Wind Turbine Project Report

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Project Summary

The objective of this project was to create a wind turbine tower that would optimize weight and stiffness, and to design turbine blades that would maximize power generation while minimizing cost. Specifically, we wanted to design a wind turbine that would fit within the design guidelines set out by the project specifications and requirements as well as generate at least 2 W of power, have a stiffness greater than 10 N/mm, a weight less than 1000 g, and a high tower-stiffness to weight ratio.

The net weight of our tower was 460 g and its height was 16 inches. The tower's stiffness was 9.521 N/mm (at optimal load, 1 kg) and the maximum power generated by our turbine was 2.069 Watts.

Our project satisfied the goal of maximizing power generation and minimizing costs. We were able to generate more than 2 watts of power and keep our total cost below $120. We were also able to minimize our tower's weight; it was less than half the weight of the benchmark weight, 1000 g. In addition, our project met all the specification and requirements.

One aspect of our project that could be improved is the stiffness. While our project fell within the 2nd tier of stiffness values (6-9.99 N/mm), it fell just short of our goal of having a tower stiffness of greater than 10 N/mm. Even though we didn't reach our desired tower stiffness, we still did well considering we were less than .5 N/mm off of our desired value. In addition, our combined stiffness/weight ratio was much better than expected because of having such a low weight.

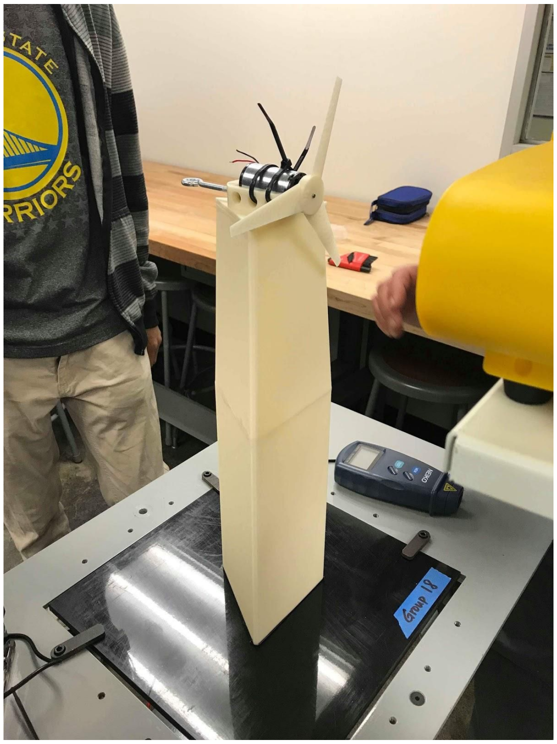

Figure 1: A picture of our tower before testing

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Introduction

Our group was tasked with designing a wind turbine capable of producing a minimum of two watts while still being light and affordable. We were provided with a ⅜ inch thick ABS plastic bottom plate with dimensions of 12 x 12 inches for our tower to be glued to. The motor/generator was provided to us as well. The tower had to be no taller than 16.00 inches with ±1/16 inches of error. The total volume of the tower (material being ABS Plastic) could not exceed 18 in^3. We were tasked with designing the upper platform that would house the motor/generator with a 3/16 inch hole in the rear, in line with the motor shaft, to support the eyebolt during testing. The hub of the propeller was provided to us however, the design of the blade was to our discretion. The total swept area of the blades could not exceed a 6.0 inch diameter, and all parts needed to be manufactured via the 3D printing process supplied to us. The 3D printer our group was allowed to use was limited to a footprint of 9x9x9 inches, and our tower needed to be made of at least two parts because of these limitations to reach the maximum height requirement. Finally, the tower needed to be symmetrical relative to the center of the lower platform with a minimum of three contact points with the foundation that is provided. To accomplish these tasks, our group divided the development of the turbine into two distinct parts: blade design and tower design. The goal of the blade design was to maximize the efficiency of the blade and minimize cost of production. The goal of the tower design was to develop a structure that supported the weight of the motor and motor casing, and withstood external forces with minimal structural deflection, yet still be light and affordable.

When designing the blade, we considered such aspects as the angle of attack of each blade relative to the wind, the number of blades on the hub, and the length of each blade. The first variable we considered was blade length. Intuitively, a longer blade means a larger surface area for the wind to push against, and thus generate more power. However, a longer blade also means that more material will be needed to produce the structure which equates to a higher cost of production. The project requirements limited the total swept area of the blades to be no greater than 6 inches in diameter. Because the cost of producing a blade of this size is already relatively low ($5.60 total), and a longer blade is the most efficient option, we decided to design a blade that would sweep out the area of a circle with a diameter of 6 inches.

The next variable we considered for blade design was the number of blades attached to the hub. The more blades the turbine has, the more power can be generated, however, more blades also means higher cost of production. In light of lowering the cost of production, we decided to choose between two or four blades. If the tower were to have two blades, the cost would be lower. However, as the blades spin, there would be a point where the two blades will become more unstable and make the tower more susceptible to shaking or toppling over in high wind conditions. A blade count of four would increase the performance of the turbine, however, the cost increase of producing a fourth blade is marginal compared to the overall power generation of a turbine with only three blades. To compromise, we decided that three blades would generate a sufficient amount of torque while still being cost efficient.

Blade shape is another important design variable that needed to be considered as the shape of the blade is a major factor that will determine its speed and drag. We considered flat blade designs and curved blade designs. We determined that flat blades are inefficient in converting wind energy into power because the wind pushes the blade differently at the top and bottom of the blade. A curved blade design with a curve at the top creates a lower pressure near the tip of the blade which allows it to spin faster. Because the curved blade produces the most torque by spinning faster, we decided to design a blade with a curved upper half of the airfoil.

Blade material and weight are also relevant factors to consider when developing the most efficient blade. The lighter the blade, the faster the wind can move it, and weight is dependent upon the material we used when manufacturing the blade. Since the only material we were allowed to use due to the guidelines of the project, we manufacture our blade using ABS plastic from a 3D printer.

Possibly the most important design characteristic of the blade is the angle of attack. The angle of attack is defined as the angle between an airfoil (wing) chord line and the relative wind.

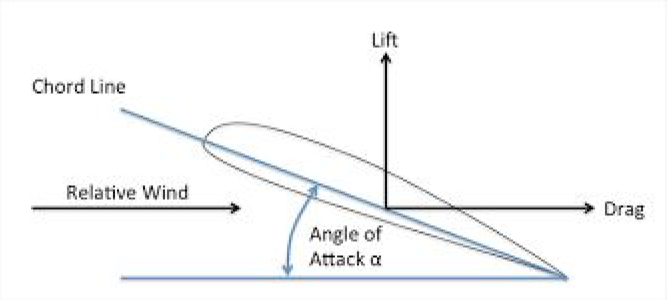


Figure 2

The angle of attack determines how much of the airfoil will interact with the wind, and thus how efficient the blade will be. Since the power generated by the turbine is directly related to the torque, maximizing the angle of attack is necessary when developing the most efficient airfoil. When determining the proper angle of attack, we needed to consider the angle at which the blade will stall and not generate any lift, and thus no torque. Also, the orientation of the blade relative to the wind is important when developing the most efficient blade. A horizontal blade generates more power than a vertical blade, however, it requires a taller tower to support it. Since height is not a major concern, we decided to develop a horizontal blade with an angle of attack of 7 degrees relative to the hub.

The wind turbine's support structure was designed to be extremely stiff and light, while also maintaining a maximum volume of 18 in^3. Stiffness is how much an object resists change due to applied force. It is inversely proportional to deflection, the amount an object deforms, and directly proportional to the area moment of inertia, which is dependent on surface area. To maximize stiffness, we ideally would have created a tower with as large a base as possible. However, this would have made our tower very heavy and would not have met the volume constraint so we hollowed out the base and left exactly 2 mm of thickness on each side for stability. If we had created a solid base with the dimensions of the hollowed out part of our current base, it would have been heavier and less stiff. Creating a large and hollow base increased the stiffness while decreasing the weight.

We picked an equilateral triangle as the shape for the tower because triangles are extremely rigid. When under stress, triangles will not deform into different shapes. Other shapes such as rectangles will change shape (rectangles will turn into parallelograms) under stress and are unsuitable for the base. The triangle at the base of the tower is larger than the one at the top because we could save volume while also have a decent weight distribution. Additionally, the edges of the tower are all filleted to reduce volume and weight.

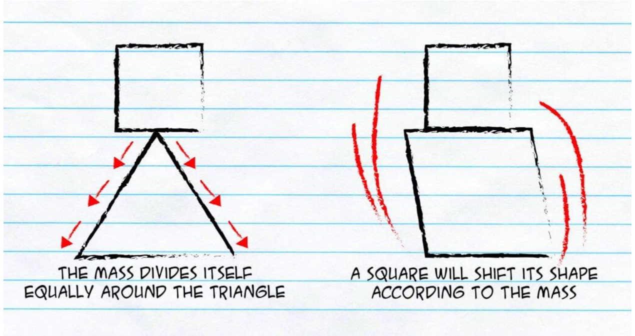


Figure 3 (http://blog.zapzapmath.com/three-magic-number/)

We chose to put the blade on the flat side of the tower because it allowed the tower to be more balanced. We wanted to reduce the distance between the load of the blade and the tower's center of mass because the tower could potentially topple if that distance is too large. The tower's center of mass is near the flat side of the tower so the blade was placed there.

Theory

3 Blades vs. 4 Blades

Increasing the number of blades increases aerodynamic efficiency; however, increasing the number beyond 3 only has marginal effect on efficiency. While there is a 3% increase in aerodynamic efficiency from increasing the number of blades from 2 to 3, there is only a 0.5% increase from 3 to 4 blades. Additionally, as the number of blades increase, the overall cost of the system increases drastically. The blades need to be designed thinner to maintain the aerodynamic efficiency, yet thinning the blades reduces the bending stress tolerance.

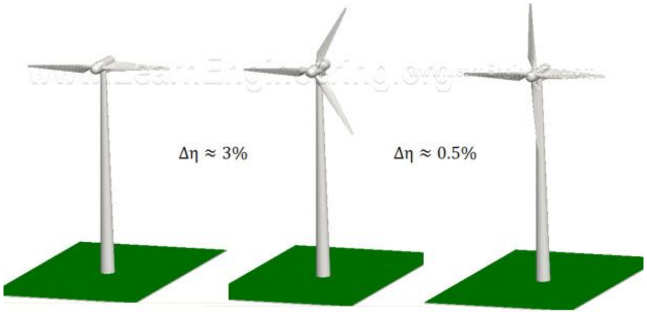


Figure 4

Fluid dynamics

The blades were designed in a way that the air creates an airfoil around the blades as it flows by. The front slanted surface of the blade has greater area, so the air flows slower due to greater surface friction compared to the upper back part of the blade where the air flows relatively faster. Due to Bernoulli's principle, higher pressure in the bottom surface and lower pressure on top creates a lift that turns the blades.

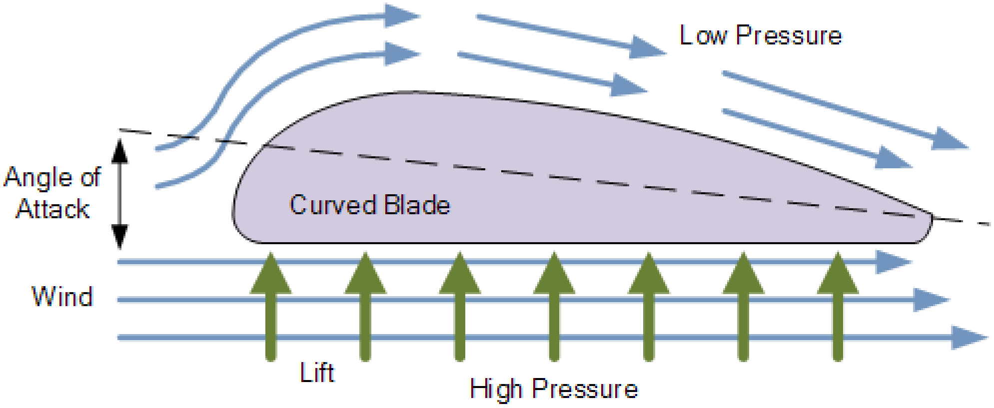


Figure 5

Lift = $C_L * (0.5\,\rho V^2) * S$ *where* C_L *− coefficient of lift*, ρ = *air density*, S = *wing area*

Drag = $C_D * (0.5\,\rho V^2) * S$ *where* C_D *− coefficient of drag*, ρ = *air density*, S = *wing area*

Power Generation

The output of a wind turbine is proportional to the area swept by the rotor. Also, the power is proportional to the cube of the wind speed.

Wind Power = P= 0.5 x ρ x A x Cp x V3 x Ng x Nb
ρ = Air density in kg/m3
A = Rotor swept area (m2)
Cp = Coefficient of performance
V = wind velocity (m/s)
Ng = generator efficiency
Nb = gear box bearing efficiency

Design-Build-Test

Sketches and Pictures

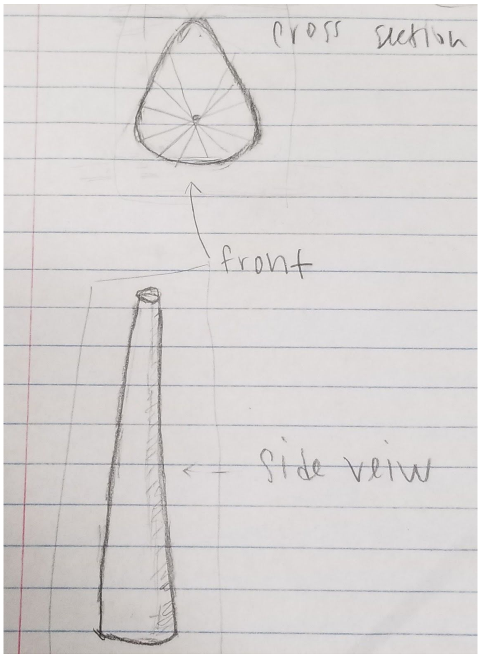


Figure 6: Pictured above is the side view, front cross section view of our tower.

Figure 7: Pictured above is the isometric view of exploded sketch of the tower.

Figure 8: Pictured above is the printed tower.

Type, Shape, Dimensions, and Cost

Our tower is 16 inches tall and has a volume of 18 in^3. It has a triangle base with filleted edges and resembles an arrowhead or guitar pick. The sides of the triangle become proportionally shorter as height increase. The thickness of our tower is 2 mm. It is made out of ABS plastic and the total cost was $115.40.

Major Tools Used During Build

While building our tower we used a few tools. First of all, our tower was printed on a high-end 3D printer in the Mechanical Engineering Machine Shop in Etcheverry Hall. After our tower was finished printing, we file down some of the sharp edges at the top of our tower. We then used a ruler and sharpie to measure and mark an outline of where we planned to glue our tower. Finally, we used loctite to glue the different parts of our tower together and to glue the base of our tower to the bottom board.

Types of Tests and Purpose

For this project, we had to test power generation and stiffness of our turbine. The purpose of the power generation test was to see how efficient the design our turbine blade was by measuring the max power output. It was also used to find the optimal loading condition for power generation. The stiffness test was used to measure the deflection of our turbine. By measuring the deflection of our tower, we would be able to judge its overall strength.

Testing and Procedure

1. Secure tower and bottom board to table using an allen key.
2. Position the blower and use the wind speed measuring meter to guarantee that the wind speed is 25 mph.
3. Attach the blade onto the motor and ziptie the motor to the turbine. Connect the load box to the motor.
4. Make sure to zero the potentiometer. Switch to variable load and then turn the fan on.
5. Turn the potentiometer in small increments. At each increment, record current, voltage, and power.
6. Move on to the stiffness testing. Once again, secure the tower and bottom board to the table using an allen key.
7. Tie a string to the eye bolt and run the string over the pulley.

8. Position the dial indicator at the front of the tower. Make sure to zero the device and not to touch the table after.
9. Increase the weight on the end of the string gradually and record the deflection at each increment.

Major Tools and Equipment during Testing

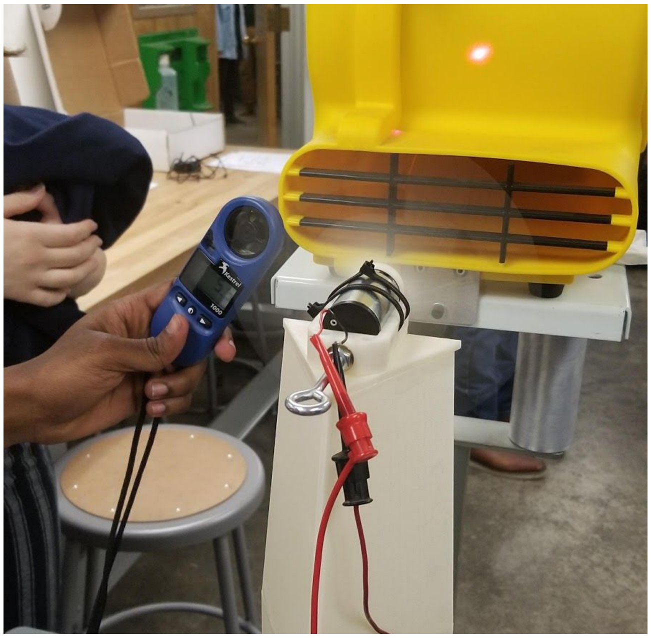


Figure 9: We used several different tools and measuring equipment during the testing process. First of all, our group used a wind speed measuring meter (shown above) to measure the speed of the wind from the fan before we started the testing.

Figure 10: We also used a tachometer (shown above) to measure the speed in rpm of the blade. To use the tachometer, we attached a piece of reflective tape to the blade. The tachometer has a laser which uses the reflective tape to generate a reading of the blade speed.

Figure 11: Finally, we used an electrical meter to measure voltage, current, and power and a load box to draw power. The load box has a potentiometer which controls how much power is drawn. The electrical meter and load box were located in one device (shown above).

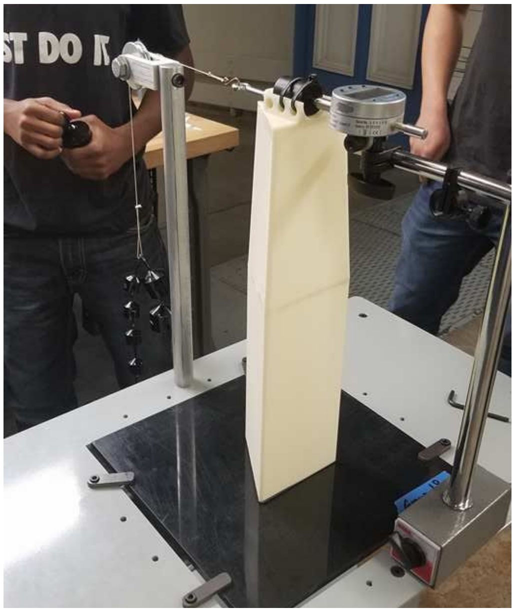
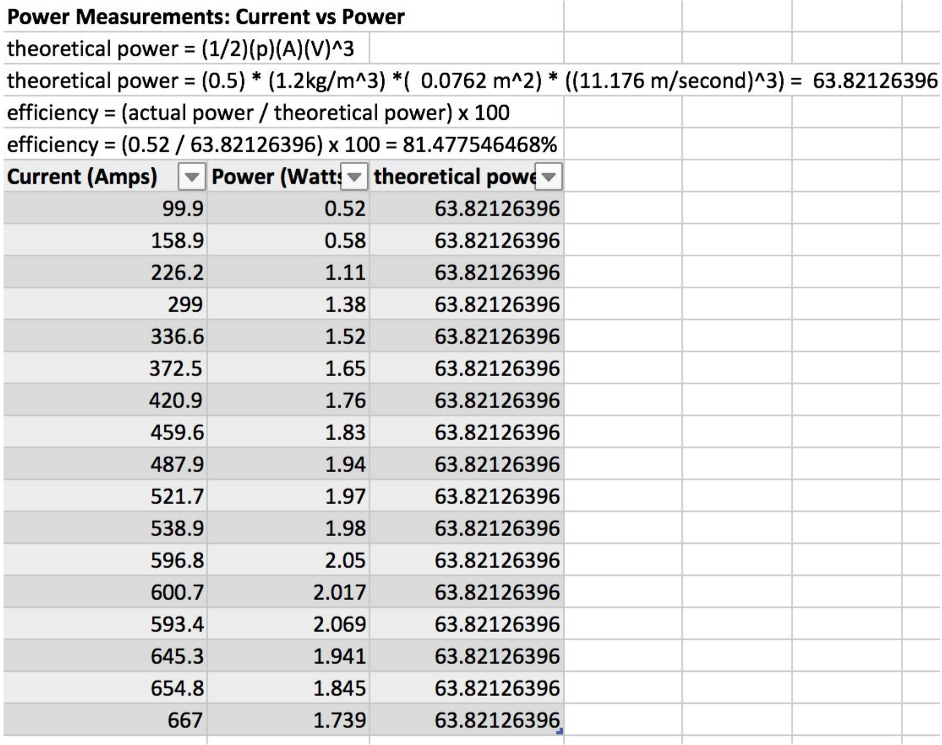


Figure 12: For the strength testing, we used a dial indicator (shown above) to measure the deflection. An eyebolt was connected to the top of our turbine. We attached a string to the end of the eyebolt; the string was then wrapped around a pulley. We added weight to the end of the string in increments of .1 kg.

Results of Tests

After doing the power generation testing, we found that our max power generated was 2.069 watts. From the stiffness testing, we found that our deflection at 1kg was 1.03 mm and our max deflection with 5kg was 5.95 mm.

Data Plots



Power Measurements: Current vs Power

theoretical power = (1/2)(p)(A)(V)^3

theoretical power = (0.5) * (1.2kg/m^3) *(0.0762 m^2) * ((11.176 m/second)^3) = 63.82126396

efficiency = (actual power / theoretical power) x 100

efficiency = (0.52 / 63.82126396) x 100 = 81.477546468%

Current (Amps)	Power (Watt	theoretical powe
99.9	0.52	63.82126396
158.9	0.58	63.82126396
226.2	1.11	63.82126396
299	1.38	63.82126396
336.6	1.52	63.82126396
372.5	1.65	63.82126396
420.9	1.76	63.82126396
459.6	1.83	63.82126396
487.9	1.94	63.82126396
521.7	1.97	63.82126396
538.9	1.98	63.82126396
596.8	2.05	63.82126396
600.7	2.017	63.82126396
593.4	2.069	63.82126396
645.3	1.941	63.82126396
654.8	1.845	63.82126396
667	1.739	63.82126396

Figure 13: This table above shows the measured current and power during testing procedure. The peak is around 2.096 watts. The calculated theoretical power is 63.821. The efficiency is 81.48%.

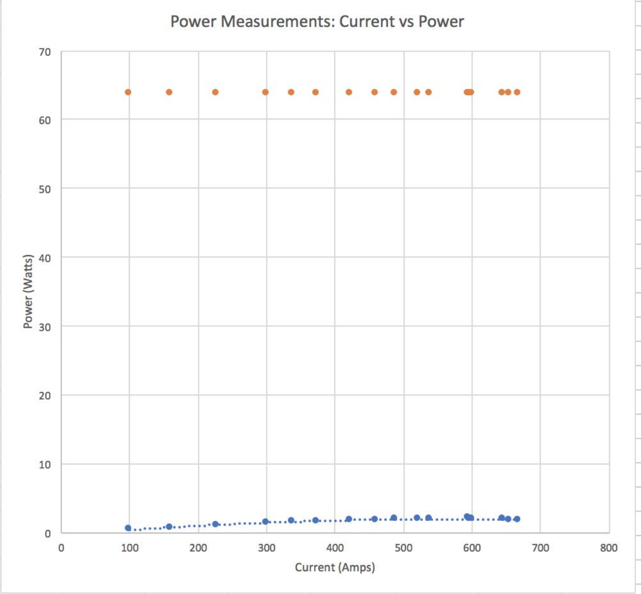
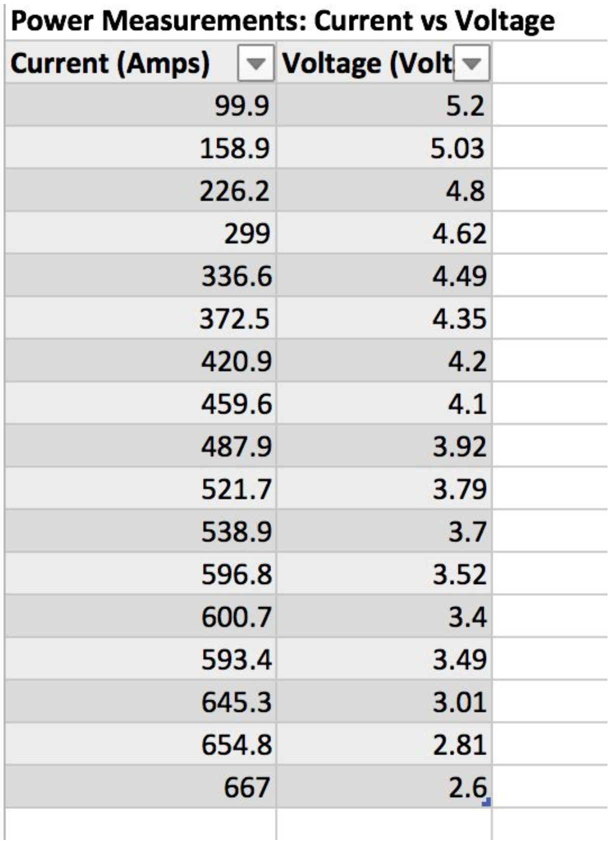


Figure 14: The graph above displays the best fit line (blue) through the data points that describe the relationship between current and power. As current increases, the power increases. As it approaches the peak (power = 2.096 watts), the rate of current increase decreases and approaches zero. The orange line is the calculated theoretical power.



Power Measurements: Current vs Voltage

Current (Amps)	Voltage (Volt
99.9	5.2
158.9	5.03
226.2	4.8
299	4.62
336.6	4.49
372.5	4.35
420.9	4.2
459.6	4.1
487.9	3.92
521.7	3.79
538.9	3.7
596.8	3.52
600.7	3.4
593.4	3.49
645.3	3.01
654.8	2.81
667	2.6

Figure 15: The table above displays the measured current and voltage collected during testing procedures. The peak is around 3.49 voltage.

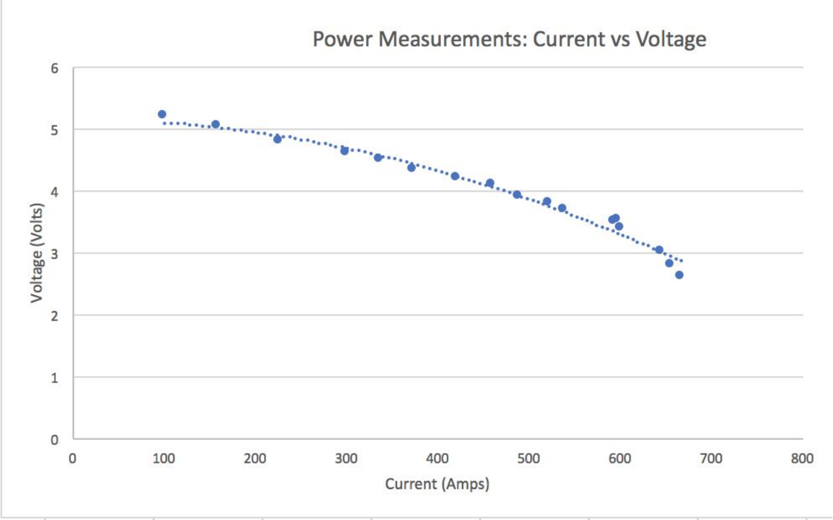


Figure 16: The graph above shows the best fit line (blue) through current and voltage data points. As current increases, the voltage decreases.

Deflection Measurements

Load	Deflection
0.1	0.1
0.2	0.21
0.3	0.31
0.4	0.42
0.5	0.52
0.6	0.67
0.7	0.73
0.8	0.83
0.9	0.93
1	1.03

Figure 17: The table above shows the observed deflection for each load added onto the tower by increments of 0.1 N during testing. As load increases, the deflection increases.

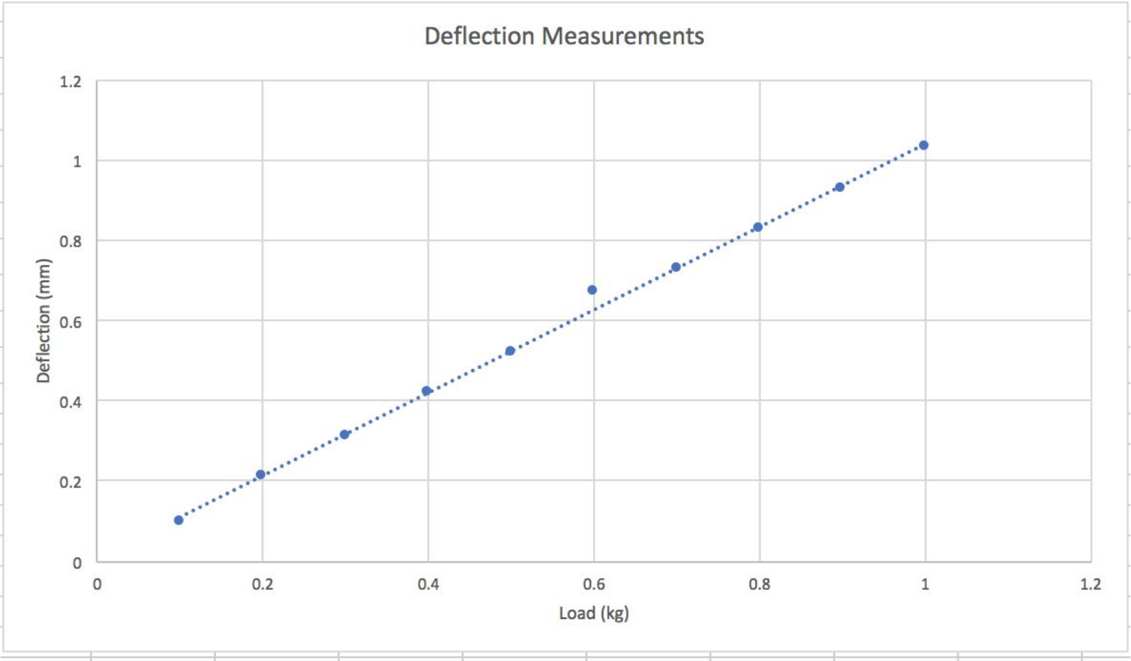


Figure 18: The graph above shows the relationship between load and deflection. The best fit line (blue) is upward sloping, meaning as load increases, deflection also increases in an increasing linear direction.

CAD Drawings

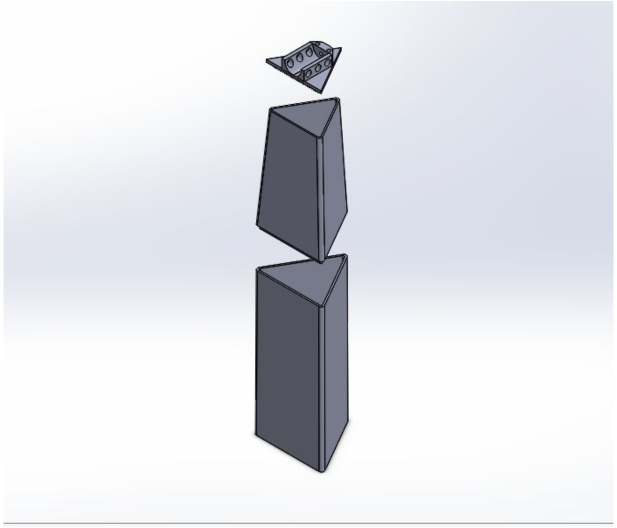


Figure 19: Exploded View of Our Tower

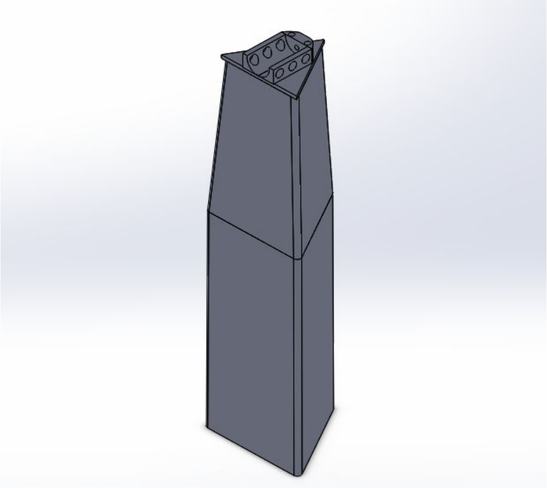


Figure 20: Full Tower Assembly

Figure 21: Blade Design

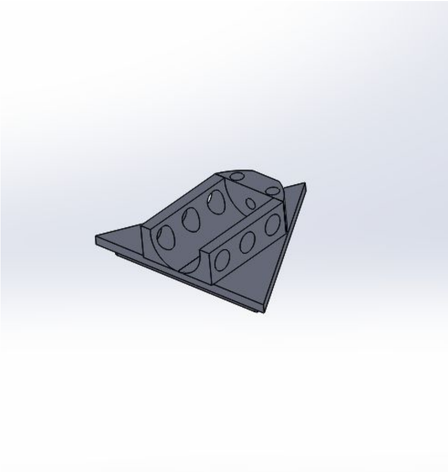


Figure 22: Motor Casing Section

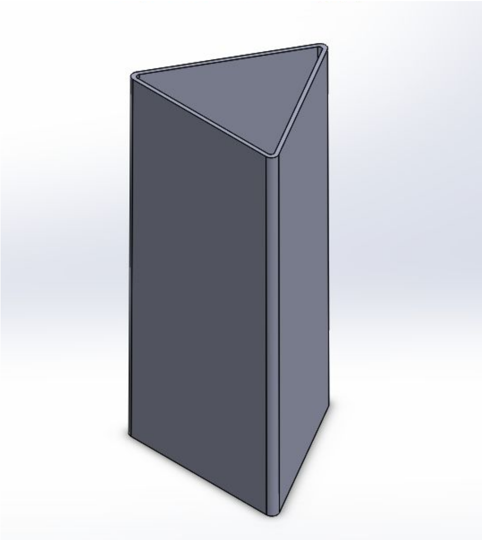


Figure 23: Bottom Section of our Tower

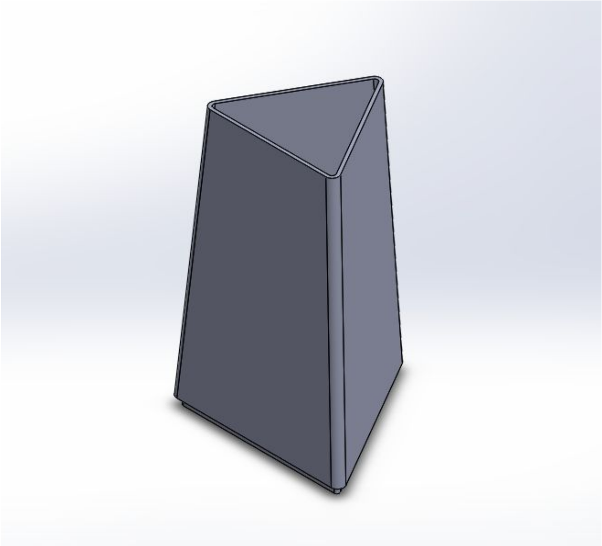


Figure 24: Middle Section of our Tower

Conclusion

The goal of this project was to design and build a wind turbine tower and blade that would excel at two tests: power generation and stiffness testing. We started the project by designing the blade; after researching greatly, our group decided to use an angle of attack of 7 degrees as it is very efficient in generating power. Once we finished our blade, we designed our tower. Our group concurred that a tower of triangular shape would distribute the weight of the tower best and would also reduce deflection from the weights during testing. Having 3 blades is optimal because it is cost efficient while producing a great amount of power. Compared to flat blades, our blades' curvature allow the wind to spin blades at a faster speed. Our tower and blade was 3D printed with ABS plastic at the Mechanical Engineering Machine Shop. During testing, we found that our turbine generated a max power of 2.069 watts. For stiffness testing, our tower's deflection at 1kg was 1.03 mm and the max deflection with 5kg was 5.95 mm. Compared to the rest of the groups that had finished testing, both our power generation and our stiffness testing were outstanding. In addition to this, our tower had better efficiency compared to towers in real life. The majority of towers in real life have max efficiency of 59%; our tower had a max efficiency of 81.48%.

Recommendations for Future Work

To improve the efficiency of the blade, we can increase the blade angle of attack to increase the surface area of the blade that interacts with the wind, increasing the torque of the blade. We can also chose a blade design a blade with greater curvature to maximize the speed of the blade.

For the tower design, we would make the surface area of the tower's base much wider to improve the overall stiffness of the design. When we were doing the deflection testing, the tower began to detach from the bottom surface when a 5 kg load was added. This could be avoided by increasing the surface area because surface area is directly proportional to stiffness. A mesh support structure inside the hollow tower might also be helpful for improving the stiffness because the tower would be more stable.

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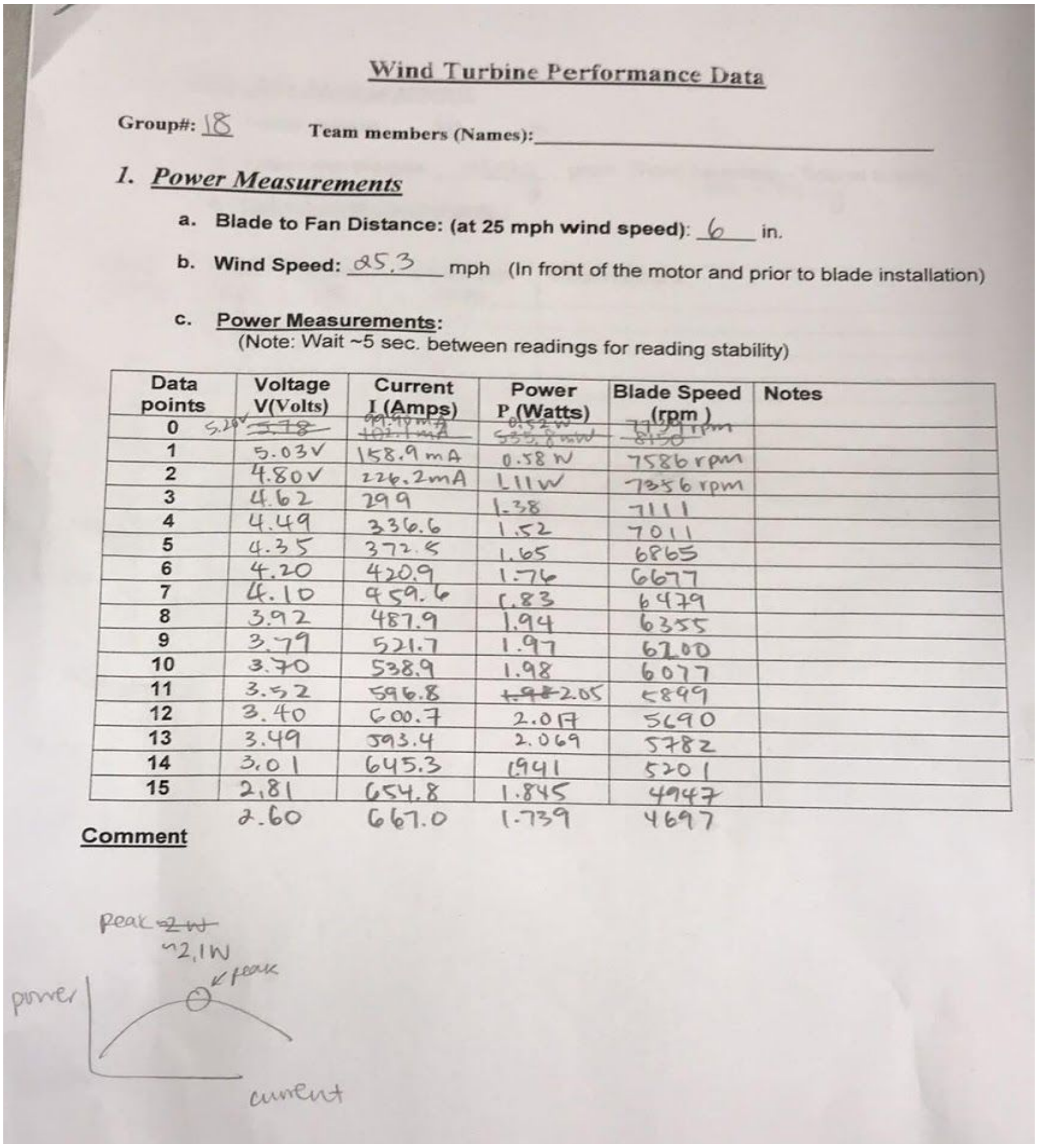
Appendix A

Wind Turbine Performance Data



Wind Turbine Performance Data

Group#: 18 **Team members (Names):**

1. *Power Measurements*

a. **Blade to Fan Distance: (at 25 mph wind speed):** 6 in.

b. **Wind Speed:** 25.3 mph (In front of the motor and prior to blade installation)

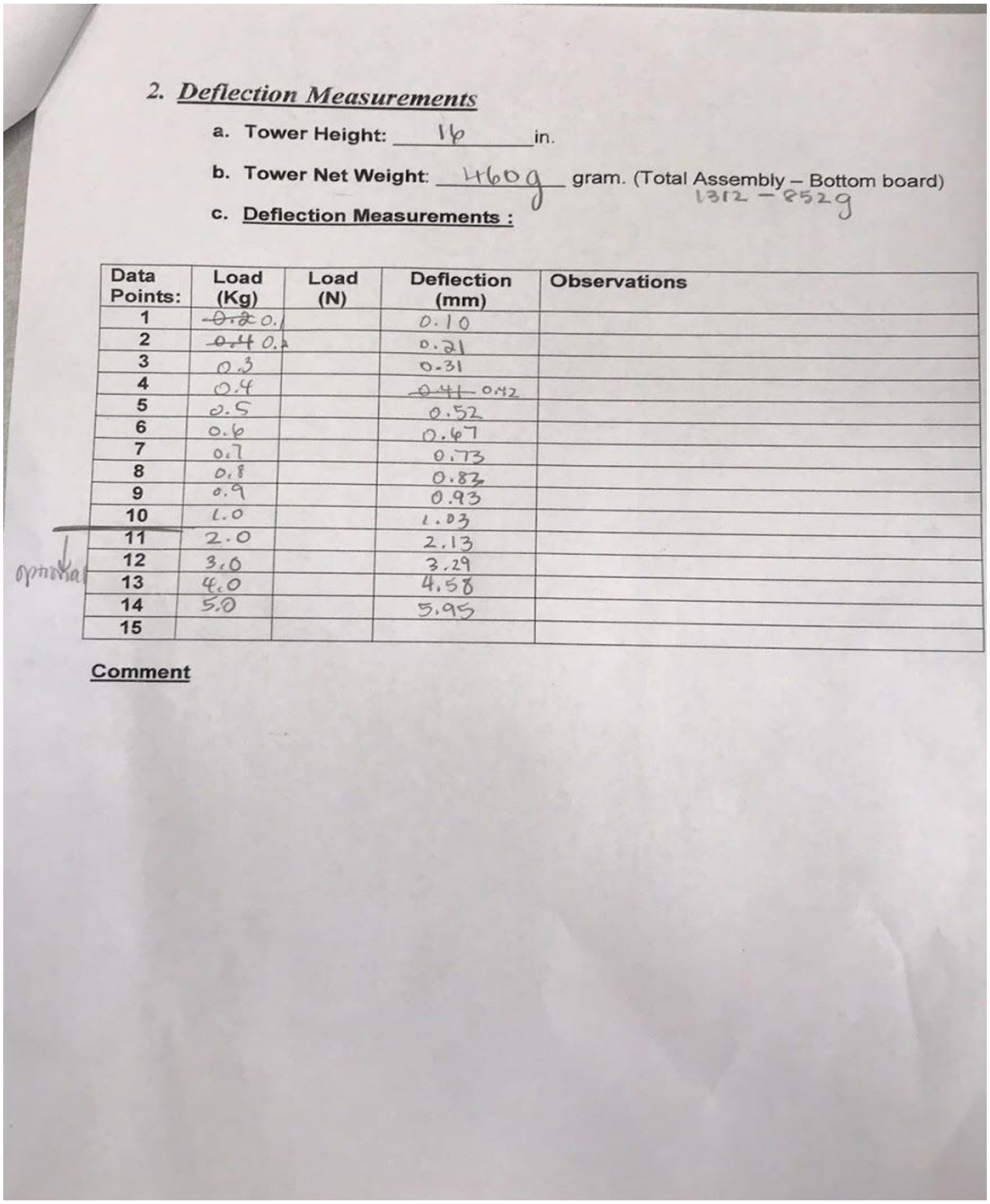
c. **Power Measurements:**
(Note: Wait ~5 sec. between readings for reading stability)

Data points	Voltage V(Volts)	Current I (Amps)	Power P (Watts)	Blade Speed (rpm)	Notes
0	5.20V ~~5.78~~	~~99.90mA~~ ~~101.1mA~~	0.52W ~~535.8mW~~	7759 rpm ~~8150~~	
1	5.03V	158.9mA	0.58W	7586rpm	
2	4.80V	226.2mA	1.11W	7356rpm	
3	4.62	299	1.38	7111	
4	4.49	336.6	1.52	7011	
5	4.35	372.5	1.65	6865	
6	4.20	420.9	1.76	6677	
7	4.10	459.6	1.83	6479	
8	3.92	487.9	1.94	6355	
9	3.79	521.7	1.97	6200	
10	3.70	538.9	1.98	6077	
11	3.52	596.8	~~1.98~~ 2.05	5899	
12	3.40	600.7	2.017	5690	
13	3.49	593.4	2.069	5782	
14	3.01	645.3	1.941	5201	
15	2.81	654.8	1.845	4947	
	2.60	667.0	1.739	4697	

Comment

peak ~~2W~~
~2.1W

Deflection Measurement Data



2. *Deflection Measurements*

a. **Tower Height:** 16 in.

b. **Tower Net Weight:** 460g gram. (Total Assembly – Bottom board)
1312 – 852g

c. **Deflection Measurements :**

Data Points:	Load (Kg)	Load (N)	Deflection (mm)	Observations
1	~~0.2~~ 0.1		0.10	
2	~~0.4~~ 0.2		0.21	
3	0.3		0.31	
4	0.4		~~0.41~~ 0.42	
5	0.5		0.52	
6	0.6		0.67	
7	0.7		0.73	
8	0.8		0.83	
9	0.9		0.93	
10	1.0		1.03	
11	2.0		2.13	
12	3.0		3.29	
13	4.0		4.58	
14	5.0		5.95	
15				

optional

Comment