Studying the Efficiency of Various Wind Turbine Designs Through CFD Simulation and Experimental Testing

Massimiliano R. Orfanini[1] and Eleonora L. Orfanini[2]
Bachelor of Science in Mechanical Engineering with Aerospace Minor, Boston, MA, 02115, Unites States of America

Eduardo J. Meza Ubeda[3]
Bachelor of Science in Mechanical Engineering with Aerospace Minor, Boston, MA, 02115, Unites States of America

Emily S. Sievers[4]
Bachelor of Science in Mechanical Engineering with Aerospace Minor, Boston, MA, 02115, Unites States of America

Haifa El-Sadi[5]
Professor of Aerospace and Mechanical Engineering
Mechanical Engineering Dept., Faculty of Engineering, Wentworth Institute of Technology

As fossil fuel resources deplete, the importance of advancing renewable energy technologies grows; one of those technologies being the wind turbine. Thus, the challenge for many engineers is to improve the design of wind turbines. As turbines use wind as their renewable source, it is beneficial for the engineers developing them to have a strong understanding of Aerodynamics. This project aims to apply knowledge of Aerodynamics to the design of vertical wind turbines and to understand the relationship between turbine design and efficiency through CFD Simulation and Testing. This project's focus is on Vertical Axis Wind Turbines (VAWTs). As the name implies, the VAWT is oriented so that the wings rotate along the vertical axis. VAWTs are mostly used in urban settings, as VAWTs do not require a larger land mass to cover and are more convenient for individual use. However, VAWTs yield less power output than their counterpart, the Horizontal Axis Wind Turbine (HAWT), so it is relevant to improve the VAWT so that they can play a larger role in the transition to renewable energy. Through the duration of this project, the group will test how different blade shapes, and the number of blades affect the drag and power generated from the wind turbine.

[1] Undergraduate Student, Mechanical Engineering, AIAA Student Member 1421032.
[2] Undergraduate Student, Mechanical Engineering, AIAA Student Member 1422008.
[3] Undergraduate Student, Mechanical Engineering, AIAA Student Member 1422010.
[4] Undergraduate Student, Mechanical Engineering, AIAA Student Member 1326924.
[5] Faculty Advisor, Department of Mechanical Engineering, AIAA Member.

I. Introduction

Wind energy is often associated with the use of wind turbines to produce electricity. Wind turbines are commonly used today, although this technology has been used among people for many years. One of the earliest uses of wind power originated when sailors used sailboats to explore the seas and new lands, giving birth to an era of sea transportation. Although, throughout history, the use of wind power was mostly by sailboats at sea, developments in technology allowed for wind power to be utilized on land. Introduced in Persia, the earliest wind turbines were built on a vertical axis and used for grinding grains and extracting water. This technology was later adopted by the English, who created a more efficient horizontal axis design, named post-mill. As most of Europe started adopting wind power to produce flour, oils, and transport water; a new and more powerful windmill was developed, given the name "Tower Mill." Unlike the post-mill, it consisted of a cap at the top of the tower which allowed it to rotate separately from the rest of the structure, allowing for a more efficient multi-directional movement towards the direction of wind flow. It was when the telegraph was discovered, in the mid-19th century, that electricity started becoming an essential part of living. As the discovery picked up quickly around the world, scientists started to discuss the interrelation between wind power and electricity which led to the first wind turbine design by Charles Brush. Its goal was to supply enough electricity for his experiment on the "Electric Arc Lighting System." Although it was abandoned for many years until after the First World War, new concepts of aerodynamics were applied to produce light and efficient wind turbines [1].

The relationship between wind power and electricity is measured in $/kWh. One of the main drawbacks of wind energy is the variance in the amount of wind available at certain sites and the cost of land the turbine is settled on. These factors influence the production price of the electrical energy generated. The annual energy production at a specific site can be estimated when the characteristics of a given turbine, the power for a given wind speed, and the annual wind distribution are known. A wind turbine transforms the kinetic energy in the wind into mechanical energy in a shaft and finally into electrical energy in a generator [3].

Power increases with the cube of the wind speed and linear with density and area. In general, the tower height of a turbine is important as the wind increases with height above ground and the rotor diameter is important as it gives the area. As a rule of thumb, turbines in Denmark produce approximately 1000 kW/year. However, production is very site-dependent [3].

Sailors have discovered early on that using lift force is far more efficient than drag force as the source of propulsion. Lift and drag are the components of the force perpendicular and parallel to the wind's direction. There are currently two types of wind turbines, vertical axis wind turbines (VAWT) and horizontal axis wind turbines (HAWT). HAWTs are mostly used to produce large amounts of electricity and are usually found in rural areas where high-speed winds are found. The reason being a horizontal axis wind turbine is explained by the name itself, the blades rotate around the horizontal axis. For the turbine to work, the blades must always be pointing perpendicularly to the wind.

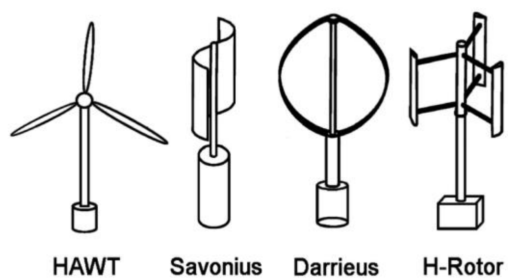


Fig. 1 Wind Energy Types Top Sellers

The Yaw System is built to ensure just that, by adjusting the rotation of the turbine about the direction of the wind. Some of the disadvantages of HAWTs include but are not limited to: difficulty aligning properly and quickly to the wind's direction, complicated mechanical components situated at the top, blade aerodynamics are complicated, and with longer blades the higher the aerodynamic noise [2]. On the other hand, VAWT blades spin around the vertical axis and are omnidirectional to the wind. The wind could come from any direction, and the blades would keep spinning without the need for a Yaw System. The most popular designs of VAWTs are Darrieus and H-Rotor which use lift force, and Savonius which uses drag force as the source of propulsion. Despite producing less energy than their HAWT counterparts, some of the main advantages of VAWTs include simpler blade geometry, complicated components located at ground/sea level allowing for easier maintenance work and it can better withstand turbulent winds in urban areas caused by surrounding constructions [2].

II. CAD Model Designs

To explore the impact of different geometrical parameters on VAWT performance, the group focused on varying the blade shape while keeping base dimensions (such as width, height, and thickness) constant across all designs. Each group member developed a unique design for further evaluation and comparison using CFD analysis.

Table 1 Dimensions and Shapes of Blade Designs

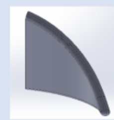
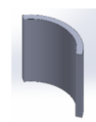
	Length (in)	Width (in)	Thickness (in)	Blade Design
Blade Design 1	3	3	0.25	
Blade Design 2	3	3	0.25	
Blade Design 3	3	3	0.25	
Blade Design 4	3	3	0.25	

Table 1 shows the base dimensions of each blade design created using Solidworks and Fusion 360 Modeling software. The data acquired in the first phase will be used to determine the most efficient blade shape, which will then be chosen for further testing in a full model consisting of varying numbers of blades.

III. Single Blade Win Tunnel Drag Force Testing

With all the blade designs printed, they were each placed into the wind tunnel to measure their lift and drag forces. Based on the experimental data, the most efficient design in terms of drag force was identified and developed into a full design minimal scale wind turbine for further testing. Since all designs were of the drag type, the lift force resulted in negative and almost nonexistent values. The drag force and lift force were recorded and are shown in Table 2, taking three measurements for each design at varying wind velocities: 25%, 50%, 75%, and 100%. For accuracy, the drag force produced by wind tunnel stand, was subtracted from the blade's drag force values. Their average values were calculated, and their behavior is shown in Figure 2 to study the impact of different velocities on the drag force.

Table 2 Wind Tunnel Drag and Lift Force of Different Designs Data

Wind Tunnel Designs Corrected				
Design #	Velocity (%)	Velocity (m/s)	Drag Force (N)	Lift Force (N)
Design 1	25	7.91	0.057	-0.003
	50	16.22	0.340	-0.050
	75	23.74	1.007	-0.097
	100	32.31	1.993	-0.147
Design 2	25	7.91	0.063	-0.003
	50	16.22	0.363	0.007
	75	23.74	1.070	-0.080
	100	32.31	2.003	0.057
Design 3	25	7.91	0.053	0.000
	50	16.22	0.320	-0.017
	75	23.74	0.910	-0.047
	100	32.31	1.910	-0.043
Design 4	25	7.91	0.097	0.003
	50	16.22	0.523	-0.007
	75	23.74	1.457	-0.110
	100	32.31	2.917	-0.130

The data acquired in Table 2 highly sustains the idea that a higher surface area will result in higher drag force values. As one can tell from Table 1, for design number 4, the area which will be subject to drag force due to wind velocity, is much greater than the surface areas of its opposing designs. Figure 2 shows a graphical representation of the designs' performance. Notice how blade design 4 had an overall greater rise in drag force compared to its counterparts.

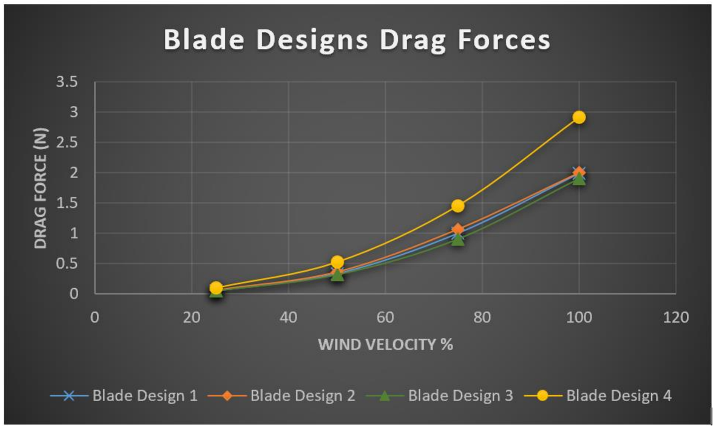


Fig. 2 Designs' Drag Force Graphical Comparison

Although the blades tested were of the drag type design, Table 2 showed that there were minor lift force effects during the wind tunnel tests. These almost insignificant lift forces, both positive and negative, will be converted into angular motion. Figure 3 displays a graphical representation of the lift forces for each design, showing that they don't have a clear trend, but each design has the highest absolute value of lift force at the highest speed. This suggests that although the pattern is not evident, the lift forces do have some effect on the wind turbines' performance.

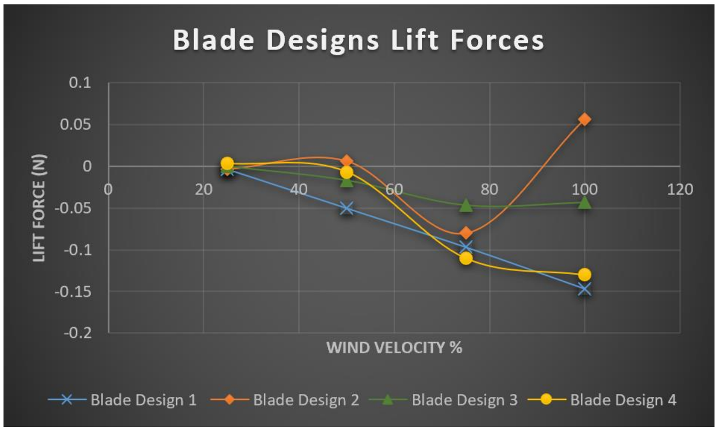


Fig. 3 Designs' Lift Forces Graphical Comparison

After examining the data in Table 2, Fig. 2, and Figure 3, the group further analyzed the design with higher drag and lift forces, that is design 4. In the upcoming phase, additional testing was conducted to investigate the impact of the number of blades on the drag and lift forces. Specifically, VAWTs with three, four, five and six blades were developed and tested. The results were used to determine the optimal number of blades for generating maximum angular velocity.

IV. Final Blade Design Wind Tunnel Drag Force Testing

During the second phase of testing, each VAWT design with varying blade numbers was subjected to four different wind velocities (25%, 50%, 75%, and 100%) in a wind tunnel. Initially, it was expected that the designs would rotate when subjected to wind, but this expectation was proven wrong as none of the VAWTs rotated. Consequently, the most useful data for identifying the most efficient design were the drag and lift forces, presented in Figure 4 and Figure 5, respectively. Table 3 shows how the drag force values for the multi-blade designs are significantly higher than the one-blade design due to the one-directional wind causing one blade to produce drag in a counterclockwise direction while the other produced a clockwise force. Since the wind tunnel didn't allow for the blades to rotate, the largest overall drag force was assumed to have the greatest potential for positive spin. However, this assumption does not consider the negative impact on the back face of the blades, which may result in an opposite direction of spin.

Table 3 Wind Tunnel Drag and Lift Force of Different Blade Numbers Data

Wind Tunnel Designs and Blade Numbers Corrected				
Blade #	Velocity (%)	Velocity (m/s)	Drag Force (N)	Lift Force (N)
3 Blades	25	7.91	0.200	-0.007
	50	16.22	1.197	-0.057
	75	23.74	3.013	-0.107
	100	32.31	5.647	-0.240
4 Blades	25	7.91	0.173	-0.050
	50	16.22	1.080	-0.183
	75	23.74	2.873	-0.457
	100	32.31	5.497	-0.877
5 Blades	25	7.91	0.207	-0.010
	50	16.22	1.303	-0.097
	75	23.74	3.340	-0.263
	100	32.31	6.280	-0.687
6 Blades	25	7.91	0.177	0.010
	50	16.22	1.033	0.007
	75	23.74	2.763	-0.077
	100	32.31	5.280	-2.800

Table 3 data further supports the idea that Savonius-type VAWTs are predominantly drag-driven, meaning that as they generate more drag than lift force due to their blade geometry. All recorded drag force values are higher than the corresponding lift force values at the same wind velocity. It is widely known that lift-driven turbines, such as modern HAWT and Darrious VAWTs, tend to operate more efficiently than drag-driven turbines. As observed in the previous section, lift force magnitudes increase as the wind velocity increases. Table 3 indicates that the 4-bladed design produces the maximum lift force at each stage, whereas the 6-bladed design yields the minimum. However, since drag force data has greater variation and overall values, it was concluded that analyzing the efficiency of Savonius VAWTs is better served by utilizing drag force data, rather than lift force data. Hence, even though the 4-bladed design has the highest lift force, the 5-bladed design is considered the most efficient as it generates the greatest drag force.

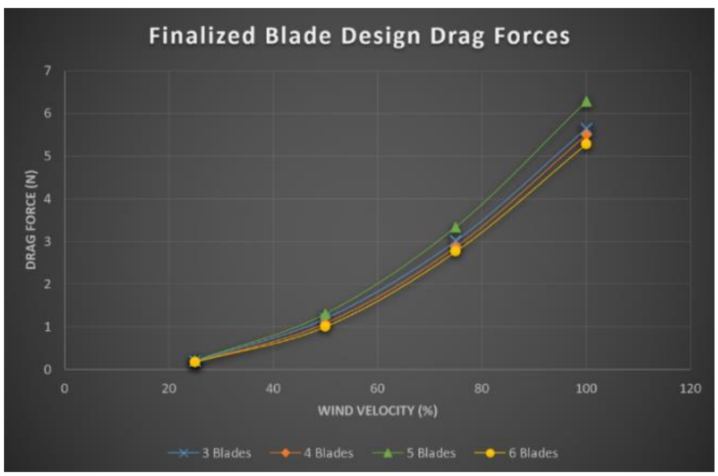


Fig. 4 Blade Number's Drag Force Graphical Comparison

As previously mentioned, Figure 4 reveals that the 5-bladed design generated the highest amount of drag force, while the 6-bladed design produced the least. The 3-bladed design generated the second-highest amount, followed by the 4-bladed design. Our experimentation has demonstrated that there is no linear correlation between the number of blades and the drag force produced. Furthermore, Figure 5 displays the graph of lift forces, demonstrating an increase in down forces as wind speed rises.

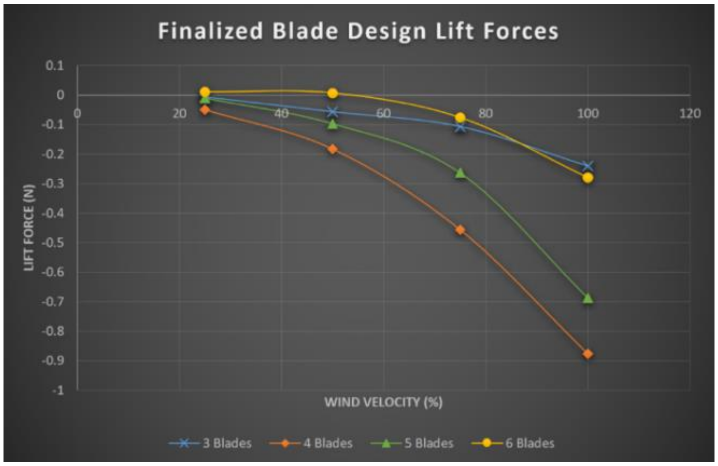


Fig. 5 Blade Number's Lift Force Graphical Comparison

Although Savonius-type VAWTs are primarily driven by drag, the lift force they generate still has a minor impact on the turbine's overall efficiency. Similarly, lift-driven turbines are still influenced by the small amount of drag they produce. As in the previous analysis, our experimentation suggests that there is no evident linear correlation between the number of blades on a VAWT and the lift force it generates.

V. SolidWorks Flow Simulation

In all simulations, a thin wall was constructed on the side of the VAWT models where the inlet velocity is placed on its surface, serving as the boundary condition. The simulation aims to determine the drag force exerted on the VAWT model at different velocities and compare the simulated data with the experimental data obtained from the Wind Tunnel experiment. As the experimental drag force at 25% velocity was negligible, the team opted not to conduct a flow simulation at this time and instead focused on the more substantial values to showcase the simulation process.

A. 3 Blades VAWT Model Convergence Graphs

Figure 6 through Figure 8 show the convergence graphs of flow simulations carried out for a 3-bladed vertical axis wind turbine design at three distinct velocities.

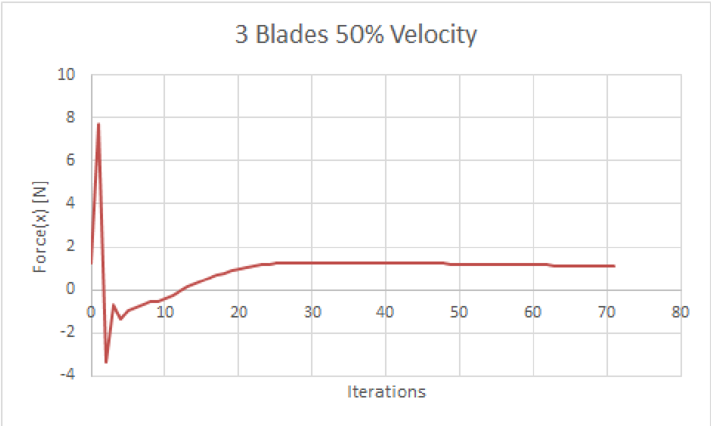


Fig. 6 Drag Force at 50% Velocity (3 Blades)

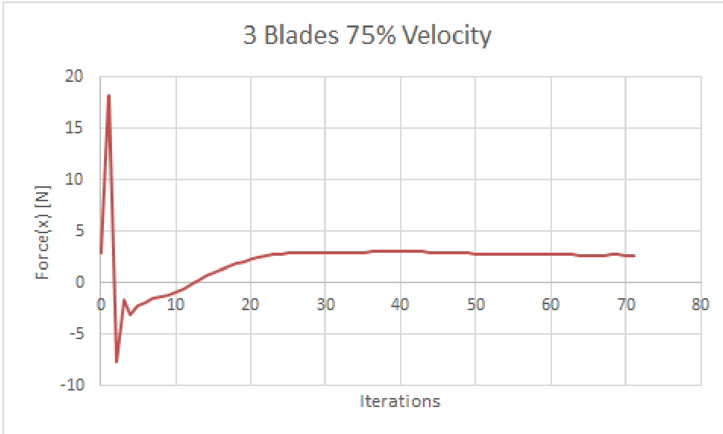


Fig. 7 Drag Force at 75% Velocity (3 Blades)

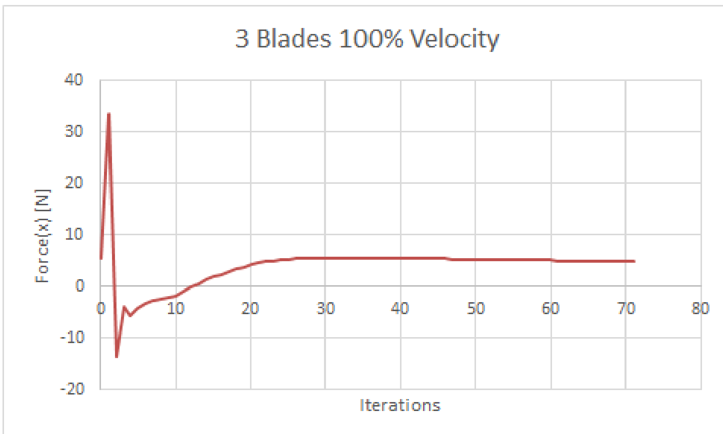


Fig. 8 Drag Force at 100% Velocity (3 Blades)

B. 4 Blades VAWT Model Convergence Graphs

Figure 9 through Figure 11 show the convergence graphs of flow simulations carried out for a 4-bladed vertical axis wind turbine design at three distinct velocities.

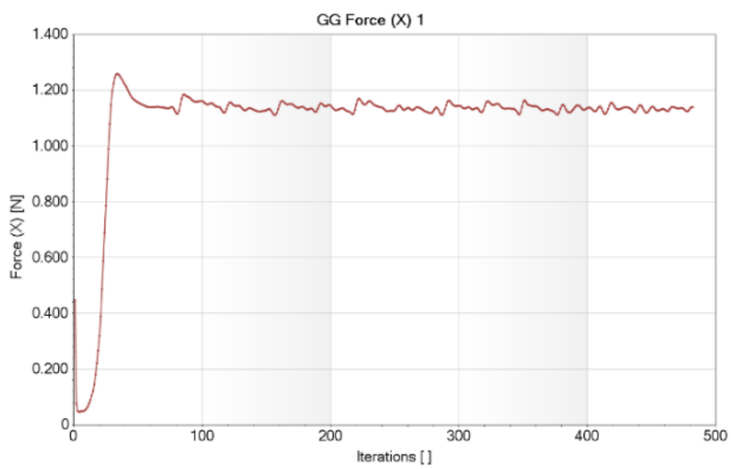


Fig. 9 Drag Force at 50% Velocity (4 Blades)

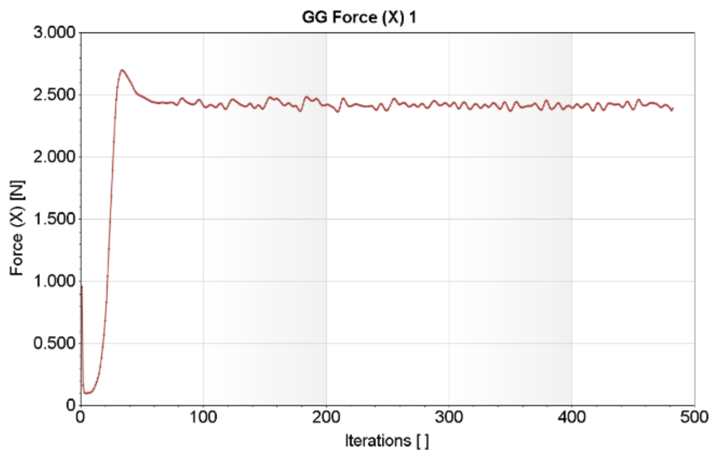


Fig. 10 Drag Force at 75% Velocity (4 Blades)

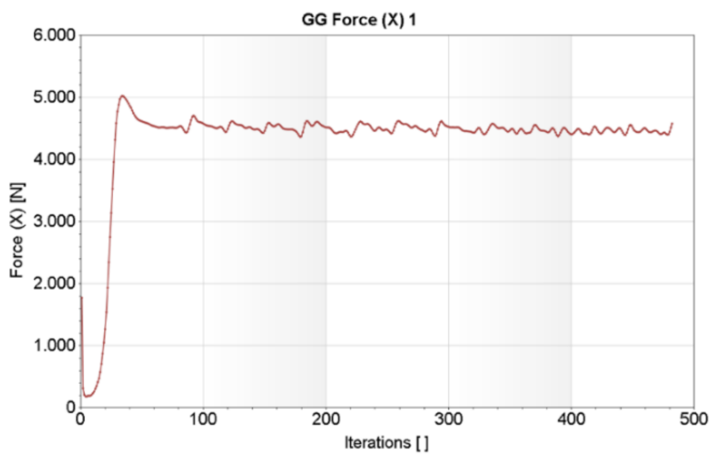


Fig. 11 Drag Force at 100% Velocity (4 Blades)

C. 5 Blades VAWT Model Convergence Graphs

Figure 12 through Figure 14 show the convergence graphs of flow simulations carried out for a 5-bladed vertical axis wind turbine design at three distinct velocities.

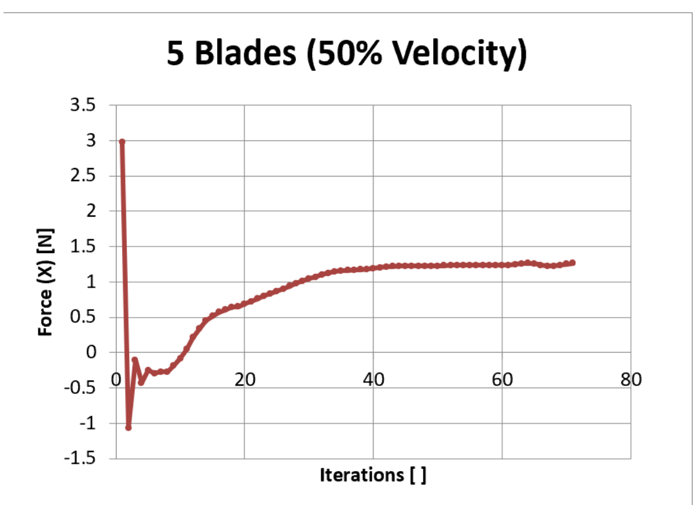


Fig. 12 Drag Force at 50% Velocity (5 Blades)

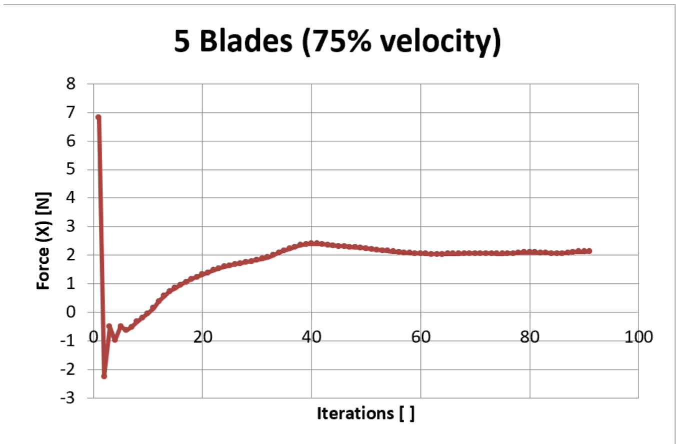


Fig. 13 Drag Force at 75% Velocity (5 Blades)

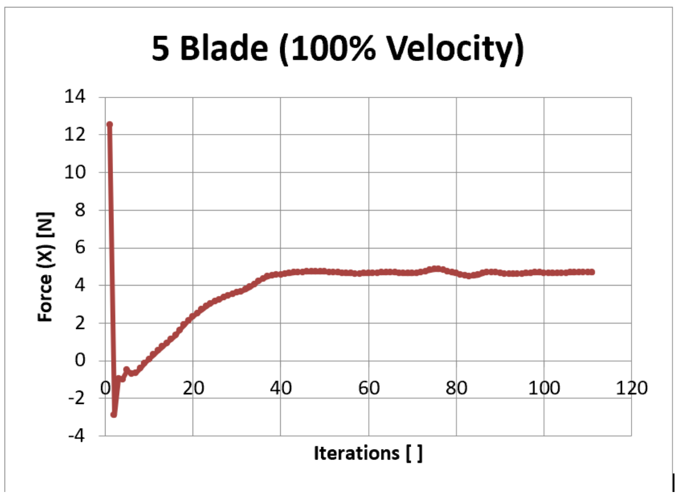


Fig. 14 Drag Force at 100% Velocity (5 Blades)

D. 6 Blades VAWT Model Convergence Graphs

Figures 15 through 17 show the convergence graphs of flow simulations carried out for a 6-bladed vertical axis wind turbine design at three distinct velocities.

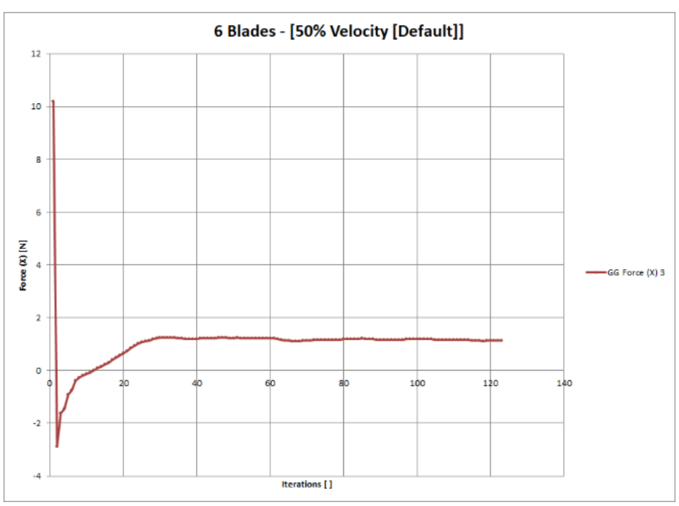


Fig. 15   Drag Force at 50% Velocity (6 Blades)

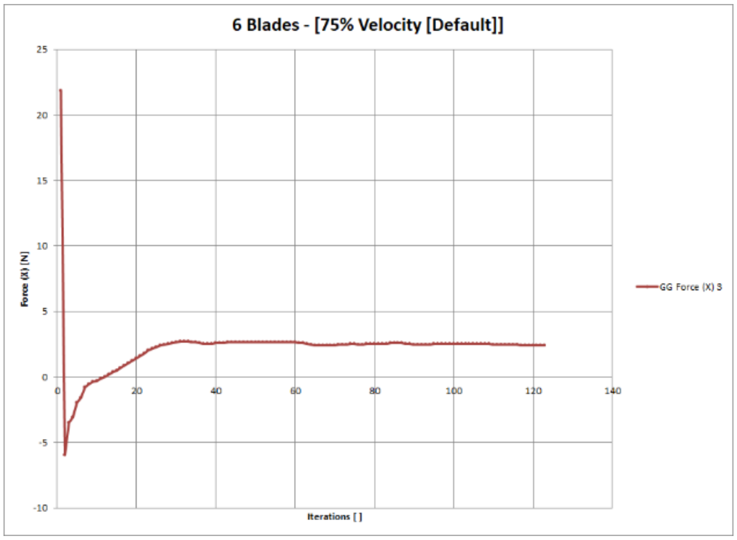


Fig. 16   Drag Force at 75% Velocity (6 Blades)

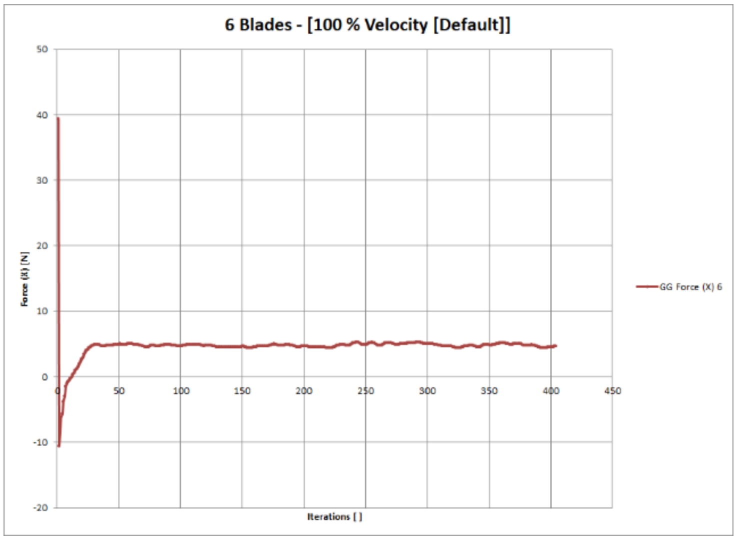


Fig. 17   Drag Force at 100% Velocity (6 Blades)

The convergence graphs for each section, shown in Figures 6 through 17, yielded average, maximum, and minimum values for drag. The average drag values obtained from these graphs were recorded in Table 4. Furthermore, a comparison was made between the simulated drag values in Table 4 and the experimental drag values recorded in Table 3, by performing percentage error calculations.

Table 4   Summarized SolidWorks Flow Simulation Results for Varying Number of Blades

Blade #	Velocity (%)	Drag Force (N)	Error (%)
3 Blades	50	1.17437	1.89
	75	2.75603	8.52
	100	5.12104	9.31
4 Blades	50	1.133	4.91
	75	2.419	15.80
	100	4.464	18.78
5 Blades	50	1.2356	5.17
	75	2.0795	37.74
	100	4.6719	25.61
6 Blades	50	1.1652	13.89
	75	2.4931	10.84
	100	4.8296	9.325

VI. Conclusion

Simulations were carried out on the different number of blades to confront experimental data acquired through wind tunnel testing, with computational fluid dynamics results obtained using SolidWorks flow simulation tools. For the validation of the results, percent error calculations were performed and summarized in Table 4. The ideal percentage error between experimental and simulated values would be less than 10%, however, that is shown to be true for only a few of the simulations. Considering that flow analyses at 50, 75, and 100 percent velocities were set up equally in terms of boundary conditions and meshing, and only one out of the three resulted in a percent error less than 10%, one can conclude that the simulation results are precise. For those velocities where the percent error is not acceptable such as the average drag force at 100% velocity for the 5-blade design, one can conclude that the wind tunnel testing was not accurate, due to possible blade orientation differences, incautious manipulation of stand placement, and turning of the prototype caused by high wind speeds in the tunnel, while setting up and running experimental testing. For accuracy in the values obtained in the simulation, the lowest average percent error throughout all blade numbers is considered, consequently, 50% velocity will be taken into account for further comparison. For the wind tunnel testing it was concluded that having a 5-blade VAWT design resulted in higher drag forces, this can be verified through SolidWorks simulation, which yielded the highest average drag force for the same number of blades at 50% velocity. After careful consideration of all data and results presented, the best design of drag type VAWT can be said to be one with the greatest surface area exposed to wind direction, therefore, with data justification, design number 4 was chosen based on the larger amount of drag force it experienced compared to its counterparts. Once the most effective design in terms of drag forces was determined, the number of blades was changed to observe its effect on the power of VAWT turbines. Both wind tunnel experimentation and SolidWorks simulations were run for better analysis of the results. As shown in tables 3 and 4 both means resulted in a 5-blade design, at 50 percent velocity, to have higher drag forces, therefore, higher efficiency in producing torque. It is through best knowledge acquired in this report and its substance that one can infer a drag type VAWT design whose surface area exposed to wind direction is of greater dimensions, and whose number of blades is five in comparison to three, four, and six, results in higher torque and, therefore, higher power produced.

References

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