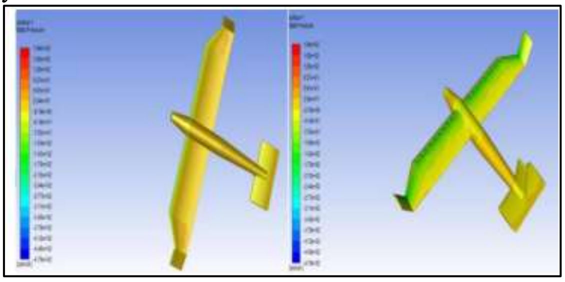


Figure 3: Effect of winglet on RC plane [4]

D. Aerodynamics Optimization of RC Plane Winglet

This paper deals with understanding the various steps involved in performing finite element analysis of computational fluid mechanics systems to enhance the aerodynamics performance of the RC plane for SAE competition. The analysis is conducted for the complete airplane and for the wing optimization. Various modifications are applied to the wing and are analyzed first and then the best cases are applied to the whole airplane. The steps include creating a modeling plan, material selection, geometric modeling, model meshing, applying boundary conditions, and obtaining the required results by solving the models. The software used to conduct the finite element analysis is Workbench. Once the results are obtained, model and result verification are done to validate the data. It is concluded that the airplane-45 degrees winglet has the highest lift force with the minimum drag.

E. Aerodynamics Optimization of Unmanned Aerial Vehicle through Propeller Improvements

This paper aimed at presenting a number of suggested improvements that can enhance the performance of a multi-rotor Unmanned Aerial Vehicle. Evaluating each suggestion in terms of the added benefits and feasibility concluded a final choice, which is incorporating a sinusoidal leading-edge profile to the propeller. This choice was numerically investigated with ANSYS Fluent 16.1 through the SST K-Omega turbulence model. The performance of the modified propeller was assessed by comparing the lift and drag results to the same propeller with a straight leading-edge under the same conditions. Both models were studied at pre-stall and post-stall conditions to see the performance effect with respect to the angle of attack. The findings of this research showed a 7% increase in the lift force and coefficient that were associated with the addition of the sinusoidal leading-edge including improved recovery from stall spanning from angle of attack that extends between 10° to 25°. This research also provides more insights into how the delayed stall and improved lift helped the multirotor to extend flight time and carry heavier payloads. It allows for the exploration of the inner working of the sinusoidal leading-edge and its relationship with the flow field over the propeller.

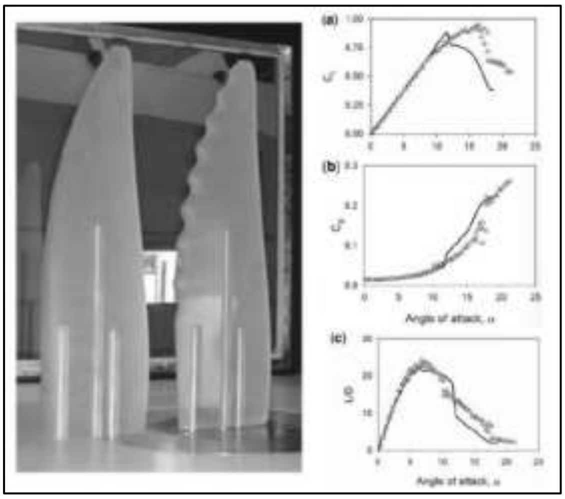


Figure 4: Blade design improvements [4]

III. Methodology

A. Baseline values

The optimization methodologies were established with the aim of improving the lift to drag rations of the wing. Each optimization approach will add significance in improving the lift to drag ratio of the wing. As for a baseline reference value, we have designed a NACA 4415airfoil blade with one meter length. This blade is just a simple extrusion of a NACA 4415 airfoil.

Figure 5: NACA 4415 Airfoil

As for a baseline reference value, we had performed CFD analysis on this blade and have plotted the various graphs such as the Lift coefficient vs angle of attack, drag coefficient vs angle of attack and the pressure distribution above and below the blade cross-section along with the boundary layer for analyzing the flow separation.[5]

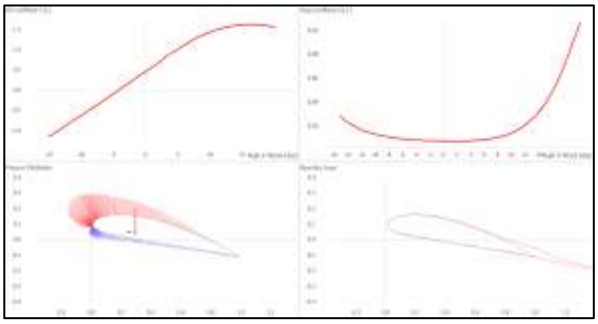


Figure 6: CFD analysis results [Lift coefficient, Drag coefficient, Pressure distribution, Flow Boundary Layer]

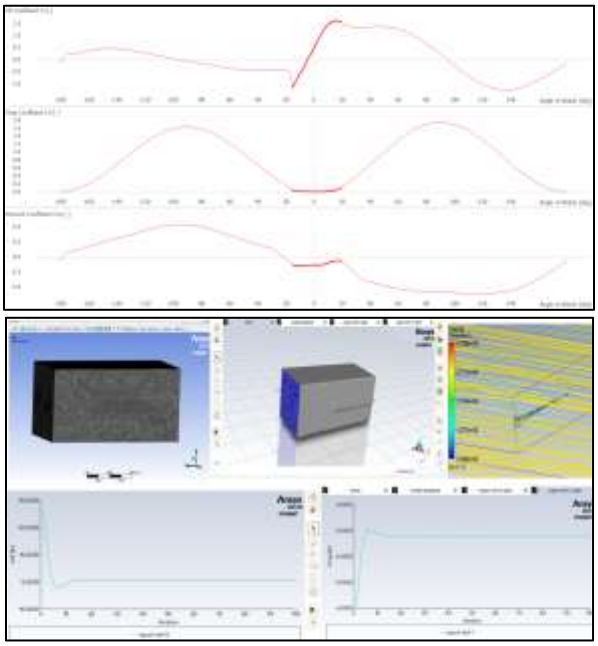


Figure 7: CFD simulation and results [Lift and Drag]

After analyzing the NACA 4415 airfoil through the CFD analysis the following Table I summarizes the baseline values for further optimization using the formulas below.

Table I: Summary table for baseline model

NACA 4415 AIRFOIL			
Lift per unit span	**Drag per unit span**	**Lift to Drag Ratio**	**Maximum angle of attack**
4.5 N m	0.12 N m	37.5	0^0

B. Using Multiple Airfoil

As an initial optimization method, we have decided to use multiple combinations of NACA airfoil along the length of the blade along with setting them to the optimal angle of attack inducing and overall twist to the blade.

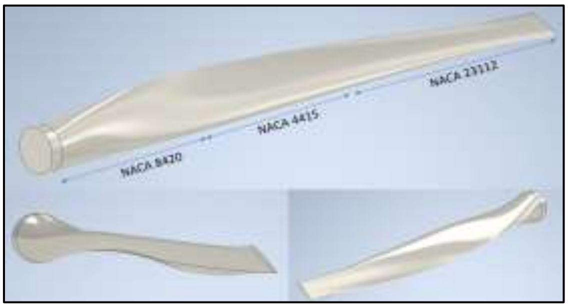


Figure 8: Multiple Airfoil Blade Design 1

The blade is now designed using three airfoil designs, each set with a different angle of attack. These airfoil and angle of attack are carefully selected using the lift and drag variations with respect to their maximum angle of attack. The use of multiple airfoils is due to the fact that the wind speed travelling at the root of the blade is slower when compared to the wind speed travelling at the tip of the blade, therefore, the airfoil near the root is smaller and have higher angle of attack when compared to the airfoil near the root [6]. Upon performing CFD results the following Table II and graphs summarizes the overall performance increase:

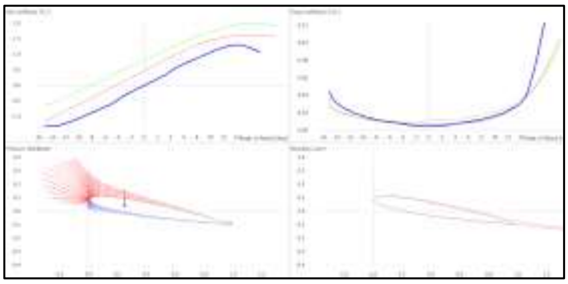


Figure 9: CFD analysis results [Lift coefficient, Drag coefficient, Pressure distribution, Flow Boundary Layer]

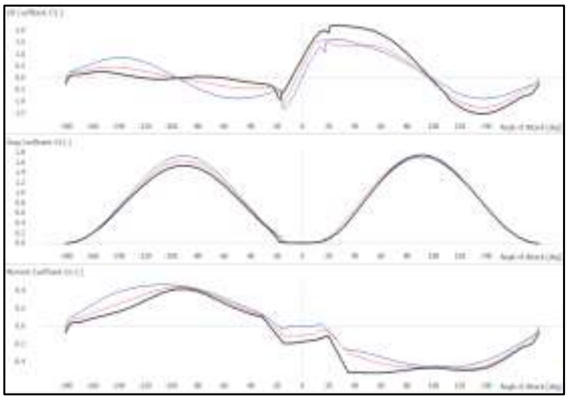


Figure 10: CFD simulation and results [Lift and Drag]

Table II: Summary table for multiple airfoil

NACA 8420 AIRFOIL			
Lift per unit span	**Drag per unit span**	**Lift to Drag Ratio**	**Maximum angle of attack**
4.8 N m	0.09 N m	48.3	10^0
NACA 4415 AIRFOIL			
Lift per unit span	**Drag per unit span**	**Lift to Drag Ratio**	**Maximum angle of attack**
4.5 N m	0.12 N m	37.5	15^0
NACA 23112 AIRFOIL			
Lift per unit span	**Drag per unit span**	**Lift to Drag Ratio**	**Maximum angle of attack**
3.9 N m	0.13 N m	30.7	30^0
Total Lift-Drag Ratio	61.525	**Percentage Increase**	64%

C. Adding Wingtip

After optimizing the airfoil combination along with the ideal angle of attack of the respective airfoils, the next optimization method was with respect to the trailing vortex generated at the end of the wind turbine blade. This trailing vortex induces drag long the blade with increases the drag acting on the blade thereby reducing the lift to drag ratio [5]. In order to reduce strength of the trailing vortex we have added extended wing tip which help in reducing the intensity and strength of the trailing vortex by increasing the surface area and having a smoother transition of the air flow across the end of the blade. It basically increases the aspect-ratio of the wing and increases lift and reduces drag [6].

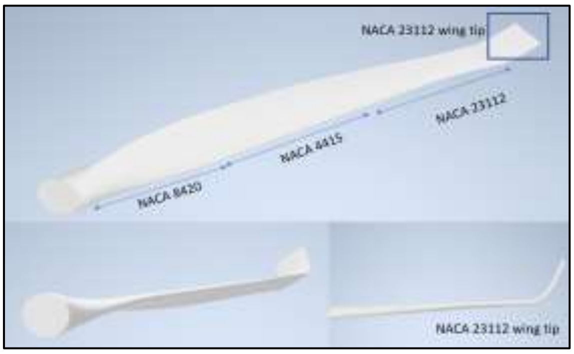


Figure 11: NACA 23112 Wingtip

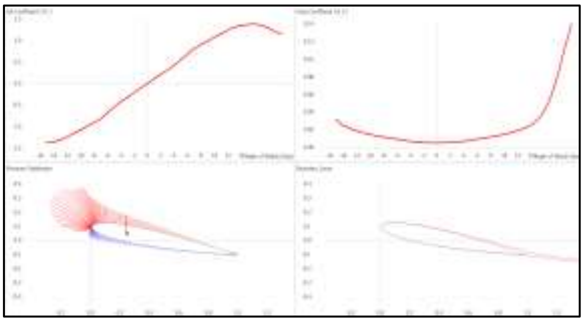


Figure 12: CFD analysis results [Lift coefficient, Drag coefficient, Pressure distribution, Flow Boundary Layer]

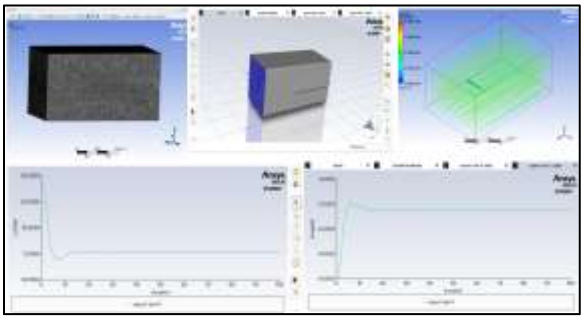


Figure 13: CFD simulation and results [Lift and Drag]

Table III: Summary table for added wingtip.

NACA 8420 AIRFOIL			
Lift per unit span	**Drag per unit span**	**Lift to Drag Ratio**	**Maximum angle of attack**
4.8 N m	0.09 N m	48.3	10^0
NACA 4415 AIRFOIL			
Lift per unit span	**Drag per unit span**	**Lift to Drag Ratio**	**Maximum angle of attack**
4.5 N m	0.12 N m	37.5	15^0
NACA 23112 AIRFOIL			
Lift per unit span	**Drag per unit span**	**Lift to Drag Ratio**	**Maximum angle of attack**
3.9 N m	0.13 N m	30.7	30^0
NACA 23112 AIRFOIL Wingtip			
Lift per unit span	**Drag per unit span**	**Lift to Drag Ratio**	**Maximum angle of attack**
3.9 N m	0.12 N m	30.7	10^0
Total Lift-Drag Ratio	64.595	**Percentage Increase**	4.98%

D. Surface enhancements

For the surface and structural material, carbon fiber is one of the best materials that can be used to design a wind turbine blade due to its superior strength to mass ratio [7]. The friction coefficient between air and carbon fiber is in the range of 0.15-0.35 which is less than the friction coefficient than fiber glass that is used in most of the modern wind turbine blade. As drag due to friction is one of the most dominant types of drag when it comes to streamline bodies this can enhance the performance of the blade to some extent [9].

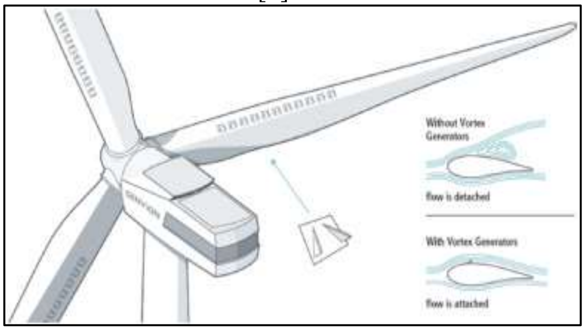


Figure 14: How vortex generators work

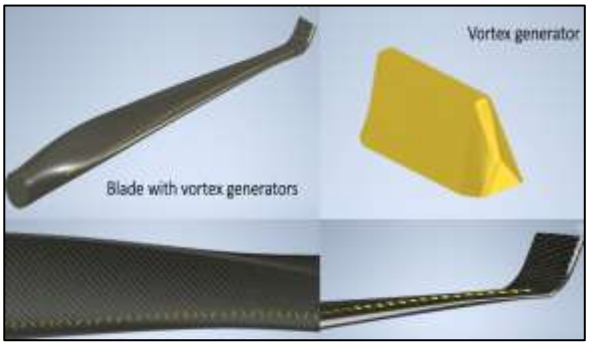


Figure 15: Vortex generators

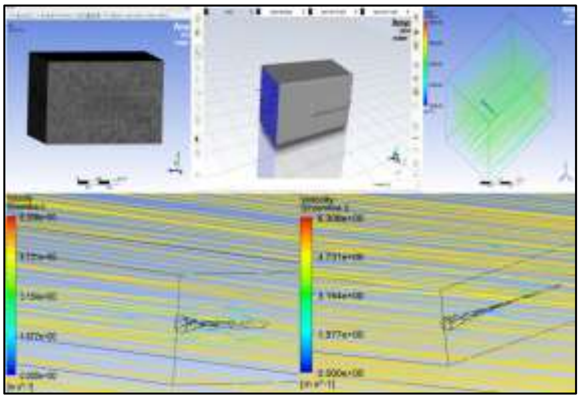


Figure 16: CFD simulation and results [Lift and Drag]

The CFD for this setup was performed by increasing the wind speed to ten meters per second as compared to five meters per second which was used as the free stream velocity for the previous CFD [10].

Table IV: Summary table for surface enhancements.

Wing (carbon Fiber and Vortex generator)			
Lift per unit span	**Drag per unit span**	**Lift to Drag Ratio**	**Maximum angle of attack**
3.8 N m	0.05 N m	65.721	30^0
Total Lift-Drag Ratio	65.721	**Percentage Increase**	2.29%

The values for this CFD simulation are not as accurate as the previous CFD results due to the fact that the surface modification is very minor and the meshing errors and sizes are a major source of error.

E. Adding Flaps

For the final optimization method, we have designed a wind turbine blade that has the capabilities that can deploy flaps that can enhance the lift force on the entire blade. The main characteristic of flaps is that in makes the flow above and below the blade un-symmetrical, which enables a pressure difference across the blade which induces a lift force across the wing [11].

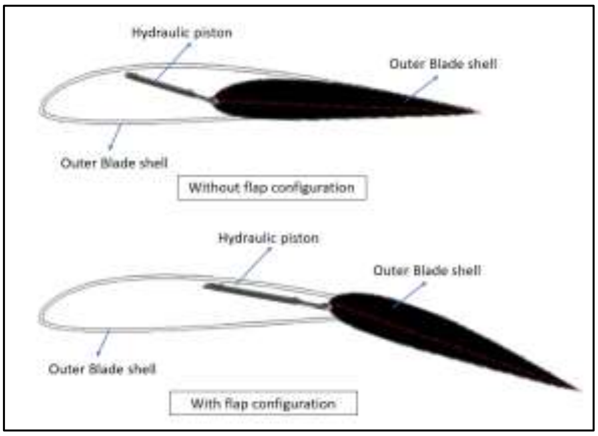


Figure 17: Addition of flaps and how they work.

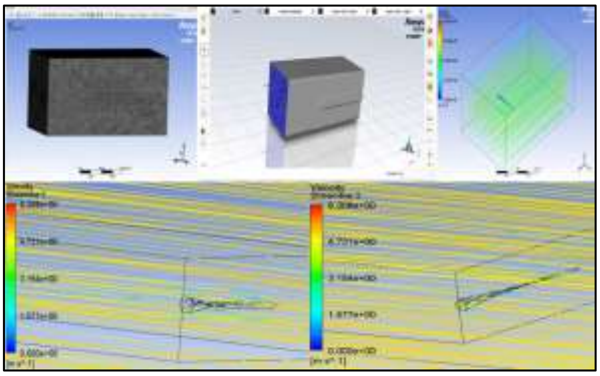


Figure 18: CFD simulation and results [Lift and Drag]

Table V: Summary table for added wing flap.

Wing with flap			
Lift per unit span	**Drag per unit span**	**Lift to Drag Ratio**	**Maximum angle of attack**
4.2 N m	0.072 N m	66.927	30^0
Total Lift-Drag Ratio	66.927	**Percentage Increase**	1.83%

The values for this CFD simulation are not as accurate as the previous CFD results due to the fact that the surface modification is very minor and the meshing errors and sizes are a major source of error.
Flaps usually increase the lift force while increasing the drag at low wind speeds. As per the CFD simulation software limitations we are unable to have an accurate result as we have faced issues with mesh sizing and complex geometry [12].

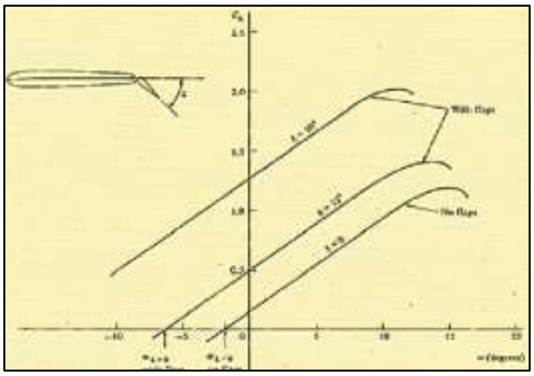
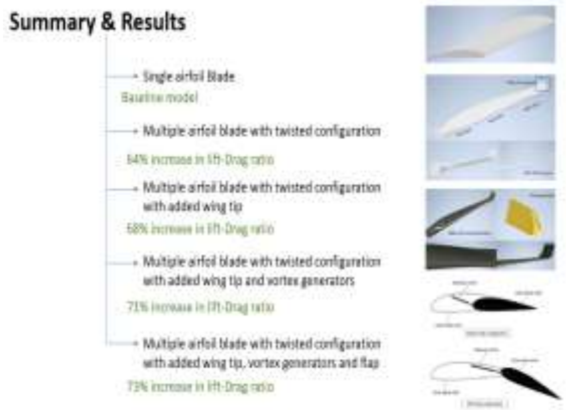


Figure 19: Significance of flap addition on lift per unit span value [7].

IV. Conclusion

In conclusion, this report focuses on the various methods by which the optimization of a horizontal axis wind turbine can be performed. The report progressively displays the various methods by which the lift to drag ratios of the wing blade can be enhanced by simply using a combination of airfoils and then inducing an overall twist across the blade and the adding wing tips to reduce the induced vortex generations at the end of the wing tips and the adding vortex generators to prevent the flow form separation from the surface of the turbine blade and the finally adding flaps to increase the overall lift force by increasing the un-symmetrical flow above and below the blade which inducing a pressure difference thereby increasing the lift force.



By starting with a single blade design which was based on a simple extrusion of NACA 4415 airfoil, the baseline lift to drag ratio was found to be 37.5 which was obtained through CFD simulations. The next optimization technique employed was by using multiple airfoils with an overall twist throughout the blade length which improved the lift to drag ratio by 64%. The next optimization was done by adding vortex generators along the length of the blade which resulted in 72% increase in efficiency compared to the baseline results. Lastly flaps were added to the blade, this is to improve the performance of the blade to with low wind speeds. The final lift to drag ratio was 73% better or greater than the baseline value using a simple extrusion of NACA 4415 airfoil blade.

V. Acknowledgements

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