Original Research Article

DESIGN AND OPTIMISATION OF HORIZONTAL AXIS WIND TURBINE BLADES USING BIOMIMICRY OF WHALE TUBERCLES

ABSTRACT

Wind speed is the major factor in generating power in a wind turbine. However, due to the non-optimum and redundant design of wind turbine blades, not nearly enough wind is captured for utilization. In the present study, modifications were done on the leading edge of the HAWT blade using tubercles showing their effects on aerodynamic performances. From this research, the following results found concerning the performances of HAWT with leading-edge tubercles were that; blades with tubercles on the leading edge will have superior performance in the post-stall regime by 27%, tubercles with a smaller amplitude and lower wavelength will produce higher lift and lower drag in the low wind speed condition, and tubercle blade will have a stable and smooth performance in varying wind speed conditions, producing higher torque and power at low wind speed. Using a small wind turbine model, SolidWorks Motion Analysis Simulation was used for dynamic modeling to evaluate and determine the force and torque of the mechanical structure. These results were compared and examined using standard wind turbine blades which showed an improvement of 30% in efficiency.

Keywords: wind turbine, tubercle blade, biomimicry, horizontal-axis wind turbines, Solidworks.

1 Introduction

Due to fossil burning and fuel consumption, worldwide energy demand has increased in the previous 35 years, raising concerns about the greenhouse effect [1]. “Wind energy has become an important component of the solution to these issues. Because wind turbines do not emit CO2 while they create power, they may help to minimize the greenhouse effect. A lot of effort has gone into developing a high-performance wind turbine. The propellers in a wind turbine transform the kinematic energy in the wind to mechanical energy in a shaft. Mechanical energy is eventually converted to electrical energy in a generator. However, one of the inherent drawbacks of wind turbines is that they can only generate wind energy if nature provides enough wind to rotate the blades” [2].

Blade pitch control and new blade designs are one of the strategies for boosting energy capture and reducing burdens in high-wind conditions. One blade design strategy is attaching or designing the leading edge of turbine blades with a wavy structure. This wavy structure called a tubercle helps aid energy capture by increasing lift and drag coefficients while drastically reducing the stalling effect of the blade characteristics when wind speeds reach a maximum threshold. The purpose of this research is to design and execute a simulation of tubercle blade control to investigate the trade-off between minimal torque changes and maximum energy gain.

2.0 Biomimicry Concept

2.1 Story Behind Inspiration

The focus of this research was shifted to the design and structural system of biological entity processes as a result of reading an article online [3]. The article was about aquatic living lifeforms and how they brought about breakthroughs in the marine research area [4]. Using the aquatic research as a guideline, the investigation was made to find a way of introducing some form of bio-organism in making a breakthrough in this turbine blade topic. Through thorough research, using flippers of aquatic lifeforms and not just any aquatic life forms but aquatic mammal lifeforms became a ground base for this research. As a result, a humpback whale’s flipper became the settling focus to be this project’s source of inspiration for its biomimicry concept, especially its tubercles. Thus, inherently became the guiding factor in coming up with a new design for this project’s blade.

2.2 Tubercles of The Humpback Whale

The capacity to perform marine maneuvers to catch food sets the humpback apart from other whales. For swift movements and turning, humpback whales use their wing-looking flippers that are incredibly mobile. The large rounded tubercles that run down the forefront of the flipper are architectural structures that are seen nowhere else on the planet. The tubercles on the top edge of the flipper operate as passive flow control devices, enhancing the flipper's performance and mobility [5]. “The presence of tubercles causes a delay in the angle of attack until stall, boosting lift and lowering drag, according to experimental analysis of finite wing models. Delay of the stall by the production of a vortex and change of the boundary layer, as well as a rise in effective span by reducing both spanwise flow and the strength of the tip vortex, are two possible fluid-dynamic methods for enhanced performance. The tubercles provide an organic design for wing-like structures that is commercially viable. Passive flow control provides the advantage of removing complex, expensive, high-maintenance, and heavy control devices while boosting capacity for lifting bodies in air and water. These tubercles and how they operate can be applied to the design of water turbines, aircraft, wind turbines, and windmills” [6].

2.3 Hydrodynamics of Tubercules

The flipper's location and quantity of tubercles suggest counterparts with specific leading-edge control systems linked to improved hydrodynamic performance. On a hydroplane, the presence of "morphological complexity" could reduce, or utilize, fluctuation in pressure at the tip to reduce drag and improve lift, preventing tip stall. Tubercles on the flipper of humpback whales, according to Bushnell and Moore in 1991[7], may reduce drag caused by lift. Biological wings, on the other hand, use cutting-edge control mechanisms to keep lift and avoid stalling at low speeds and high angles of attack.

The tubercles on a humpback whale's flipper have been compared to airplane strakes Strakes are huge vortex generators that alter a wing's stall characteristics. Because the vortices within the boundary layer exchange momentum to maintain it attached to the wing's surface, the stall is postponed. When compared to wings without strakes, strakes help maintain lift at higher angles of attack, but they don't boost maximum lift.

Experiments with flow visualization on the wavy Ahmed body revealed a periodic fluctuation in the wake width across the span. Where the body swelled up downstream, a large wake formed, and where the body protruded upstream, a narrow wake formed. On an Ahmed body with a spanwise sinusoidal form, a drag reduction of at least 30% was realized when compared to corresponding straight bodies as observed by ” Bearman and Owen” in 1998 [8]. At low speeds, flow separation from the troughs between neighboring tubercles was observed in flow studies on a model wing section with best-in-class tubercles, although associated flow on the tubercles was observed.

The leading-edge tubercles on an imagined humpback whale flipper were able to delay stall and boost total lift without considerably increasing drag, according to wind tunnel research. The NACA 0020 section with and without tubercles was used as the basis for the one-fourth-scale flipper replicas. The intertubercular spacing and size on the scalloped flipper's sinusoidal pattern reduced with increasing distal location. The static experiments were conducted at a Reynolds number (Re) = 500,000 (Re = UC/v, where U is the fluid velocity, C is the foil chord length, and v is the kinematic viscosity of water), which is approximately half of the value of the whale at lunge-feeding speed (2.6 m/s).

Up until the stall, the lift coefficient (CL) for both scalloped and baseline flippers rose monotonically with the angle of attack. The scalloped flipper's maximum lift increases by 6% above the baseline. At an angle of attack of 11°, the baseline flipper abruptly halted (i.e., lost lift). When compared to the baseline flipper with straight leading edges, the scalloped flipper with leading-edge tubercles improved the stall angle by 40%. When the scalloped flipper stalled, it did so gradually. The scalloped flipper's drag coefficient (CD) was lower than the baseline shape in the 12° to 17° range, and just marginally higher in the 10° to 12° range. CD is indistinguishable from the flippers below 10°, demonstrating that possessing tubercles has no drag disadvantage. The scalloped shape had a higher peak L/D for the lift-to-drag (L/D) ratio, which measures the drag cost of producing lift or aerodynamic efficiency as seen in figure 2.4. [9].

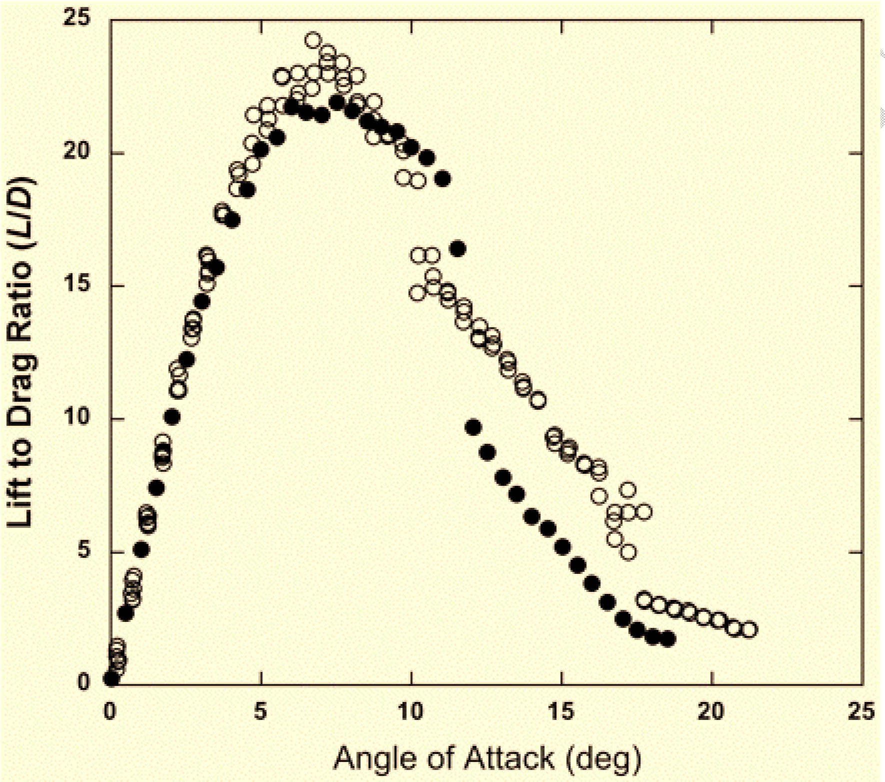


Figure 1. Lift-to-drag ratio (L/D) as a function of the angle of attack

(Based on disa from Miklosovic et al., the lift-to-drag ratio (L/D) as a function of angle of attack. Closed circles represent a baseline wing without tubercles, while open circles represent a wing having tubercles on the leading edge.)

Simulations with tubercles and sweep angles of 15° and 30° showed similar results. When compared to versions without tubercles, the sweep models required a higher to-reach stall, while the scalloped versions demonstrated improved drag performance over the majority of the range discovered by Murray[10]. Flow studies on delta wings with a sweep of 50° revealed that the wing with a straight leading edge experienced large-scale, three-dimensional separation at high angles of attack [11]. The flow is radially changed when tubercles are added. Tubercles with an amplitude of 4% of the wing chord can eliminate the separation's detrimental effects and promote re-attachment.

On the performance of two-dimensional foils based on NACA 0021, 634-021, and 65-021 sections, the effect of leading-edge tubercles was explored. Tubercles on the leading edge of foils did not stall as much as foils with a straight leading edge. Tubercles with a limited amplitude showed the best performance. In the preinstall regime, the stall was postponed to a higher degree, with CL over 50% higher for tubercle-affected foils than for the baseline foil, but with higher CD.

The results on two-dimensional foil sections show that tubercles have restrictions when the ends of a hydrofoil are restricted by walls or when the hydrofoil span is limitless. Tubercles are primarily beneficial in three dimensions [9]. Although stall is still delayed, foil portions with no wing tip that resemble infinite wings do not show reduced drag and greater lift. When a fully three-dimensional wing is canted at an angle of attack to an incident flow, the tip effects occur as a result of lift generation. As there is leakage of fluid from high pressure to low pressure around the distal tip of a lifting surface, induced drag is produced in the generation of lift from kinetic energy imparted to the fluid from variances in pressure between the two surfaces of the wing, resulting in spanwise flow and the formation of vortices at the tip. The tubercles' flow pattern is thought to sustain chordwise flow and reduce induced drag caused by tip vortices.

On flapping wings with tubercles, experiments were carried out. Tubercles were shown to influence spanwise flow, which is an important property of flapping wings with a straight leading edge. A wing's efficiency is harmed by the spanwise flow. However, a flapping wing with tubercles does not form a distinct spanwise flow area. The geometry of the leading edge does not affect the structure of the tip vortex, according to Ozen and Rockwell [12]. The pressure field formed by flapping activity may have eclipsed the tubercles' role in accelerating the development of the tip vortex. Force measurements on foils with tubercles that oscillated in roll and pitch revealed that the tubercles did not affect hydrodynamic performance. The redirection of energy from the vortices of the wake to tubercle-generated vortices, which are important for producing thrust during flapping, is thought to be the cause of reduced flapping performance. Alternatively, as evidenced by testing on static wings, the tubercles' flapping limitation could be owing to the oscillation period being too short to allow full development of the vortices over the wing. To sustain the pattern of the vortices and gain hydrodynamic advantages, a rather steady flow is required.

2.4 Viability of Tubercules.

The forces operating on a uniform part of the humpback whale) were evaluated using a panel-method simulation. According to a study by Watts and Fish, in 2001 [13], wing sections with tubercles at a 10° angle of attack had a 4.8 percent gain in the lift, a 10.9 percent reduction in generated drag, and a 17.6 percent increase in lift/drag when compared to wing sections without tubercles.

Furthermore, flow separation patterns and surface pressure were drastically affected by the tubercles in an Unsteady Reynolds-Averaged Navier-Strokes (RANS) simulation on a NACA 63-021 baseline foil either with or without uniformly spaced tubercles. Separation was prolonged almost to the trailing edge for locations downstream of the tubercle crest. This appears to be related to a rise in suction pressure, which lessens the unfavorable pressure gradient locally. In the troughs, the tubercles produce chordwise vortices that are separated. The vortices are created when flow meets the trough's surface tangentially and is sheared to the trough's center. These vortices converge along the chord depicted in the diagram below. “The vortices are arranged in a pair on either end of the tubercle's crest, with opposite spins. Because of the contact with the vortex pair, the flow right over the tubercle is propelled posteriorly. These factors prevent the local surface layer from splitting, pushing the stall line on the flipper more posteriorly. The flippers with tubercles need not stall at a greater than a flipper without tubercles when integrated over the complete structure as shown in figure 2” [14].

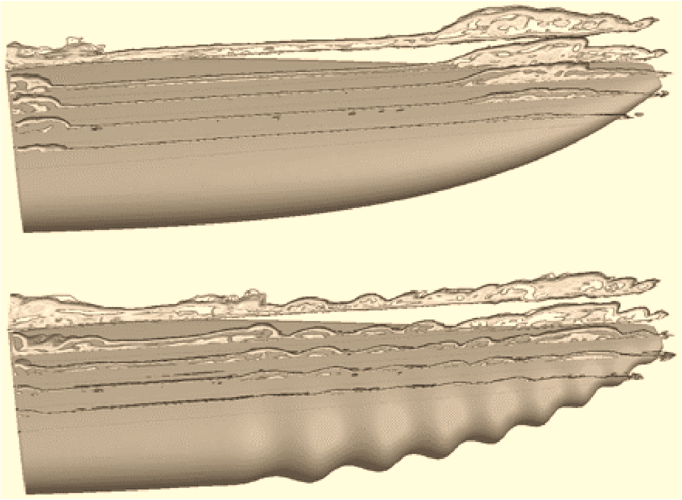


Figure. 2. Tubercle flipper showing vortexes

Tubercles installed on turbine blades can boost energy generation as seen in figure 3. A variable-pitch wind turbine with tubercles retrofitted blades generated more electricity at moderate wind speeds than unmodified blades. At low flow rates, tubercle blades were also shown to be successful in generating electricity by a marine tidal turbine. Blades having tubercles on the leading edges performed better than blades with smooth leading edges [15]

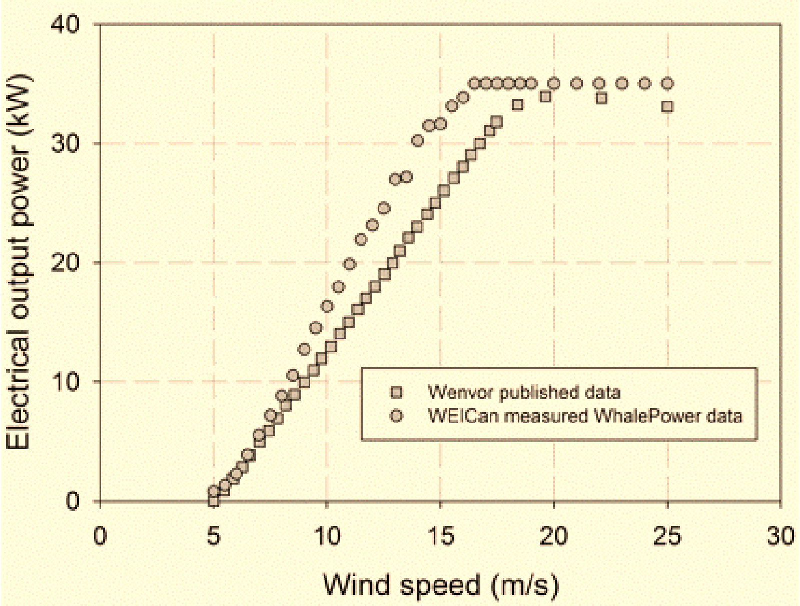


Figure. 3 Tubercles installed on turbine blades can boost energy generation

"Wind tunnel tests of model humpback flippers either with or without leading-edge tubercles have revealed the fluid dynamic gains tubercles make, including a stunning 32% reduction in drag, an 8% increase in lift, and a 40% boost in angle of attack over smoother flippers before stalling". [15]

Researchers at the US Naval Academy expanded on this research and discovered that bioinspired fins based on this concept reduced drag by a third and increased lift by 30%. "More stable airplane designs, submarines with better dexterity, and turbine blades that can harvest more energy from the wind or water," they speculated. While these blades are currently being tested in-house, investigations have revealed that they can create the same amount of energy at ten miles per hour as traditional blades can at seventeen miles per hour[15].

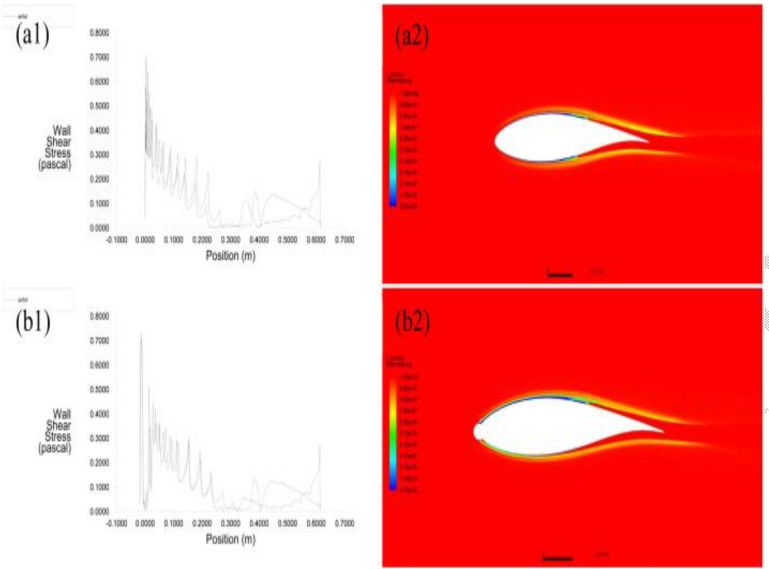


Figure 4. showing the effects of shear stresses on airfoils with tubercles are lesser than on airfoils without tubercles)

2.5 Insight gained

In horizontal-axis wind turbines, a lift is generated by the airfoil geometry of the turbine blades (HAWT). The biggest issue, though, is the likelihood of blade stalls after a certain angle of attack. According to the literature, tubercles, and other devices can improve momentum transfer in wind turbine blades and hence increase lift generation. Concurrently, these changes assist in delaying the stalling of the blade. This study examines the various alterations made to the leading edge of the HAWT blade using tubercles, as well as their implications on aerodynamic performance. The following major findings about the performance of HAWT with leading-edge tubercles are summarized: (i) blades with tubercles on the leading edge will have superior performance in the post-stall regime, (ii) tubercles with a smaller amplitude and lower wavelength will produce higher lift and lower drag in the low wind speed condition, and (iii) tubercle blade will have a stable and smooth performance in varying wind speed conditions, producing higher torque and power at low wind speed.

These findings will, later on, be tested and confirmed with CAD software. The results of these tests will bring some crucial scopes for future research for further developing the HAWT with tubercle blades delineated.

3.0 Project Simulation

In this chapter, a systematic step-by-step approach to proving our findings is sought. The findings above will be tested by various software to give us values. A complete overview of the components being used will also be expanded on to tell us how long the results take to be defined and the modeling of those components as well.

3.1 SolidWorks Software

The final horizontal axis wind turbine blade model will be created in SolidWorks as a 3D model. SolidWorks is used to simplify the simulation process and eliminate project execution faults. By modifying the filename, the model's assembly can be exported to another program. Each component of the wind turbine's aerodynamic attributes can be created in SolidWorks and read automatically in computational fluid dynamics and other tools. The design can be seen from different perspectives

3.2 Motion Analysis of Turbine Blade

Motion analysis in SolidWorks can be used to investigate the dynamics of rigid bodies. This simulation provides a simple method for observing and resolving any concerns with wind turbine blade forces or reactions. It is critical in this project to measure and quantify the forces acting on the wind turbine blade to determine how much torque is being exerted on the model's blades. If the blade pitch angle changes, the torque and inertial forces acting on the blades will change as well. Motion analysis simulations will be run at various blade pitch angles to determine which angle is ideal for operating a wind turbine.

3.3 Simulation Synopsis

The goal of this project is to use SolidWorks and motion analysis to construct and characterize a horizontal wind turbine blade model. This chapter goes over the design difficulties and considerations in greater depth. SolidWorks software is used to assemble and draw all of the required components. The inertial force and torque of the model can be monitored using SolidWorks motion to examine the wind turbine's performance.

By examining how forces and loads are distributed throughout the entire system, motion analysis in SolidWorks is used to examine the dynamics response on wind turbine blades and understand system performance. Motion analysis is used in this research to create a safer and more effective blade prototype. When the model moves, this simulation will calculate and quantify its velocities and reaction forces. The result of these will determine whether our research is either true or false.

Figure 5. Horizontal Axis Wind Turbine model in Solidworks

The model of a wind turbine, as shown in figure 5, is made up of components that were drawn and constructed in SolidWorks. All of the elements are sketched separately and then assembled to form a full wind turbine with the characteristics and dimensions specified. Three blades, a rotor, links, a tower, and a main shaft, make up the model.

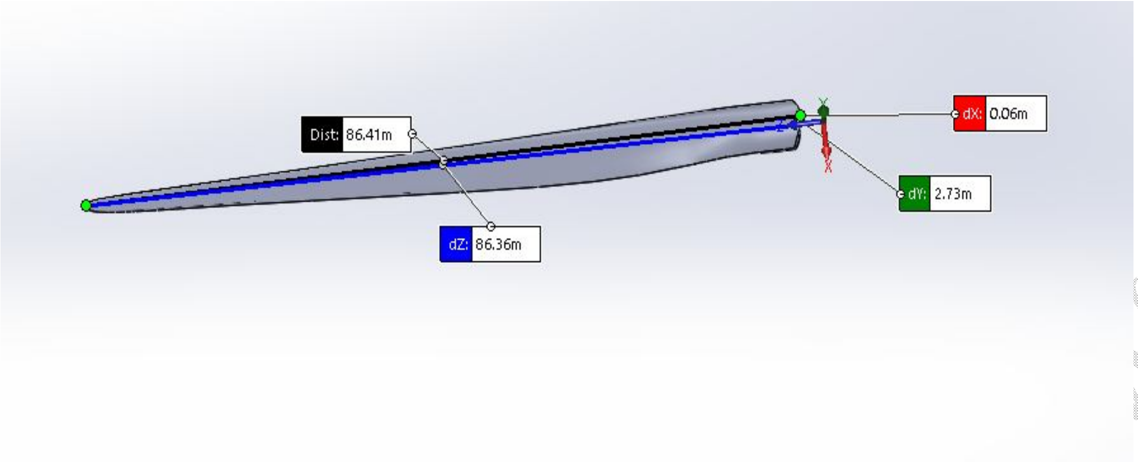


Figure 6. Showing dimensions of normal model turbine blade

4.0 **Results and Discussions**

The diameter of a wind turbine can be calculated by measuring the circumference of an imaginary circle drawn around it. The radius of the wind turbine is measured from one of the points to the hub. The most significant aspect of a wind turbine for capturing wind energy is the blades. As a result, they must be well-designed to achieve the best results.

The blade is constructed of acrylic and measures 86.41m in length. Three blades will be used in this project, and each blade will be spaced 120 degrees apart at the hub. Because of its ability to be easily molded, pressed, and shaped, plastic is used for blades. Apart from that, the usage of plastic is justified due to its versatility for prototyping.

As shown in figure 7, the full turbine model with the blade is then placed in a configured boundary space to simulate environmental wind conditions. In the end, values are then taken to confirm the turbine design is optimum and does not fail with these prevailing conditions of wind. These results undergo iteration which provides the optimum and accurate result and values of forces and torques acting on the turbine with non-modified blades. The results of the simulation are shown in figure 8. It must be noted due to the limitation of solid work computational fluid dynamics fluid or air can only move in the z-direction.

As a result, the velocity acting on the turbine is within the 10 m/s region with turbulence in a criterion of 0.21 percentile.

In figure 10, We can see the side view of the flow trajectories hitting the turbine blades and we can see that at the blades, velocity increases with ensures that maximum lift is being generated due to the difference in pressure on the blades as seen furthermore in figure 13.

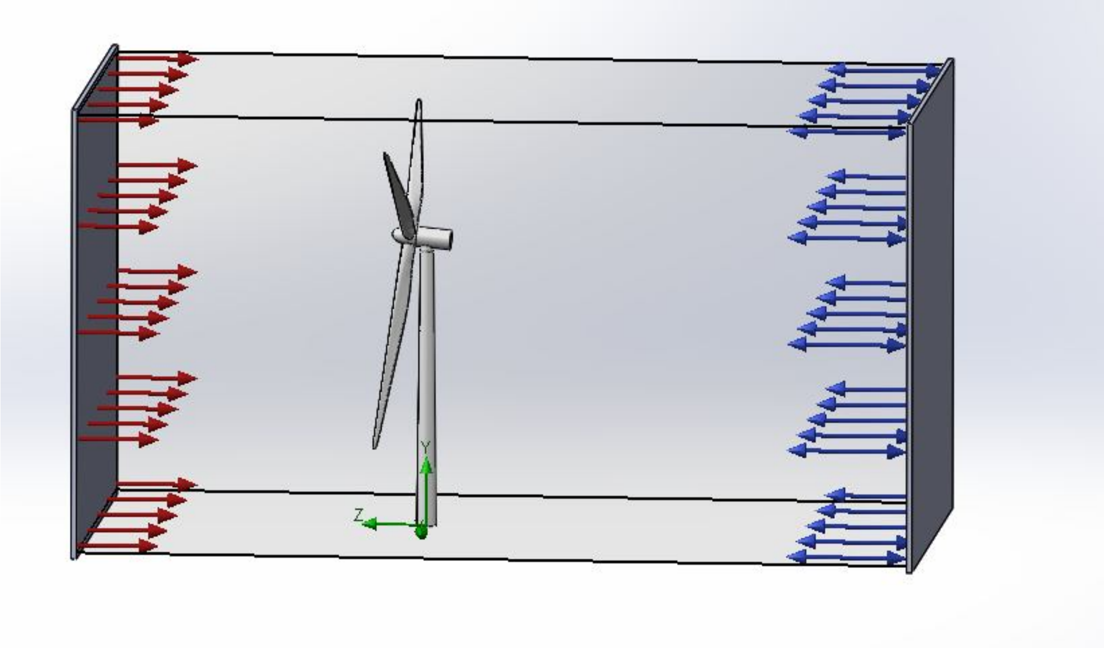
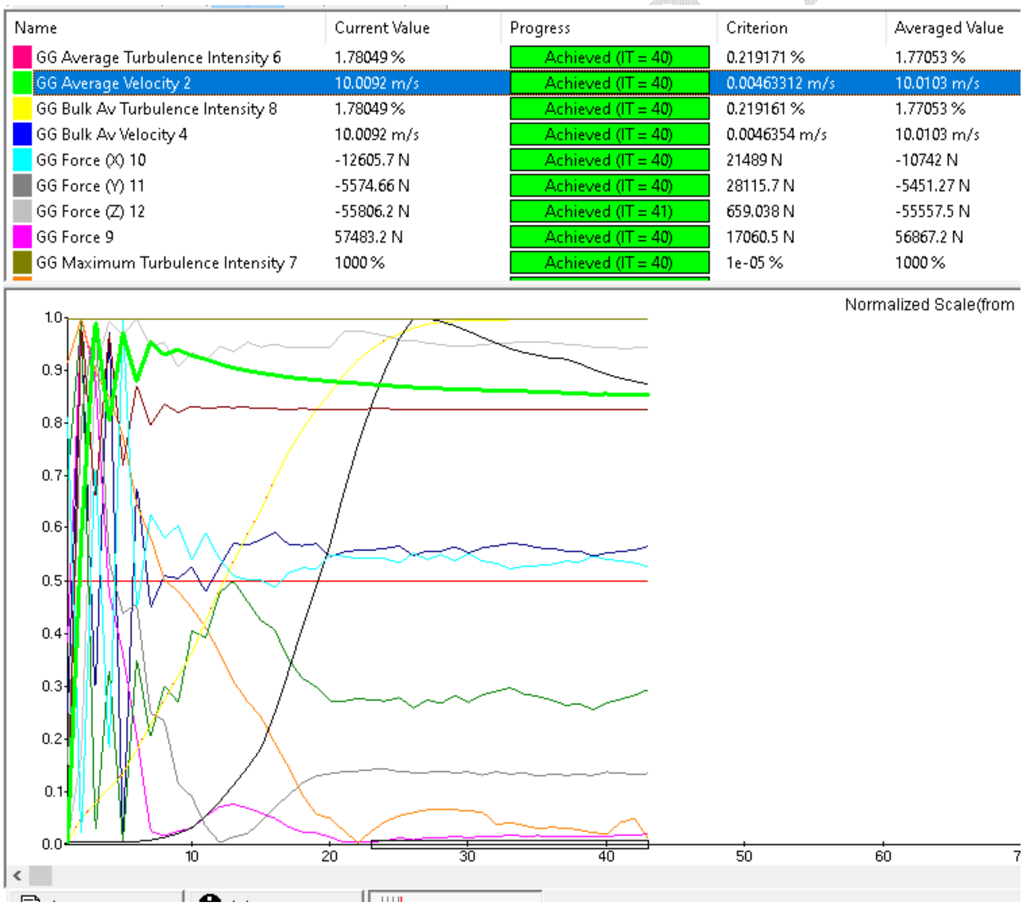


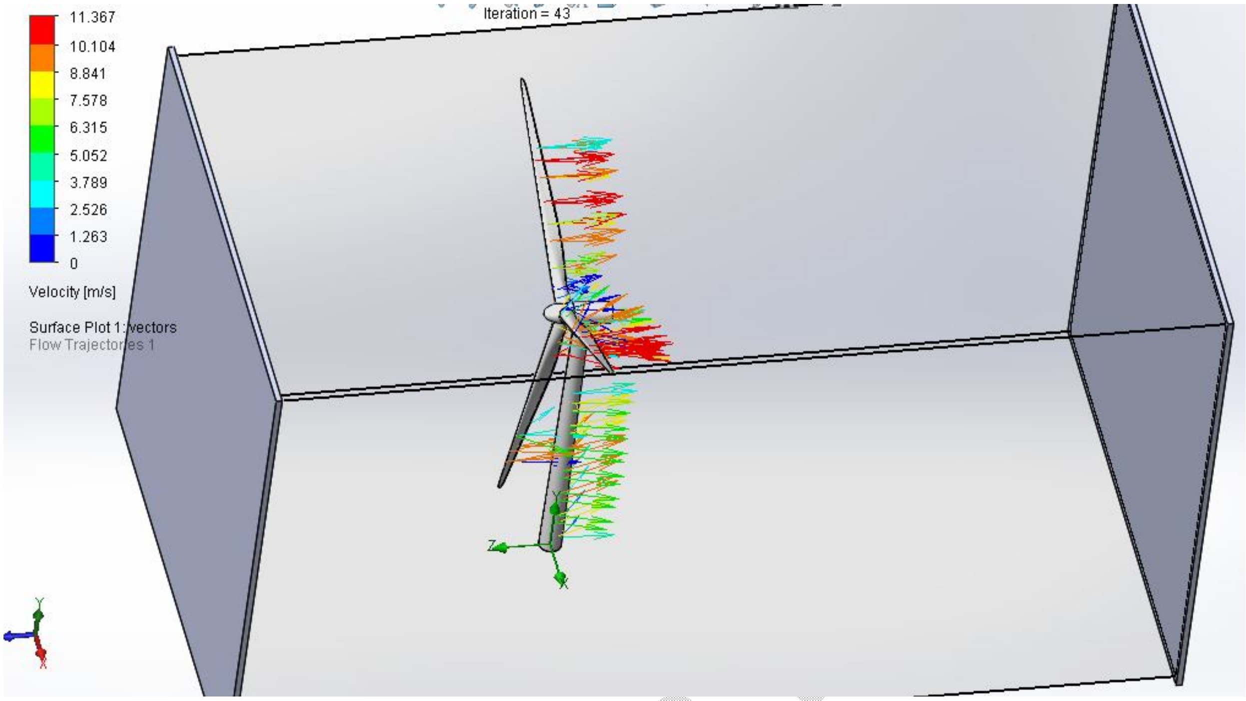
Figure 7. Turbine environmental boundary condition



Name	Current Value	Progress	Criterion	Averaged Value
🟥 GG Average Turbulence Intensity 6	1.78049 %	Achieved (IT = 40)	0.219171 %	1.77053 %
🟩 GG Average Velocity 2	10.0092 m/s	Achieved (IT = 40)	0.00463312 m/s	10.0103 m/s
🟨 GG Bulk Av Turbulence Intensity 8	1.78049 %	Achieved (IT = 40)	0.219161 %	1.77053 %
🟦 GG Bulk Av Velocity 4	10.0092 m/s	Achieved (IT = 40)	0.0046354 m/s	10.0103 m/s
🟦 GG Force (X) 10	-12605.7 N	Achieved (IT = 40)	21489 N	-10742 N
⬛ GG Force (Y) 11	-5574.66 N	Achieved (IT = 40)	28115.7 N	-5451.27 N
⬜ GG Force (Z) 12	-55806.2 N	Achieved (IT = 41)	659.038 N	-55557.5 N
🟪 GG Force 9	57483.2 N	Achieved (IT = 40)	17060.5 N	56867.2 N
🟫 GG Maximum Turbulence Intensity 7	1000 %	Achieved (IT = 40)	1e-05 %	1000 %

1 Figure 8 (Reaction forces acting on the wind turbine)

Figure 9 Reaction forces acting on the wind turbine



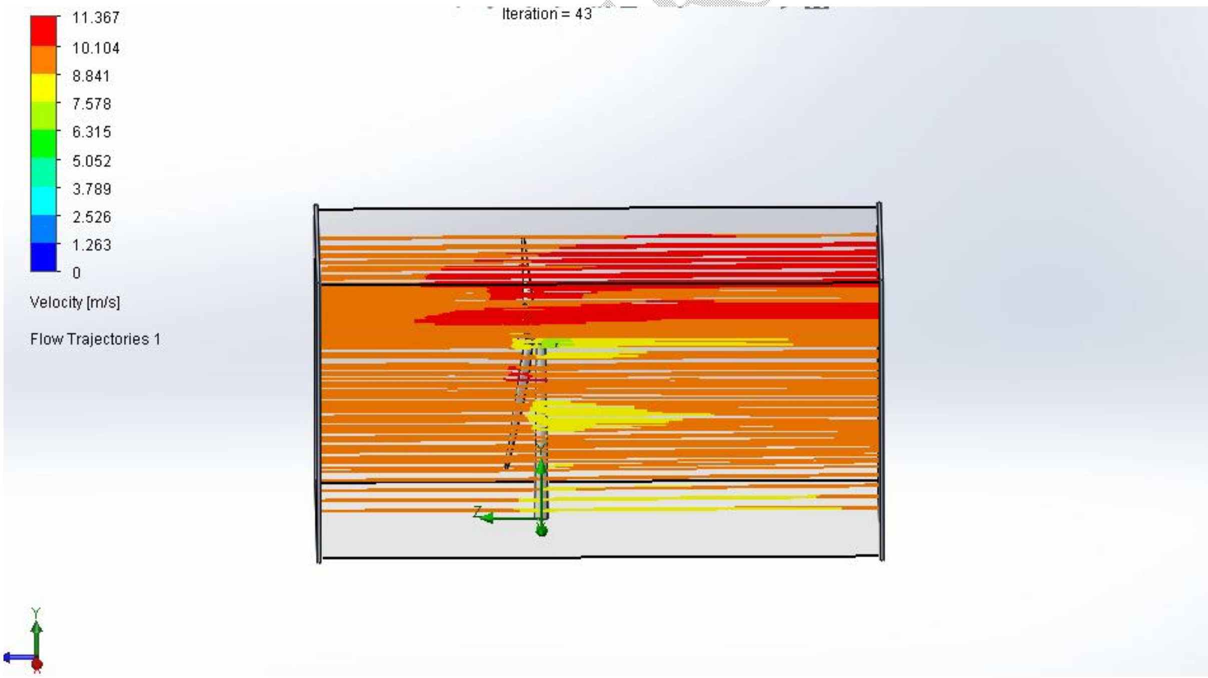


Figure 10. Results showing an increase in velocity at the wing tips

Due to the goal of this study and research which is biomimicry optimization, the tubercles are then employed on the blade. This new blade model, as seen in figure 11, is then assessed based on torque and flow velocities and then compared to the normal pre-existing blade on the normal turbine blade shown in figure 6. An experiment on the flow velocities or to simply put it, the lift and drag coefficients, of the tubercle blade is then conducted to see if our blade is truly an optimized model.

The new blade is tested in solid works which gives us better results and drastic improvements of over 30 percent. In the new simulation, we can observe that the torque generated is over 98,000 Nm while in the previous model, the torque was around 50,000Nm. Not only that, but the pressure differences on the blades as seen in figure 13. indicate that sufficient lift is generated. Further proof of that is the velocities recorded at the leading edge of the tubercle blade as compared to the tail end of the blade. As seen in figure 12, as fluid hits the leading edge of the tubercle velocity reduces but as it travels along the airfoil shape of the turbine blade it increases vastly. This change in velocity indicates lift generation as well, as demonstrated by Bernoulli’s equation the faster a fluid flows the lesser its pressure and vice versa, and those properties can be observed on the tubercle blade

However, since the whole turbine tubercle blade cannot be tested physically an airfoil model is used in a wind tunnel to record lift and drag parameters to show proof of results and theory of practice. As observed in both models of airfoils, blue being a normal airfoil and yellow being the tubercle design (Figure 16), the tubercle airfoil generates more lift and compared to the new airfoil with a 0.3 percent increase

Furthermore, in figure 15, when the tubercle design is compared, we can see vortexes are created which most importantly reduce stall and increase the pitching angle of the blade

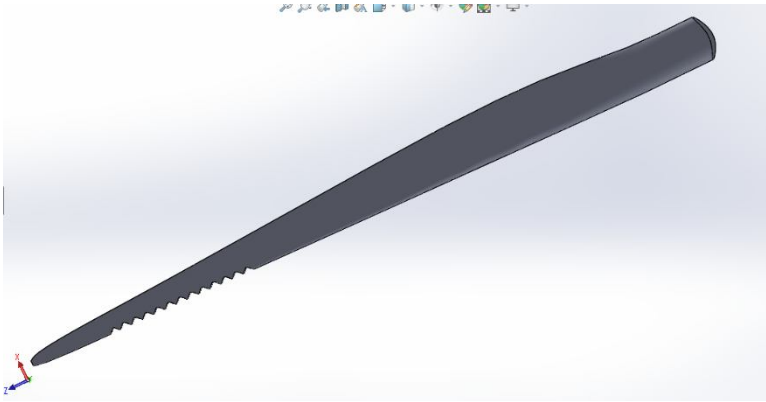


Figure 11 (Tubercle blade design)

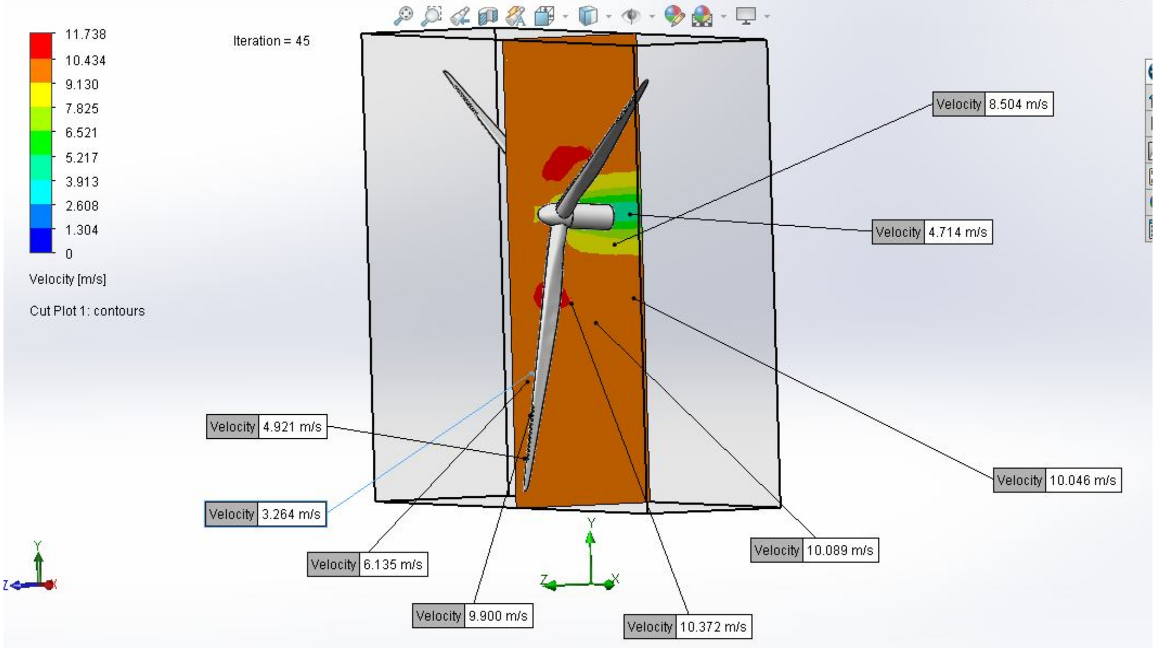


Figure 12 (showing velocities at different points on the turbine blade)

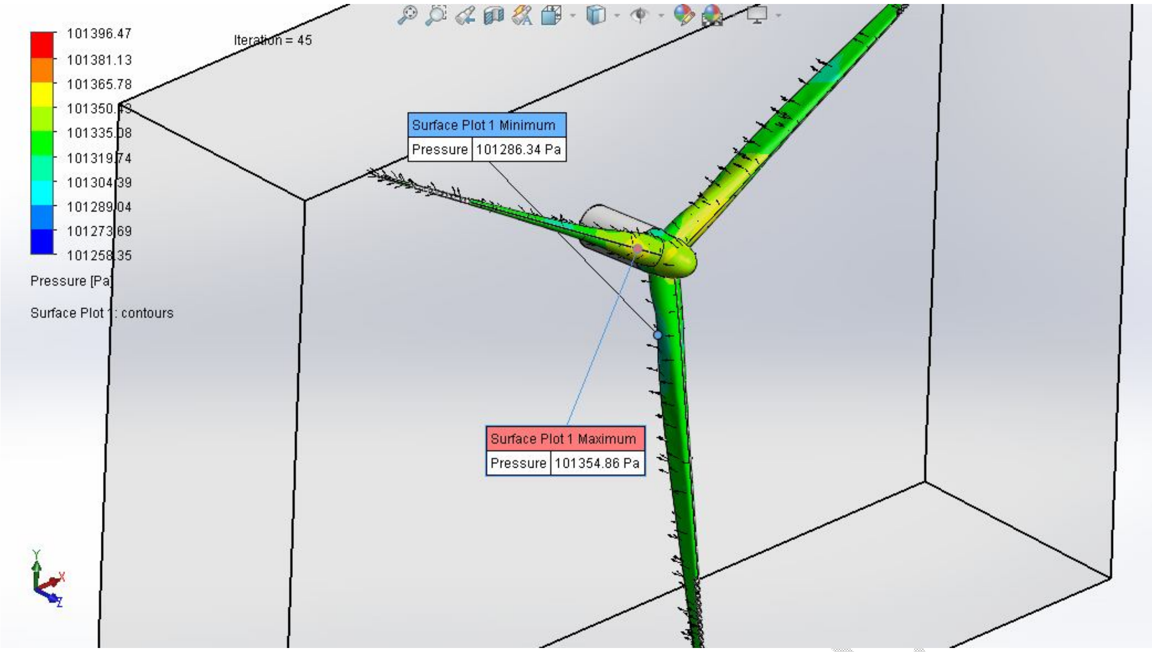
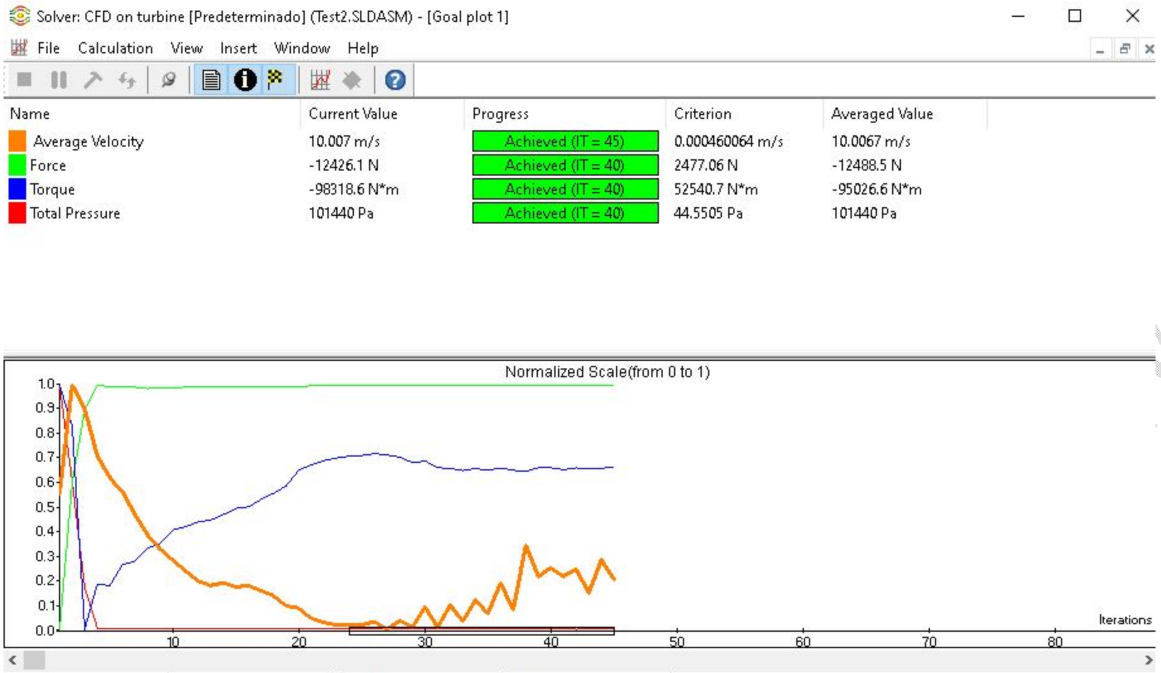


Figure 13 Results showing maximum and minimum pressures



Name	Current Value	Progress	Criterion	Averaged Value
🟧 Average Velocity	10.007 m/s	Achieved (IT = 45)	0.000460064 m/s	10.0067 m/s
🟩 Force	-12426.1 N	Achieved (IT = 40)	2477.06 N	-12488.5 N
🟦 Torque	-98318.6 N*m	Achieved (IT = 40)	52540.7 N*m	-95026.6 N*m
🟥 Total Pressure	101440 Pa	Achieved (IT = 40)	44.5505 Pa	101440 Pa

2 Figure 14 (Results showing the increase in torque)

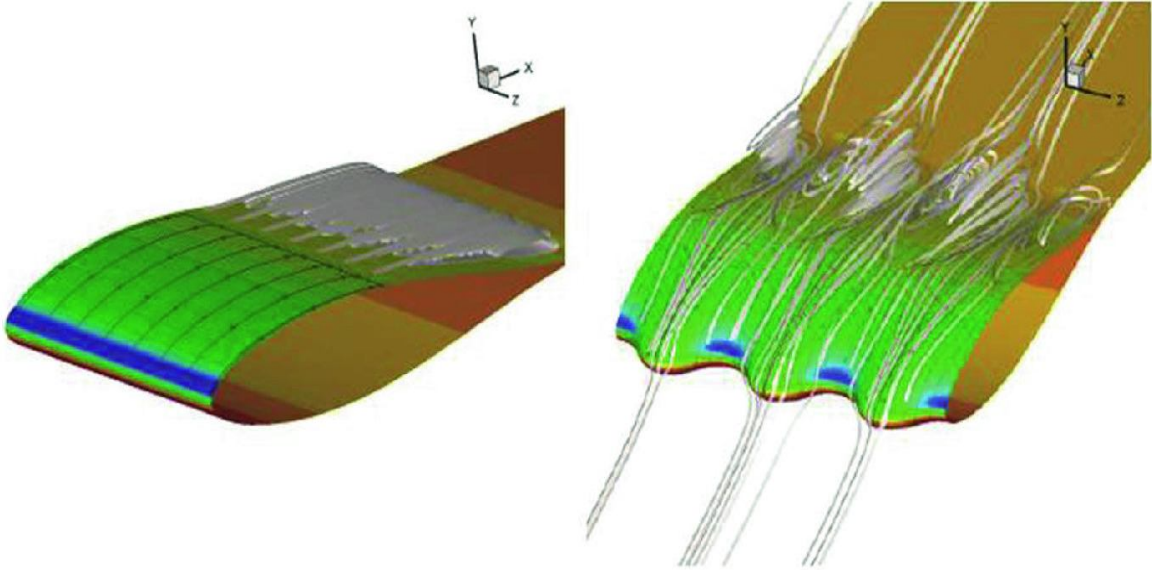


Figure 15 (Tubercle model of NACA 4415 showing vortex creation which reduces stall)

Figure 16.Hand model of tubercle airfoil and asymmetric airfoil

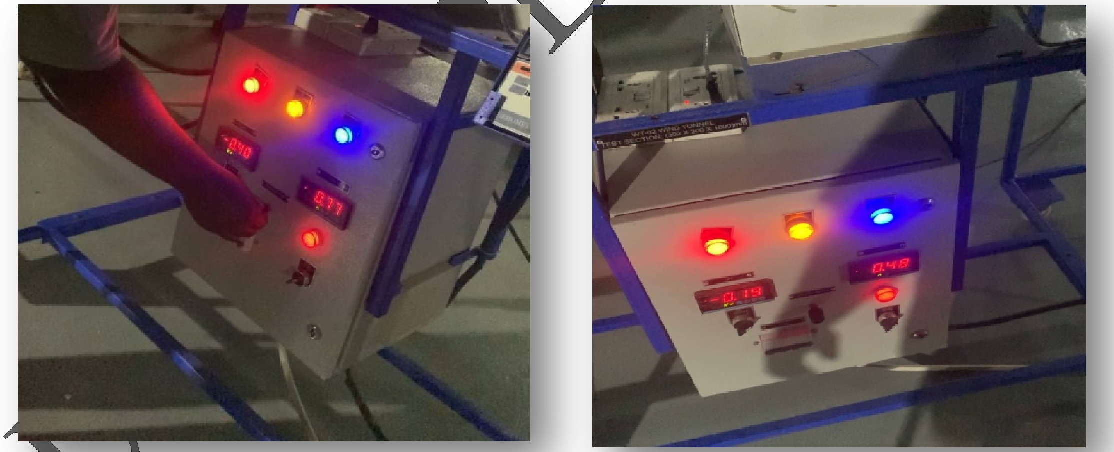


Figure 17.Wind tunnel results of lift and drag with tubercle airfoil having lift coefficient of 0.4 and asymmetric airfoil having 0.19

5.0 Conclusion

To summarize, the goal of this project was to simulate and study the efficiency of a horizontal axis wind turbine employing whale tubercles. To conclude we were able to prove that blades with tubercles on the leading edge have superior performance in the post-stall regime, tubercles with a smaller amplitude and lower wavelength produce higher lift and lower drag in the low wind speed condition, and tubercle blades have a stable and smooth performance in varying wind speed conditions, producing higher torque and power at low wind speed. It's a big deal since this project showed that tubercle blades increase the lift coefficient of any blade and reduce its stall by a drastic amount. It also figures out how much torque is required to rotate the blades at different wind speeds.

REFERENCES

[1] Jha A.R. Wind Turbine Technology (1st ed.). CRC Press.2010. https://doi.org/10.1201/9781439815076

[2] Porté-Agel F, Bastankhah M & Shamsoddin S. Wind-Turbine and Wind-Farm Flows A Review. *Boundary-Layer Meteorol.2020;* **174**: 1–59. https://doi.org/10.1007/s10546-019-00473-0

[3] Fish F E, Battle J M. Hydrodynamic design of the humpback whale flipper. J Morph. 1995.

[4] https://www.jstor.org/stable/25160222

[5] Gopinathan V, Bruce Ralphin Rose J. Aerodynamics with state-of-the-art bioinspired technology: Tubercles of a humpback whale. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering. 2021;235(16):2359-2377. doi:10.1177/09544100211001501.

[6] Akhter MZ, Omar FK. Review of Flow-Control Devices for Wind-Turbine Performance Enhancement. *Energies*. 2021; 14(5):1268. https://doi.org/10.3390/en14051268

[7] Bushnell D.M, and Moore K. J. Drag Reduction in Nature. **Annual Review of Fluid Mechanics** 1991; 23:65-79 https://doi.org/10.1146/annurev.fl.23.010191.000433

[8] Bearman P.W. *et al.*Reduction of bluff-body drag and suppression of vortex shedding by the introduction of wavy separation lines. J. Fluids Struct.1998

[9] Miklosovic DS, Murray MM, Howle LE. Experimental evaluation of sinusoidal leading edges.J Aircraft.2007 .44; pg. 1404-7

[10] Frank E. Fish, Paul W. Weber, Mark M. Murray, Laurens E. Howle. The Tubercles on Humpback Whales' Flippers: Application of Bio-Inspired Technology, *Integrative and Comparative Biology*.2011; 51 (1): 203–213. https://doi.org/10.1093/icb/icr016

[11] Chen, H., Pan, C. & Wang, J. Effects of sinusoidal leading edge on delta wing performance and mechanism. *Sci. China Technol. Sci.2013;* **56**: 772–779. https://doi.org/10.1007/s11431-013-5143-3

[12] Ozen C. A. *and Rockwell* D. Control of vortical structures on a flapping wing via a sinusoidal leading-edge.Physics of Fluids . 2010:**22**(2); 021701. https://doi.org/10.1063/1.3304539

[13] Watts P and Fish F E. The influence of passive, leading edge tubercles on wing performance Proc. Twelfth Intl. Sym. Unmanned Untethered Submers. Technol., Durham New.2001 Hampsh. 2–9.

[14] Chen S, Liu Y, Han C, Yan S, Hong Z. Numerical Investigation of Turbine Blades with Leading-Edge Tubercles in Uniform Current. *Water*. 2021; 13(16):2205. https://doi.org/10.3390/w13162205

[15] Fish FE, Lauder GV. Control surfaces of aquatic vertebrates: active and passive design and function. J Exp Biol. 2017 Dec 1;220(Pt 23):4351-4363. doi: 10.1242/jeb.149617.