Development of the Performance Characteristics of a Vertical Axis Wind Turbine

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Abstract

Performance curves aid in energy assessment and performance monitoring of wind turbines and can be used as a guide for turbine applications where a generic comparison between different types can be made before selection.This study design, build and carried out a performance analysis on a lift-type Vertical Axis Wind Turbine (VAWT). It was discovered that the efficiency of the wind turbine increased with tip speed ratios. A maximum tip speed ratio of 1.08 was achieved under limited wind speeds which meant that the rotational speed of the device was the same as the wind velocity. This occurred for a rotor solidity of 0.51. This implied that the wind turbine operated like a drag -type design since these have tip speed ratios less than or equal to 1.

Index terms— efficiency, drag-type, tip speed ratio, solidity.

1 General Background

he performance curve of a wind turbine depicts the relationship between the Efficiency and Tip Speed Ratio at varying wind speeds and is an important characteristic of wind turbines. Horizontal Axis Wind Turbines (HAWT) are the most common types of turbines presently where they are utilized in irrigation systems, water pumping and electricity generation. Despite possessing numerous advantages, Vertical Axis Wind Turbines (VAWT) are not as common as they have few drawbacks such as low starting torques required for operation. Performance curves aid in energy assessment and performance monitoring of wind turbines and can be used as a guide for turbine applications where a generic comparison between different types can be made before selection. Wind turbines must operate at their optimum tip-speed ratio to enhance its efficiency, maximizing the amount of power extracted from the wind stream. Due to its rarity, a prototype Vertical Axis Wind Turbine was built and its performance characteristics are developed and analyzed upon testing.

2 II.

3 Vertical Axis Wind Turbines

Vertical axis wind turbines incorporate either straight or curved blades (seen on Darrieus rotors) where their axes are spun perpendicular to the wind stream. Vertical axis wind turbines possess the ability of capturing wind energy from any direction. Despite this, vertical axis wind turbines have not benefitted from years of development that have been undertaken by their Horizontal axis counterparts ??Paraschiviou, 2002). Both lift-type VAWT and HAWT contain approximately the same efficiencies however, Horizontal Axis designs are still commonly used presently. Vertical Axis Wind Turbines are often classified in accordance to their aerodynamic and mechanical characteristics, their lifting surfaces or their movement of the rotor's blades about a vertical axis along a path in a horizontal plane. There a presently four types of vertical axis wind turbines.

4 i.

Articulating straight-blade Giromill, ii.

Savonnius Rotor (drag-driven device), iii.

Variable-geometry Musgrove which permits reefing of the blades and iv.

The "Jump rope" shaped Darrieus rotor where the blades are fixed. The H-Rotor or Giromill as shown in Figure 1 is a variation of the Darrieus concept and is most commonly used. It is also a vertical axis type wind turbine in the shape of an H (Hemami, 2012). The vertical segments consist of the active blades which are connected to the output shaft by middle segments (usually arms). The blades are also constructed with an airfoil cross-section; hence these types of turbines work on the principle of lift and have relatively high tip-speed ratios. These lift forces on the blades create a torque that enable rotation. When two blades are incorporated in the design, the H-rotor operation begins to pulsate since the downward blade moves 180º to 360º wake of the upwind blade hence capturing less energy than the other blade. Due to this effect, H-Rotor turbines consist of three or more blades in the design to allow for smoother operation.

Vertical Axis Wind Turbines have several advantages over the Horizontal Axis designs. Some include: (i) Components such as generator or gearbox can be positioned on the ground or low levels for easy access and maintenance. (ii) They do not need any yaw mechanism to turn them in the direction of the wind (Hau, 2006).

5 T

(iii) Increased safety since components located at low levels would keep workers away from climbing tall towers for maintenance and repair purposes. Wind turbines are responsible for the transformation of kinetic energy available in the wind stream into mechanical energy. This energy can further be converted into electrical energy once a generator is connected to the system (Hansen, 2015). The maximum available energy, P max once the wind speed attains zero velocity is theoretically given as follows:P max = 1 2 x ? x A x ?? ?? 3

Where ? = density of air in kg/m 3 , A = area where wind speed has been reduced, ?? ?? = velocity of wind in m/s. This equation is useful as it demonstrates the increase in power with the cube of the wind as well as an increase with density and area. However, the velocity of the wind cannot be reduced to zero hence a power coefficient, C p is introduced known as the Coefficient of Performance. This provides the relationship between the actual power extracted and maximum available power in the wind. For ideal turbines, a theoretical C p value, denoted as the Betz' Limit is given as 16 27 = 0.593. Practically, most wind turbines do not operate near this limit with modern optimized turbines reaching up to 50% efficient at most.

6 b) Wind Turbine Aerodynamics

An object placed in a path of a wind stream experiences two forces from the wind. These forces are known as aerodynamic forces and can be broken down into a lift force and a drag force. Figure 2 demonstrates a simple rectangular object placed in the path of a wind travelling. When the wind passes over the plate, the plate is pushed, and this is due to the force component that is parallel to the wind direction. However, depending on the angle of the plate, the incoming wind causes a pressure difference on both sides. This pressure difference forces the plate to be pushed upwards as shown in Figure 2. The component of the force that is parallel to the wind stream is called the drag force while the one that is perpendicular is known as the lift force. One of the main factors that gives rise to this movement is the angle of attack with respect to the wind and the object. When the angle of attack is small, the lift force is greater than the drag force and as the angle of attack increases, the drag force significantly increases. Figure **??** shows the lift forces acting on a VAWT in the wind. Wind turbines that rely on lift forces to produce the torque required for rotation incorporates the use of airfoil blades which are similar in concept to plane wings as shown in Figure **??**. The same concept applies to the airfoil cross section like that described for the plate shown in Figure 2. These airfoil blades can provide larger lift forces that cause a coupling effect, allowing them to spin quite faster than those that work on the principle of drag while providing a higher efficiency. The blades of VAWT can be supported with the horizontal struts in different orientations. The three main types of blades support can be categorized as (i) cantilever support, (ii) simple support, and (iii) overhang support. To minimize the parasitic drag, cantilever or one horizontal supporting strut per blade is preferred (Ramkissoon, Manohar and Adeyanju 2015). There are a wide variety of different airfoil cross sections with the National Advisory Committee for Aeronautics, NACA, designing many with varying profiles and characteristics.

As shown in Figure **??**, the cross section of an airfoil can be broken down into several parts. These are: Designing and obtaining the performance characteristics of wind turbines are influenced by three main indicators. These are the variation of power, torque and thrust with wind speed **??**Burton, 2001). Power determines the amount of energy captured and harnessed by the turbine's rotor, the developed torque contributes to the sizing of any gearbox required when matching a generator to a turbine's output while rotor thrust often has significant influence on tower design. Hence assessing and expressing the performance by means of non-dimensional characteristic performance curves is most appropriate regardless of its operational conditions. In making assumptions that no deterioration of aerodynamic performance of the rotor blades occurs, the non-dimensional aerodynamic performance of the rotor blades will be dependent on the tip speed ratios. The tip speed ratio of a wind turbine is a nondimensional factor and is characterized by the relationship between wind speed and rate of rotation of the rotor. Hence the coefficient of performance, power, torque and thrust parameters can all be expressed as a function of tip speed ratios.

The Coefficient of Performance, C p of a wind turbine can be obtained from the equation:C p = ?? ?????? ?? ???? = ?? ?????? 0 . 5 ?? ?? ?? ?? ?? ?? 3

Where P out is the output mechanical power from the turbine (Watts), P in is the power input from the wind stream (Watts), ?? is the air density at area of operation (kg/m 3) A = rotor area (m 2) V = velocity of the wind (m/s). The Tip-Speed Ratio can be calculated as follows:? = ?? ?? ð ??”ð ??” ??

where r = radius of rotor (m), ? = rotational speed of turbine (rad/s), V = velocity of wind (m/s). The maximum theoretical efficiency of a wind turbine is given by the Betz' Limit of approximately 59% (Ragheb, 2014).

However, most wind turbines in practical operate below this limit and this is shown in Figure 5 where the performance curves for various turbines were developed. For 2-bladed turbines, it can be observed that the maximum efficiency achieved is 45% at an operational tip-speed ratio of 0.6 while efficiencies of 10% and 22% are achieved at its cut-in and cut-out speeds respectively. Hence this data provides an indication that the turbine should operate at its optimum tip-speed ratio to maximize efficiency. The number of blades of a wind turbine contributes to another nondimensional parameter known as solidity. Solidity is known as the ratio of blade area to the rotor swept area.

Horizontal Axis Wind Turbines with a low number of blades are categorized as low solidity rotors which constitutes to a low fraction of the solid area swept by the turbine's rotor. Due to this, the rotor must now spin faster to extract maximum power from the wind since most of the wind passes unperturbed through the several gaps in the fewer blades present at low speeds. The faster moving rotor would increase the solid area swept by the blades hence allowing the wind turbine to properly harness the energy available.

7 Methodology

A small model was designed and built for testing as shown in Figure 6. NACA 0018 cross-section was chosen to create the airfoil blades due to its thick cross-section and ease of manufacture. The airfoil coordinates were generated online using NACA's Airfoil Plotter and the shape of the airfoil was produced with a chosen design chord length of 0.13m as shown in Figure 7. Cedar wood was used to construct the blades due to its high strength to weight ratio and its ability to be easily carved into its required shape. Aluminum was the chosen material for the shaft, hub and rotor arms where a hollow 0.038m diameter pipe was used for the shaft at a design length of 0.66m. The hub was constructed using a standard 0.10m thick aluminum sheet with a chosen design diameter of 0.23m. Three hollow aluminum bars measuring 0.03m x 0.01m were used for the rotor arms at a length of 0.36m each. Each blade was mounted onto the arms via two L-shaped aluminum brackets at their centers. The brackets were adjusted to ensure that the blades' chord line was perpendicular to the rotor arms. To allow for rotation, a used air-conditioning motor was used where the wind turbine's shaft was fixed onto the motor's shaft. The motor's shaft was mounted onto the motor bearings found inside. This was selected due to ease of rotation and lack of friction generated by the inner bearings. The entire wind turbine was then bolted onto a wooden table with steel legs of 0.77m tall which was fixed onto the ground during testing for increased height and stability. The height of the entire device including the table measured approximately 1.7m. A Solid Works simulation of the rotor arms is provided in Figures 8, 9 and 10. Figure 8 shows the stress analysis of the rotor arm, Figure **??** the factor of safety while Figure 10 The Stress Plot of the rotor arm obtained on Solid Works Simulation highlighted that the maximum stresses induced in the component due to the weight of the blades did not exceed the yield strength of the material used. This showed that the arms did not fail under the required loading.

From Figure **??**, it can be shown that a minimum factor of safety of 2.3 was achieved from the program. A factor of safety of 3 was utilized for the design calculations with both sets of values being almost consistent. The maximum deflection of the arm was found to be 6.945 x 10 ?001 mm as shown in Figure 10.

When conducting the simulation, a fixed-joint was used in the program while a static load of 6.11N was applied to the free end where the blade is to be positioned. The wind turbine was tested on a hill top at Gran Couva, Trinidad so as to achieve a wide range of wind speeds for data analysis. The hill top was selected due to the absence of buildings and structures which contribute to wind shear and turbulence of the wind. To obtain the power output of the wind turbine at different wind speeds, a simple dynamometer system was constructed as shown in Figure 11.

A spring scale was used to measure the force output as opposed to a self-calibrated spring since the spring balance had already been calibrated from the factory and would produce more accurate results. A simple spring was also not utilized because upon extension, the spring can sag at the center due to its horizontal layout, affecting the readings. A small rubber belt of circular cross-section was chosen.

Figure 11: Showing the dynamometer built A flat-type rubber belt provided too much friction with the rotating pulley mounted onto the shaft, creating a "jumping" action during contact. Hence a thin rubber belt of circular cross section was settled upon which provided sufficient frictional contact with the pulley. The spring scale was bolted onto a wooden block where one end of the belt was attached, and the other end connected to a hand-adjustable wooden block. The angle of wrap was varied to ensure sufficient frictional contact of the belt was made with the pulley during rotation.

The force exerted by the turbine's shaft and rotational speed of the shaft were recorded at different wind speeds as shown in Table 1.

Since parameters such as wind speed, rotational speed and force output needed to be measured simultaneously, three persons were involved in recording the values. The results obtained were then utilized in obtaining the Tip Speed Ratios and Efficiencies of the wind turbine at different wind speeds as shown in Table 2.

8 Results and Discussion

Based on the results obtained from Table 2, a graph of Coefficient of Performance against Tip Speed Ratio was plotted as shown in Figure 12. This figure provides information on how the efficiency of the turbine varies with a non-dimensional parameter known as the tip speed ratio. Vertical Axis Wind Turbines (VAWT) operating on the concept of lift usually have tip speed ratios greater than 1 which implies that they are capable of rotating faster than the wind stream. The graph can also be used to determine the optimum operating conditions of the wind turbine. This is where at a certain value of tip speed ratio, the wind turbine has the highest efficiency and must be designed to operate in these conditions.

Figure 12: Graph Showing the Coefficient of Performance against Tip Speed Ratio However, the optimum conditions of the prototype were not obtained due to a limited range of wind speeds available during testing. As shown in Figure 12, there is an increase in turbine efficiency with an increase in tip speed ratio. However, due to practical conditions the absence of a wide range of wind speeds limited the results obtained hence a maximum tip speed ratio of 1.08 was achieved with a coefficient of performance of 24.4%. This was achieved for a rotor solidity of 0.51. At low tip speed ratios, less than 1, it can be observed from Figure 13 that the wind turbine generally has low efficiencies. This occurs because the rotor spins quite slowly, allowing the incoming air to pass through the gaps in the rotor. Hence, the wind turbine is not able to maximize the energy from the wind. The efficiency increases with tip speed ratio until it reaches its optimum conditions. This is usually represented by a peak in the curve as shown in Figure 13. After reaching its optimum operating conditions, the efficiencies tend to decrease with increasing tip speed ratios despite the turbine spinning at high speeds. This occurs because the rotor rotates very quickly acting as a solid wall. The incoming wind is now blocked from penetrating the turbine's rotor and the turbine is not able to harness enough energy from the wind. Theoretically, wind turbines can extract approximately 59% of the wind energy.

Based on the results obtained, the maximum efficiency of the turbine under limited testing conditions was found to be 24.4% with the potential to be more efficient at higher wind speeds and tip speed ratios. A fairly low rotor solidity of 0.51 provides an indicator of the potential of the wind turbine to attain higher efficiencies. The use of the handmade dynamometer could have played a part in limiting the power output due to slippage between the belt and rotating pulley inducing power losses and affecting the efficiency of the device at varying wind speeds. The presence of the rotor arms could have also affected the air flow over the airfoil, therefore inducing losses and affecting the efficiency of the device.

Vertical Axis Wind Turbines are known to have low starting torques where some of them make use of a starter motor for rotation to commence. Upon testing the prototype, it was found that the wind turbine started spinning at a wind speed as low as 0.95m/s. No assistance was given to the device to start spinning. A graph of power output against wind speed for the prototype was plotted as shown in Figure 14. It can be observed that the wind turbine started producing power at approximately 1.5m/s where there is an exponential increase of power generated by the device with increasing wind speeds.

For an increase in wind velocity, it can be observed that there is an increase with the tip speed ratios as well as shown in Figure 15.

The tip speed ratios increase up to approximately 1.08 at a wind speed of 4.24m/s. This means that the wind turbine was spinning about the same speed of the wind which is not consistent with lifttype devices. However, at higher wind speeds, there could have been higher tip speed ratios, greater than 1, indicating that the turbine is rotating quicker than the speed of the wind. At high tip speed ratios, usable power can be extracted from the turbine for generating electricity.

At high speeds, wind turbines are subjected to high stresses that can cause the components to fall apart. Wind turbines are usually designed with stall, a similar concept experienced by aircrafts. Wind turbines can either be stall-regulated or pitch-regulated. Pitchregulated wind turbines usually consist of an active control system where the pitch angle is varied. This is performed by turning the blade about its own axis where the torque and rotational speed are significantly reduced at high wind speeds. The blades pitch, causing turbulence of the wind flowing over the airfoil surface breaking up the lift and inducing drag forces. Pitch-regulated wind turbines experience increasing power up to rated wind speed after which the power output remains constant. Stallregulated wind turbines however, depend on their blade design to reduce lift forces at high wind speeds, reducing the power output of the turbine. A stall mechanism was not incorporated in the prototype and the rotating turbine was decelerated and stopped by hand due to the absence of a braking mechanism.

V.

9 Conclusion

The main objective of this project was to design, build and test of a Vertical Axis Wind Turbine (VAWT). A lift-type device was constructed, and two days of testing were performed at a hill-top. Upon testing, the following data was obtained:

The wind turbine began spinning in wind speeds as low as 0.95m/s.

There was an increase in turbine efficiency with tip speed ratio which was consistent with existing lifttype turbines.

Under limited wind speeds, a maximum tipspeed ratio of 1.08 for a rotor solidity of 0.51 was achieved which meant that the turbine was spinning just as quickly as the wind. However, lift-type VAWT usually have tip speed ratios greater than 1 and this could have been obtained at higher wind speeds. [1]

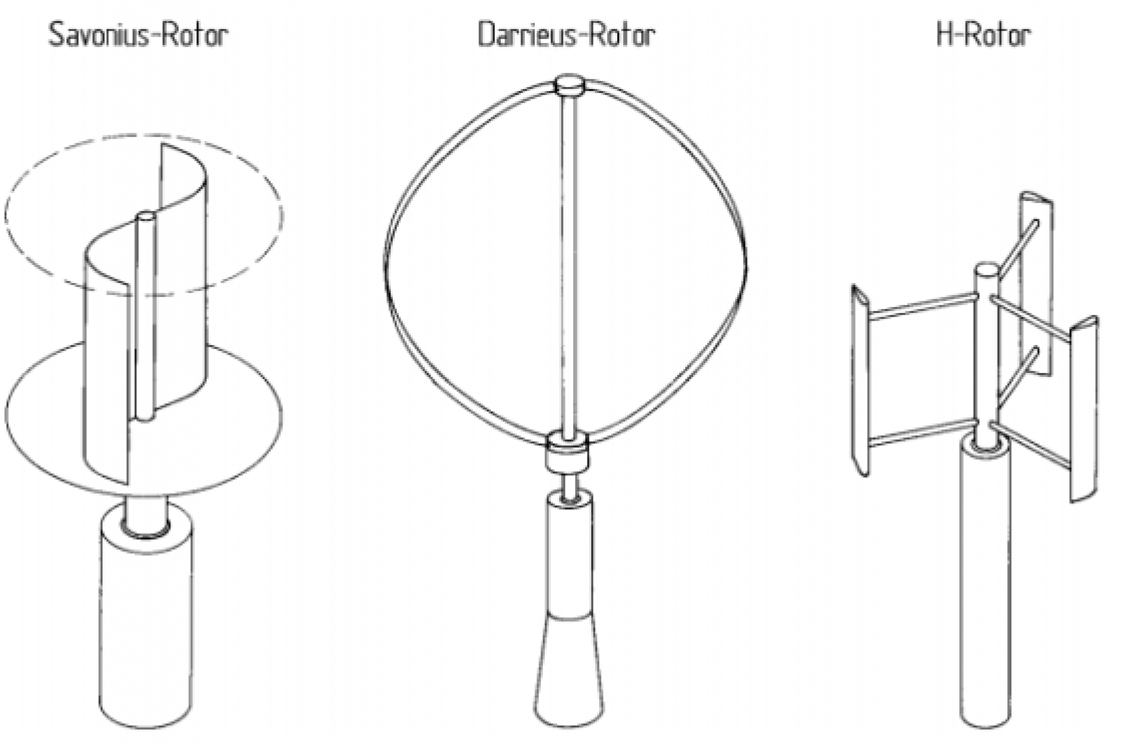

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Figure 1: Figure 1 :

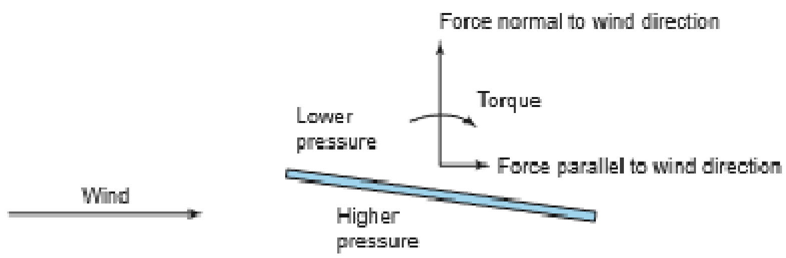

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Figure 2: Figure 2 :

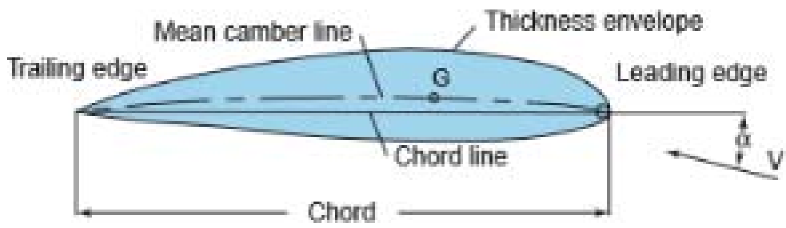

Figure 3: -

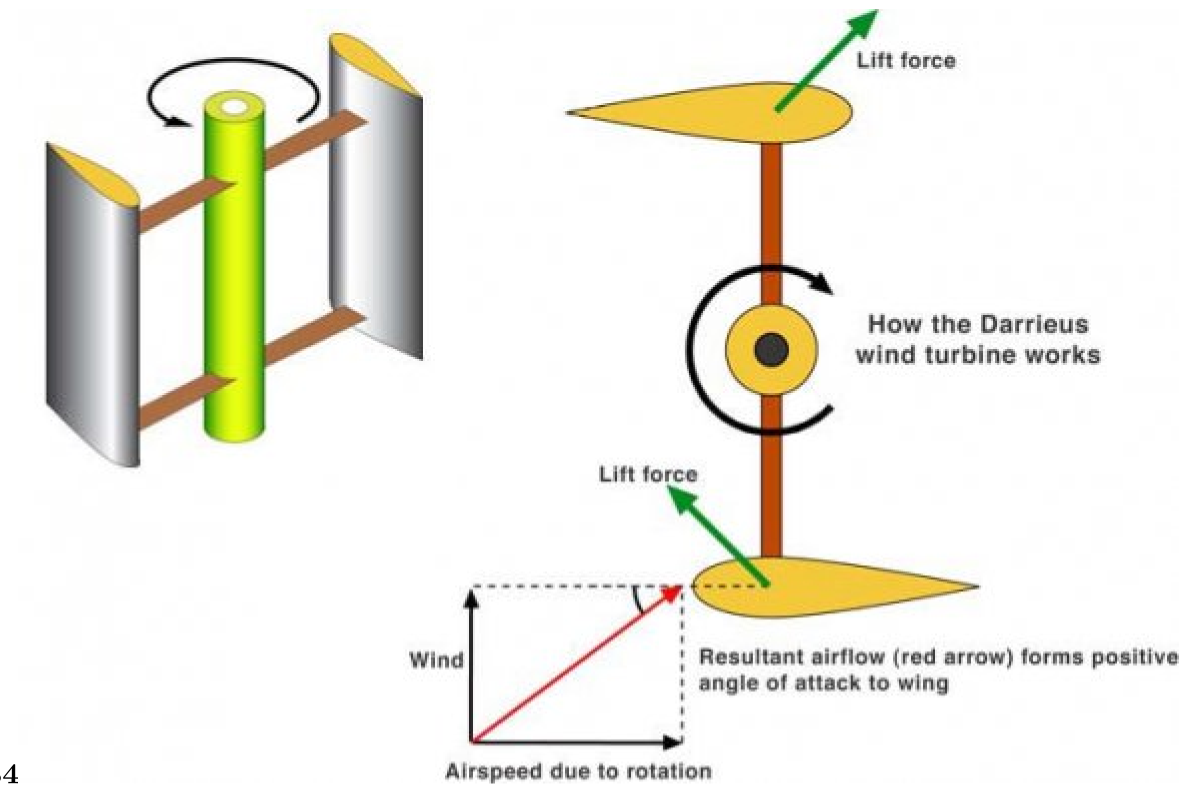

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Figure 4: Figure 3 :Figure 4 :

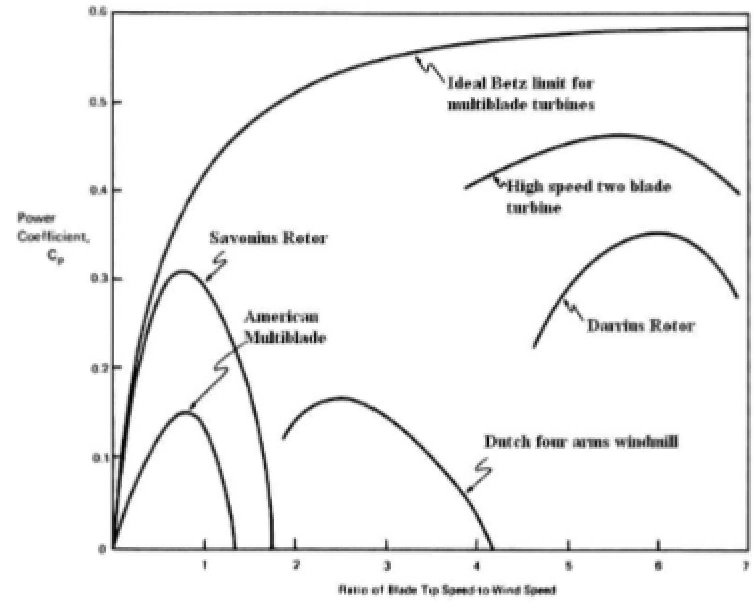

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Figure 5: Figure 5 :

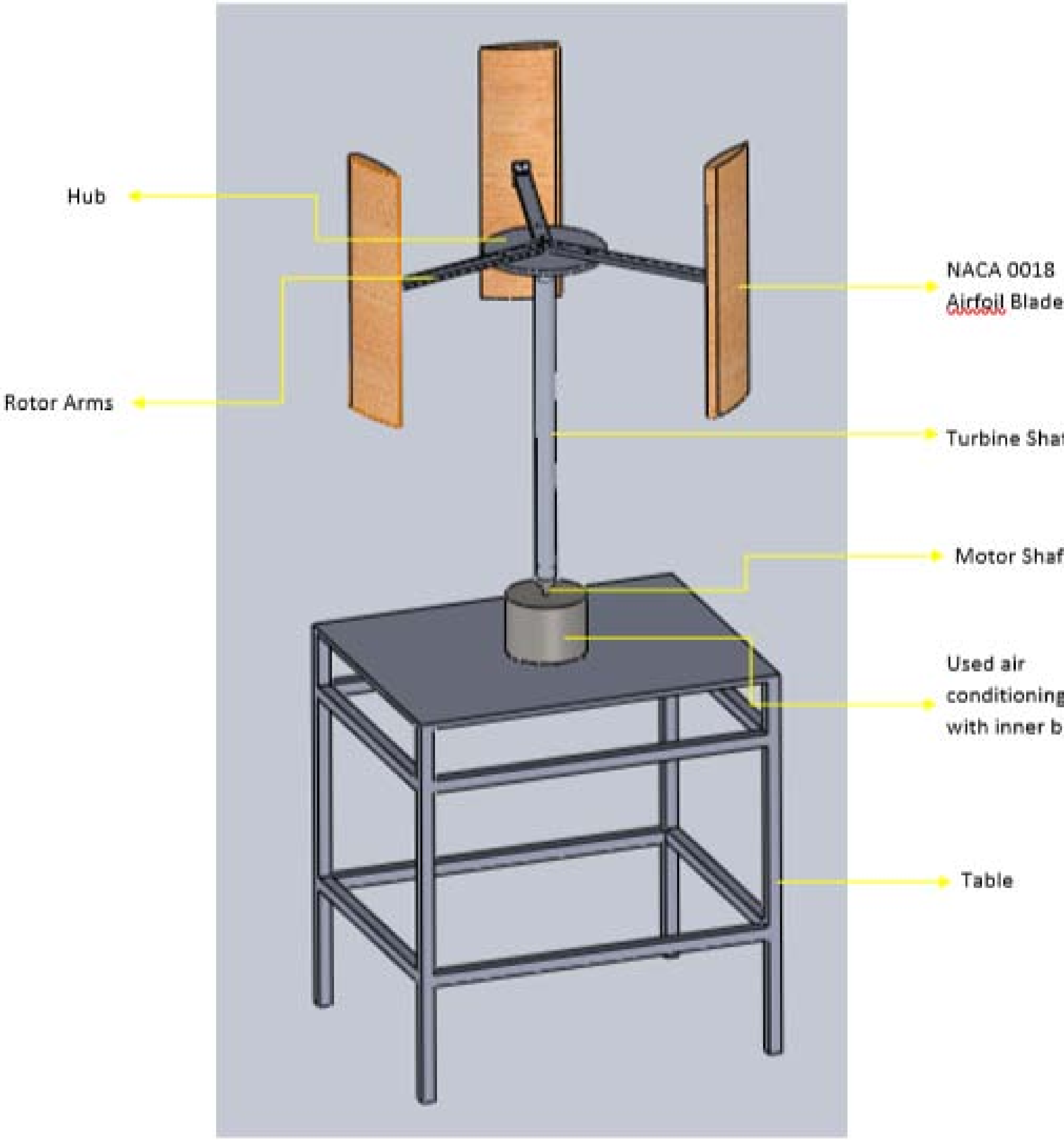

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Figure 6: Figure 6 :

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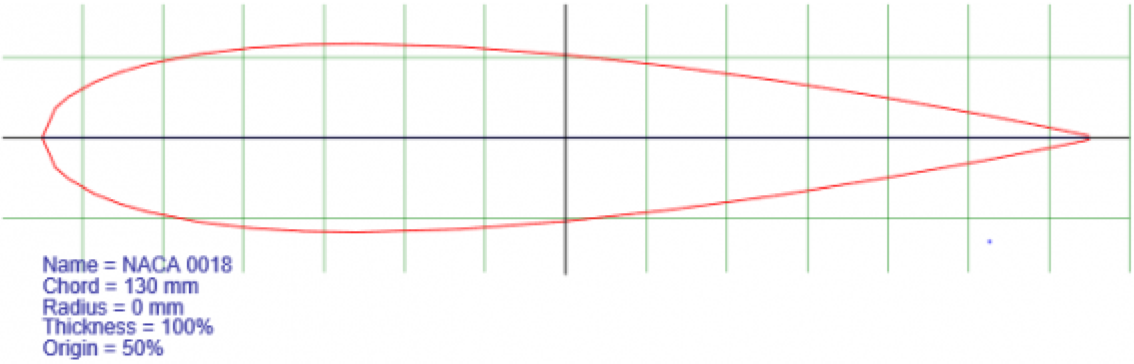

Figure 7: Figure 7 :

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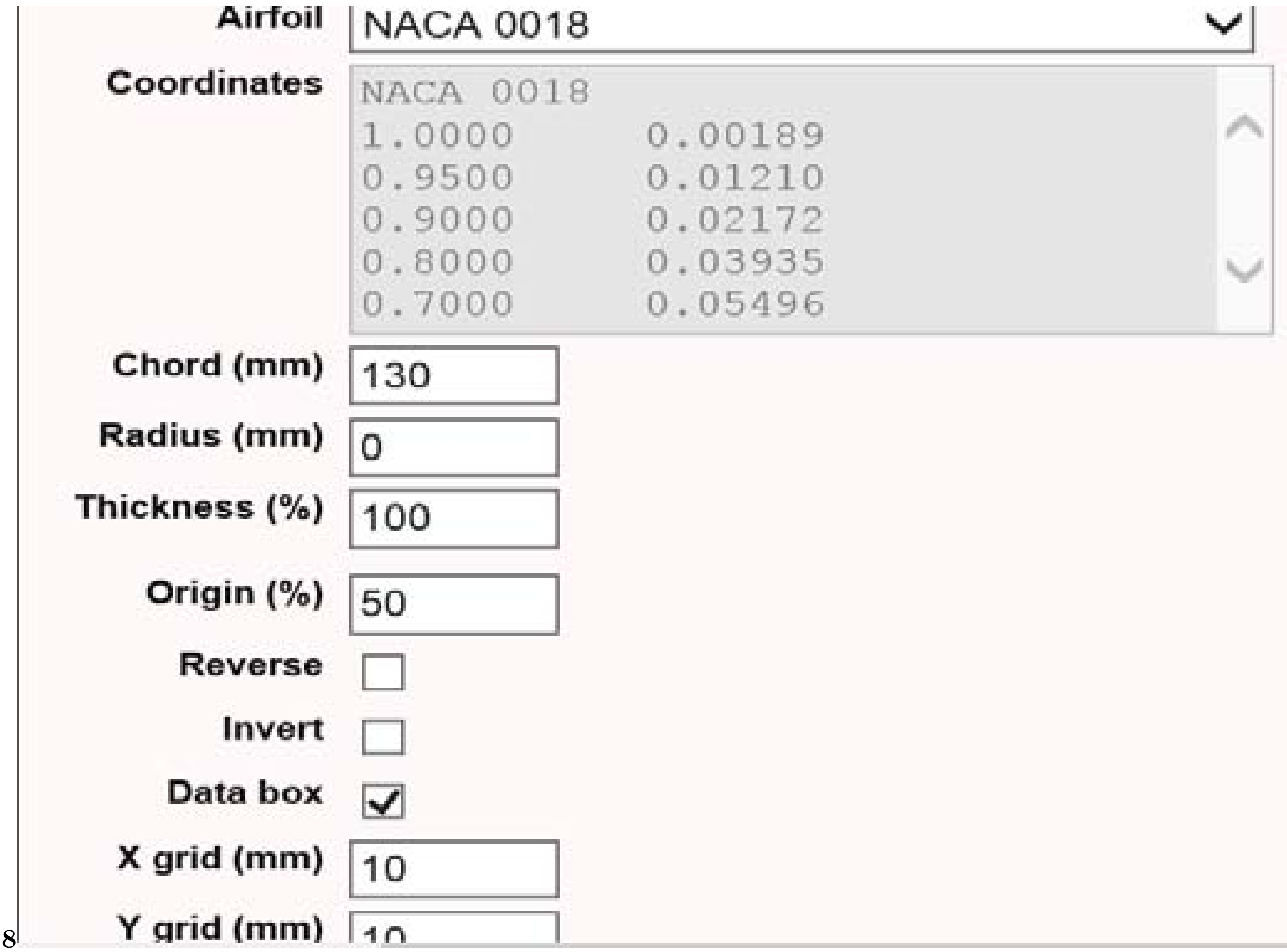

Figure 8: Figure 8 :

NACA 0018

1.00000	0.00189
0.95000	0.01210
0.90000	0.02172
0.80000	0.03935
0.70000	0.05496
0.60000	0.06845
0.50000	0.07941
0.40000	0.08705
0.30000	0.09003
0.25000	0.08912
0.20000	0.08606
0.15000	0.08018
0.10000	0.07024
0.07500	0.06300
0.05000	0.05332
0.02500	0.03922
0.01250	0.02841
0.00000	0.00000
0.01250	-0.02841
0.02500	-0.03922
0.05000	-0.05332
0.07500	-0.06300
0.10000	-0.07024
0.15000	-0.08018
0.20000	-0.08606
0.25000	-0.08912
0.30000	-0.09003
0.40000	-0.08705
0.50000	-0.07941
0.60000	-0.06845
0.70000	-0.05496
0.80000	-0.03935
0.90000	-0.02172
0.95000	-0.01210
1.00000	-0.00189

910 :

Figure 9: Figure 9 :Figure 10 :

13

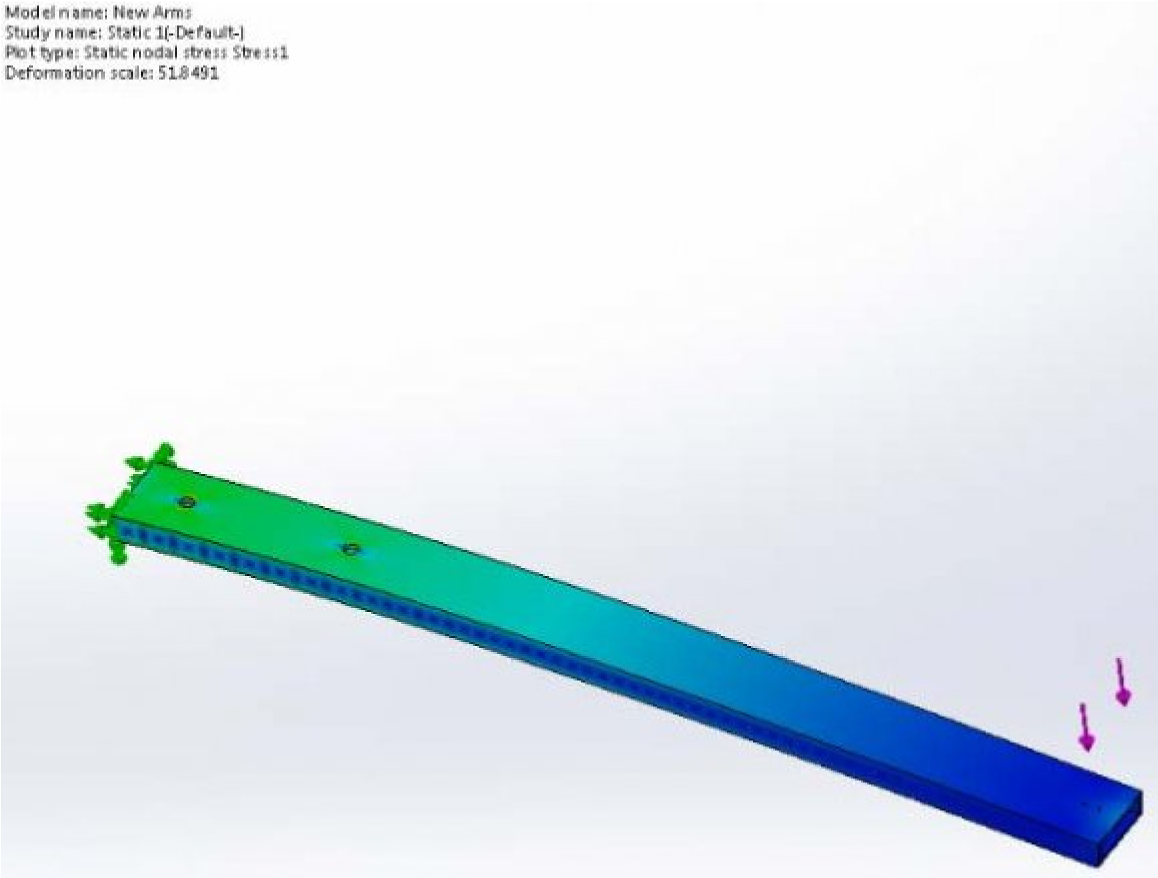

Figure 10: Figure 13 :

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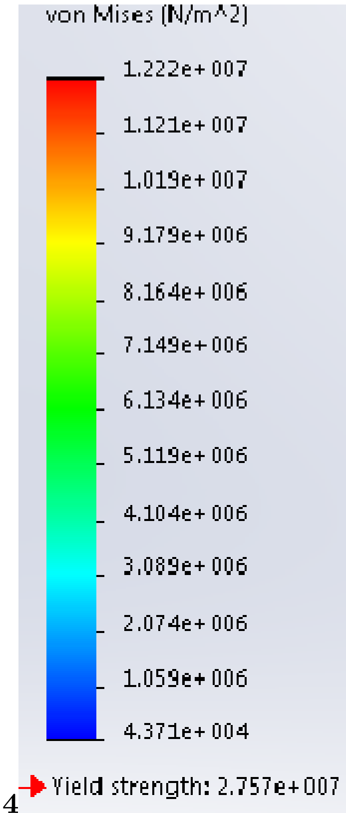
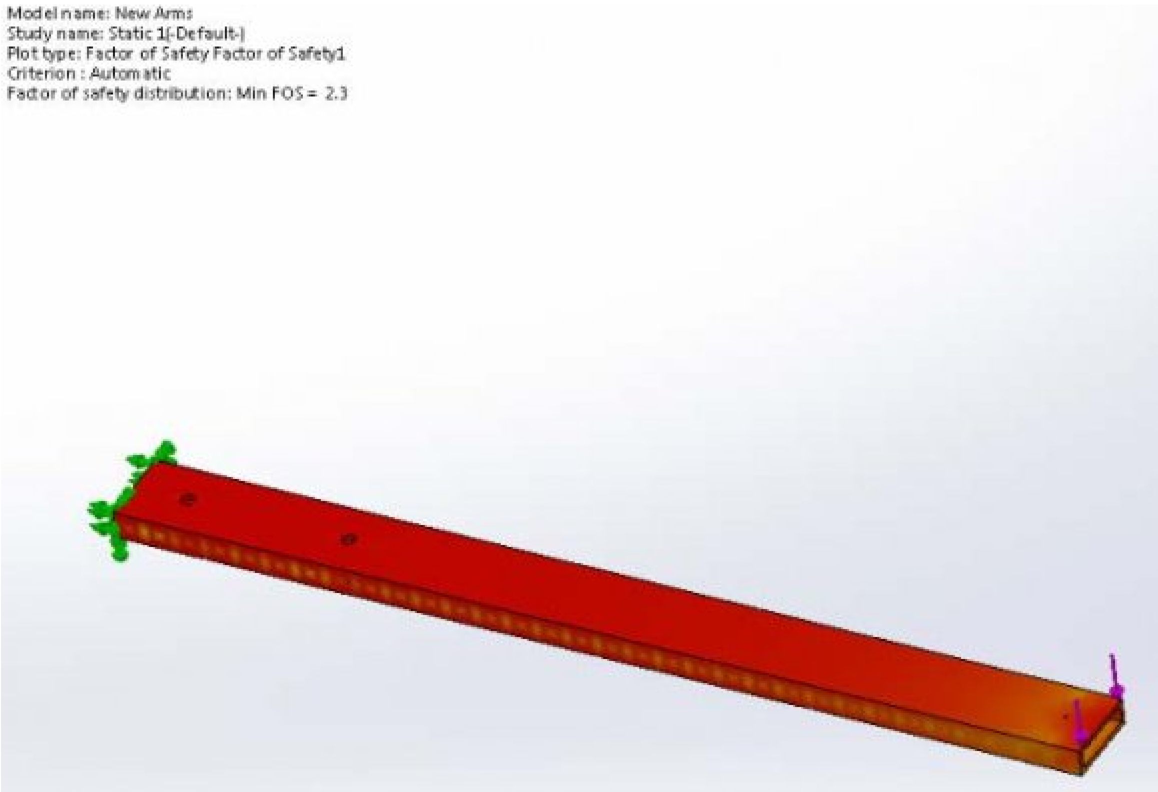


Figure 11: Figure 14 :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Study name: Static 1(-Default-)
Plot type: Factor of Safety Factor of Safety1
Criterion : Automatic
Factor of safety distribution: Min FOS = 2.3

Figure 12:

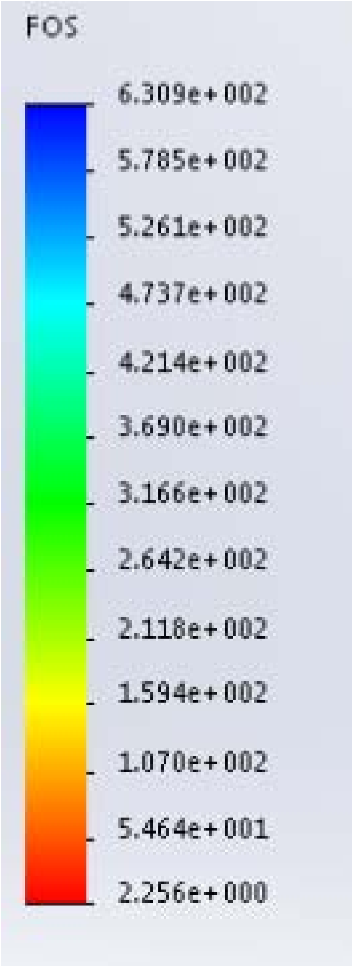
15 

Figure 13: Figure 15 :

1

Wind Speed (m/s)	Revolutions per minute (RPM)	Mass Reading on Spring Scale (kg)	Force (N)
0.95	10.50	0.060	0.59
1.12	20.63	0.080	0.78
1.44	25.02	0.12	1.18
1.84	34.38	0.22	2.16
1.93	36.38	0.24	2.35
2.67	55.95	0.42	4.12
3.14	59.97	0.60	5.89
3.68	83.08	0.72	7.06
4.15	107.05	0.80	7.85
4.24	119.37	0.80	7.85

Figure 14: Table 1 :

2

Tip Speed Ratio (TSR)	Coefficient of Performance (%)
0.44	14.80
0.69	19.61
0.73	22.90
0.75	23.60
0.76	23.00
0.78	24.00
0.84	24.08
0.89	23.40
1.02	23.40
1.04	24.40
IV.	

Figure 15: Table 2 :

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