**Three Dimensional Modeling for Design (E26)**

**UC Berkeley - Mechanical Engineering**

# Designing, Modeling, and Testing a Small Scale Wind Turbine:

***Optimizing power production and structural stiffness***

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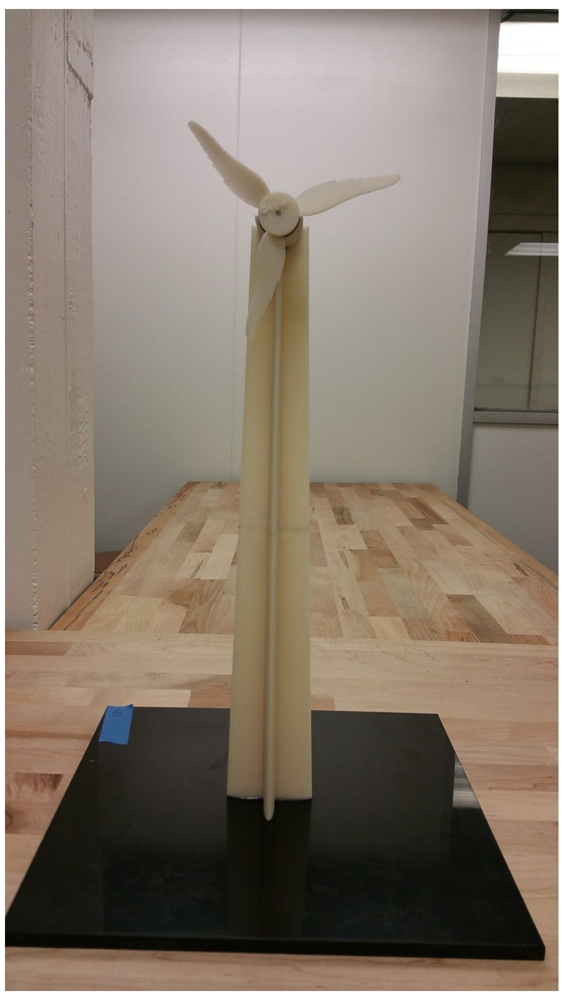

## Project Summary

**Objectives:** The objective of our project was two-fold. We wanted to create a small model of a wind turbine which consisted of turbine blades that would generate the most power and a tower structure that would have the maximum stiffness-to-weight ratio. Under the conditions of a wind speed of 25 mph and using a 6 VDC motor (80 mA, 8500 rpm), we wanted to design turbine blades that rotate the motor shaft of the motor in order to produce the most power. Stiffness would be found by applying a normal force to the top of the structure and then measuring its displacement. The goal was to make a tower structure that had the least deflection and the smallest volume.

**Key aspects:** Our wind turbine consisted of three main parts: the turbine blades, the tower structures (base and top), and the motor housing. The diameter of the turbines blades was limited to 6 inches, and the tower structure height constrained to 16 inches. The volume of the entire wind turbine was not to exceed 20 cubic inches.

**Performance data/ outcomes:** Our max power generated was 1.267 W at a current of 0.351 A. The curve of best fit for the power vs. current graph was quadratic, rising steadily to the peak power. Power measurements at higher currents were more variable, however. The deflection of our tower structure at 1 kg was 2.79 mm. The total weight of our wind turbine was 1.246 kg, the height of the tower from base to motor shaft was 16 inches, and the total cost to print was $69.55. Our stiffness value was 3.4645 N/mm so our stiffness-to-weight ratio was 0.283 1/mm.

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**Introduction**

In a rapidly growing world where natural resources are quickly being depleted due to overconsumption of natural resources, renewable resources are now becoming more essential to meet the demands of the ever growing consumption of energy. As a result for this demand, many industries are gathering all of their resources to come up with new alternatives to fossil fuels. One of these alternatives that solves this ever growing energy crisis is the wind energy industry. Currently the wind energy makes up approximately 4% of the united states energy generated with over 48,800 wind turbines currently installed across the United States, which is estimated to increase up to 20% in the year 2030 according to the Wind Energy Foundation and the American Wind Energy Association [3][6]. Today, across the world there is over 225,000 wind turbines that generates 19% of the world energy needs, which is growing rapidly each day [5]. Wind is created by uneven heating in the earth's atmosphere which moves a high pressure area to a low pressure area [4]. By using wind turbines to capture the free, kinetic energy of the wind, we will be able to help solve evergrowing the energy crisis that plagues the world.

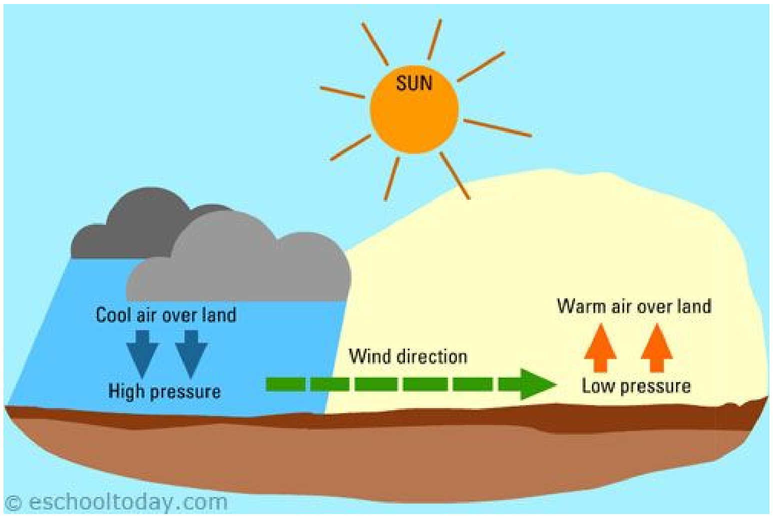



Figure 1: How winds form [4]

During this semester we were tasked to construct a tower structure and turbine blades with certains limitation that had to be analyzed and tested during a demo presentation. The tests first included how much power our project was able to output with a fan that created winds around 25 mph, and the second test was the stiffness of the 3-D printed ABS tower structure which had to take into consideration the volume and cost of production. Some of the requirements that were required were to design a support structure that needed to have a motor shaft that was 16 inches with a tolerance of 1/16 inch from the top of the platform given to us. Our volume of the project was not to exceed 20 cubic inches, as well as creating a turbine blade that was not allowed to exceed a sweep of no more that 6 inches in diameter. Lastly, the blades weren't allowed to exceed 2.5 inches including 0.25 inch height with no constraint on the width of our blade. The material that we were given was a CAD model for the hub of the motor which also included a 12 by 12 inch lower support platform made of ABS plastic material. All of the materials that we had to create were created from a program called Solidworks, and all of them had to be 3-D printed with the constraints that we were given while trying to maximize the power output and strength of the structure.

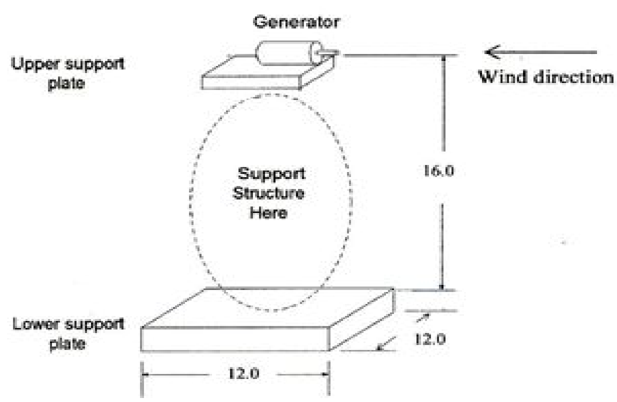



Figure 2: Diagram of basic project construction [7]

Our group decided that a beam type of structure would be the best type of structure to get the maximum support necessary minimizing volume. We overall thought that the structure would be best to deflect wind into multiple directions while trying to save on cost of the material. Also the blade portion of the project had be also very efficient. The design of the blade was one with three blades since in lecture it was stated that increasing the blade number from two to three would help yield a much better power output of an additional 3% without sacrificing the blade's stiffness. With this taken into consideration, we also had to also find the best angle of attack and the overall thickness of the blades while being limited by the 3-D printer's capabilities.

The 3-D printer was only able to print objects that could only fit the dimensions of 10x10x12 inches and as a result we were not able to print the whole structure as a whole so we decided to split the tower structure into two pieces of equal height. Our blade design also had a larger angle of attack than normal. Our design of the structure focused on creating the most stiffness with the least amount of material, resulting in minimal cost with the maximum amount of strength.

We first tested our blade by placing an industrial fan in front of the tower and measuring the current voltage and power after applying varying loads to the system. We were given a custom built meter during the demo presentation to read off the values of the current, voltage, and power which were dependent on how much electrical resistance applied by turning the dial of the load box. We were also given a small wind speed gauge that allowed us to measure the velocity of the airflow produced by the fan that was placed in front of our structure. Lastly we were given a laser measurement tool so we read total rpm of our blade at each load level. With the meter we were able to record our blades efficiency as well as the graphs of the current vs. power and current vs. voltage our blade design gave us a maximum blade speed of 5230 rpm and a maximum power output of 1.27 watts of power which we felt was average compared to the overall highest power output of somewhere over 2 watts.


Figure 3: The load box (potentiometer) [7]

The second test was the deflection test during this test our overall structure. During this portion of the test we were supervised and given weights to place on the back of our structure to see how much it deflect. Overall, our structure deflect more than we had wanted.

Figure 4: A tower deflecting due to load [7]

**Theory**

The fundamental principle of the wind turbine is the energy conversion from the wind energy to electricity energy. The wind turns the blades that turn the motor shaft connected to a power generator, which create electricity for use.  In fact it is ideal to reduce the wind speed by about two thirds downwind of the turbine, though even then the wind just before the turbine will have lost about a third of its speed. This allows a theoretical maximum of 59% of the wind's energy to be captured (this is called Betz's limit). In practice only 40-50% efficiency is achieved by current designs. Thus, a number of factors are need to be considered in blades design to make the most of wind energy.

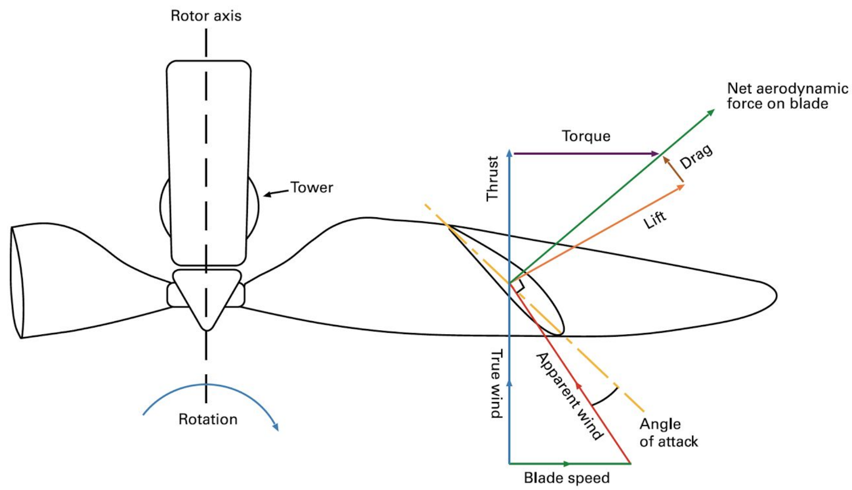



Figure 5: Direction of forces affecting turbine blade [1]

The blade length determines how much wind power can be captured, according to the "swept area" of the motor disc. Of all the energy in the wind, only about half can realistically be extracted (Betz's limit).

The planform shape gets narrower to towards the tip to maintain a constant slowing effect across the swept area. This ensures that none of the air leaves the turbine too slowly (causing turbulence), yet none is allowed to pass through too fast (which would represent wasted energy).

The thickness increases towards the hub to withstand the structural loads, in particular the bending moments. However, a thicker structure increase the drag force, so careful consideration is required.

The apparent wind angle changes along the blade because of the increase in translational speed toward the tip of the blade. Hence to maintain optimum angle of attack of the blade section to the wind, it must be twisted along its length.

Typically the rotational speed is chosen so that the tips are moving at seven to ten times the wind speed, and there are usually no more than three blades. Higher speeds and higher numbers of blades mean each blade must be narrower, therefore thinner, which makes it harder to make them strong enough. At very high rotational speeds the blades also start to become aerodynamically inefficient, noisy, and prone to erosion and bird strikes. At low rotational speeds, swirl in the wake and tip reduces efficiency, while the thrust loads on the other components increase.

Because the wind power varies so greatly (with the cube of wind speed), the turbine must be able to generate power in light winds and withstand the loads in much stronger winds. Therefore, above the optimum wind speed, the blades are typically pitched either into the wind (feathering) or away from the wind (active stall) to reduce the generated power and regulate the loads. The power of wind is calculated with the following equation:

$$P_w = \frac{1}{2} C_p \times \rho \times A \times v^3$$

**Equation1: Wind energy**

Where

- $C_p$ = Betz limit = 0.59 (Theoretical maximum efficiency)
- $\rho$ = air density ($kg/m^3$) = 1.225 $kg/m^3$
- A = motor swept area $= \pi R^2 = 0.073\ m^2$
- V = speed of the wind = 11.4 $m/s^2$

The power (mA) of the blade given the constant wind speed is calculated by multiplying the voltage(V) and current (mA). P (mA) = Voltage(V ) *Curent(mA). If the load (resistance) is in series connection with the motor, power reaches maximum when the load has equal resistance as the rest of the circuit.

The stiffness of the tower is defined to be the rigidity of an object, or the extent to which it resists deformation in response to an applied force. Using the measured data, it can be calculated by using the following formula:

$$K = \frac{F}{Y} = \frac{3EI}{L^3}$$

**Equation 2: Deflection law**

Where

- F = applied load (N)
- Y = deflection of the tip (mm)
- L = length of the tower (m)
- E = Elastic modulus of the tower material (2.4-2.6 GPa for ABS)
- I = Area moment of inertia ($m^4$)

Ideally, maximum power with the least deflection is preferred in this project.

## Design

Our group designed the turbine blades first. Before beginning any CAD designs, we discussed what features we thought were important to generate the maximum power. Understably, we reasoned that three blades would provide optimum stability and power generation (as most real turbines have three blades). Understably, we also determined that it would be best to utilize the entire 6 inches for our blade tip diameter. With those things set, we worked together to design the remaining three main components: the airfoil shape, the angle of attack of the wind, and the pitch of the blade. By having one blade modeled, we would use the circular pattern tool in Solidworks to create three equally spaced blades around the turbine hub.

The shape of the blade's cross section, or airfoil, is a key consideration in our design. Lift is generated by a pressure difference created by air traveling faster on the top of the airfoil and slower on the bottom. Our airfoil was constructed with a flat bottom and a spline on top. The thickness-to-length ratio of the airfoil averaged was about 15%. There were five cross sections, each on a different plane equally spaced from the center of the hub to the blade tip. The airfoil for the first plane was deliberately thicker as we wanted a strong base so the blades would not break off. The airfoil on the second plane was significantly longer and thinner. Up to the fourth plane, the airfoils were simply scaled and rotated projections. The airfoil on the final plane was again slightly thicker to prevent breakage.

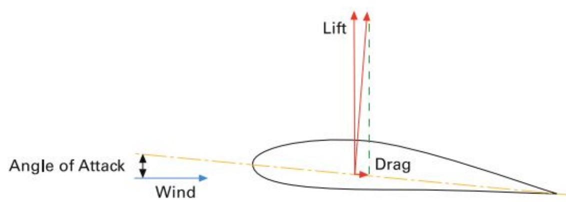



Figure 6: How lift is generated [1]

For every airfoil, there is an optimum angle of attack for the wind. As this angle increases, the lift force also increases, but too large of an angle will produce too much drag and thus cause inefficiency and instability. We decided on an angle of attack around 50 degrees, which is rather large by the standards of most commercial wind turbines. Our reasoning, however, was that because our blades would be spinning at much higher velocities, apparent wind speed felt by the tips of our blades would be more of a governing factor.

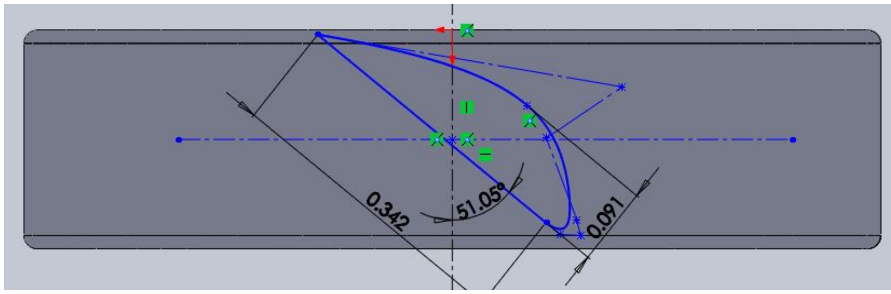



Figure 7: Solidworks sketch of our blade (first plane)

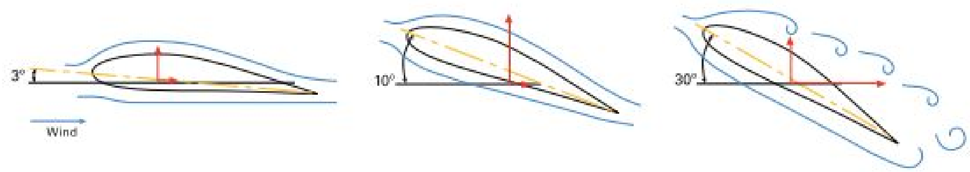



Figure 8: Optimum angle of attack used in industry [1]

Lastly, most commercial turbine blades have a pitch of around 15 degrees. From first plane to the last plane, our blades twisted about 33 degrees so that the blade tip was nearly orthogonal to the direction of the wind. The faster the blade is moving through the air, the greater the apparent wind angle. Again due to the high rpm of the blades, we weighed this aspect more heavily and wanted to decrease this apparent wind angle.

The design for the tower structure was more straightforward. Our main consideration was stiffness given the constraint that our entire wind turbine was to be under 20 cubic inches. Inspired from a lecture presentation, we wanted to incorporate the I-Beam structure into our design given that it had a very good stiff-to-weight ratio in general. Our initial design for the cross section was a simple I-Beam, but after going to Prof. Youssefi's office hours, we realized that tower would be biased for load applied in one direction. To remedy this, we reasoned that a cross design would fix this issue.

We then projected this cross section to a plane 16 inches directly above with a sizing ratio of 60%. We lofted the base and the top to make the basic 3-D shape of our structure. Because of the dimensional restrictions of the 3-D printer, we split the structure in half at the 8 inch mark. For the top half, we cut extruded a 1.18 inch diameter half circle at the very top in order to accommodate our motor housing. Lastly, in order to make the glueing process stronger, we decided to create an interlocking feature created from an extrusion of 0.4 inches tall on the bottom half and an extrusion cut of the same dimensions on the top half.

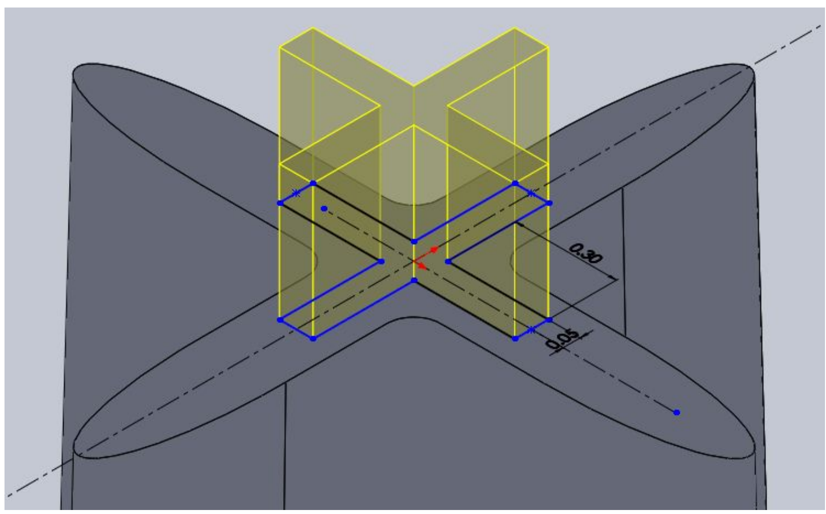


Figure 9: The interlocking feature for the tower structure

## Build

We sent our designs to be 3-D printed. When the finished product arrived, we realized that our blades were too thin on the back edge of the airfoil, because the resolution of the print was not high enough. Rather than reprint, we fixed this issue by applying a coating of super glue to the back edges of the blades. The glue helped reinforce the blades while still maintaining their thin shapes.

There was also a slight problem with the finished product of the bottom and top half of the tower structure. We did not take in the printing error to account when dimensioning the interlocking feature, and subsequently, the two parts did not fit together. To fix this issue, we used a dremel to sand down the edges of our extrusion so that the two pieces would eventually fit.

**CAD drawings**

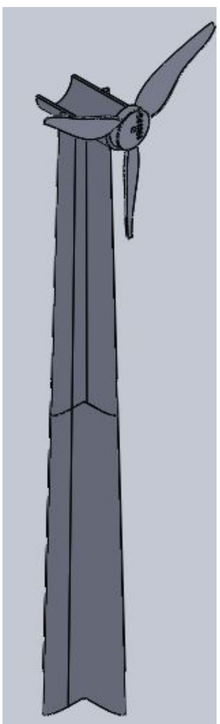


Figure 10: Assembled view

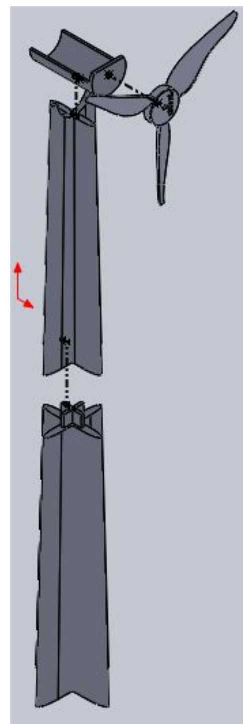


Figure 11: Exploded view

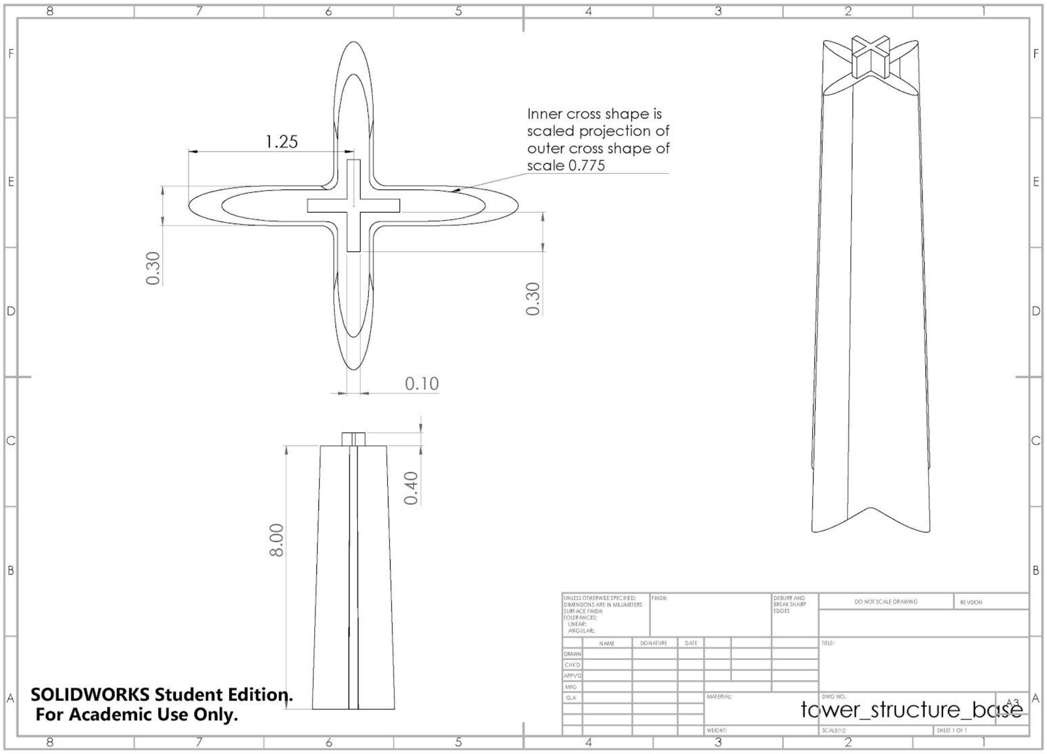



Figure 12: 2-D drawing of base of tower structure

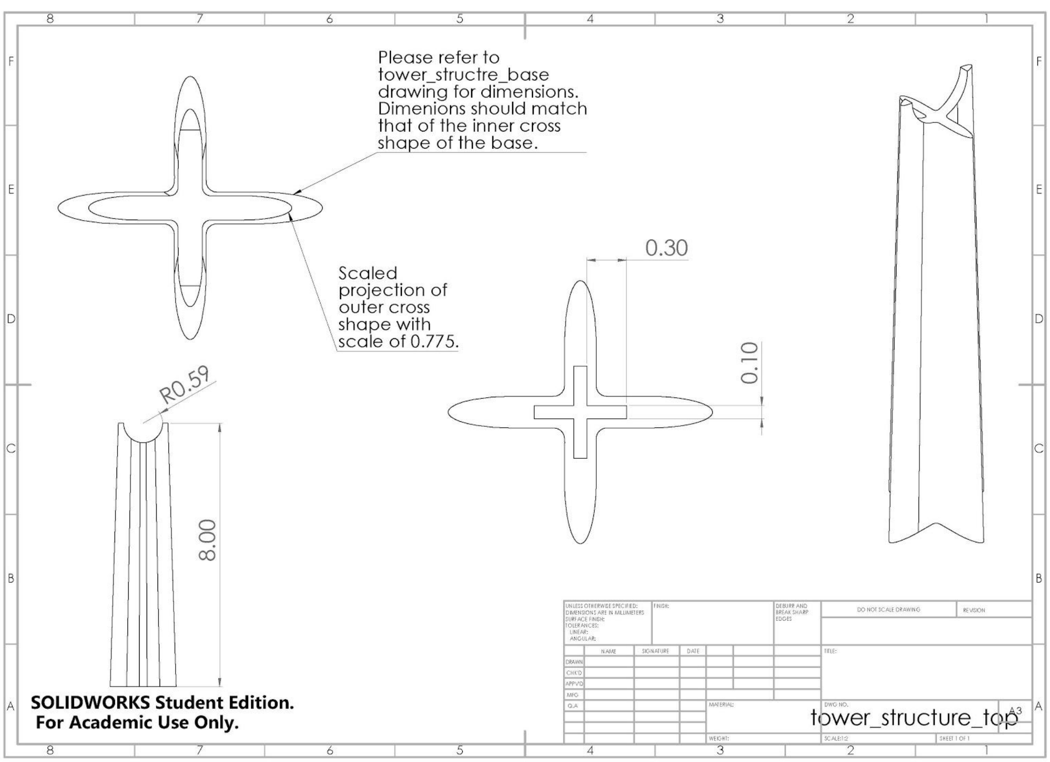



Figure 13: 2-D drawing of top of tower structure

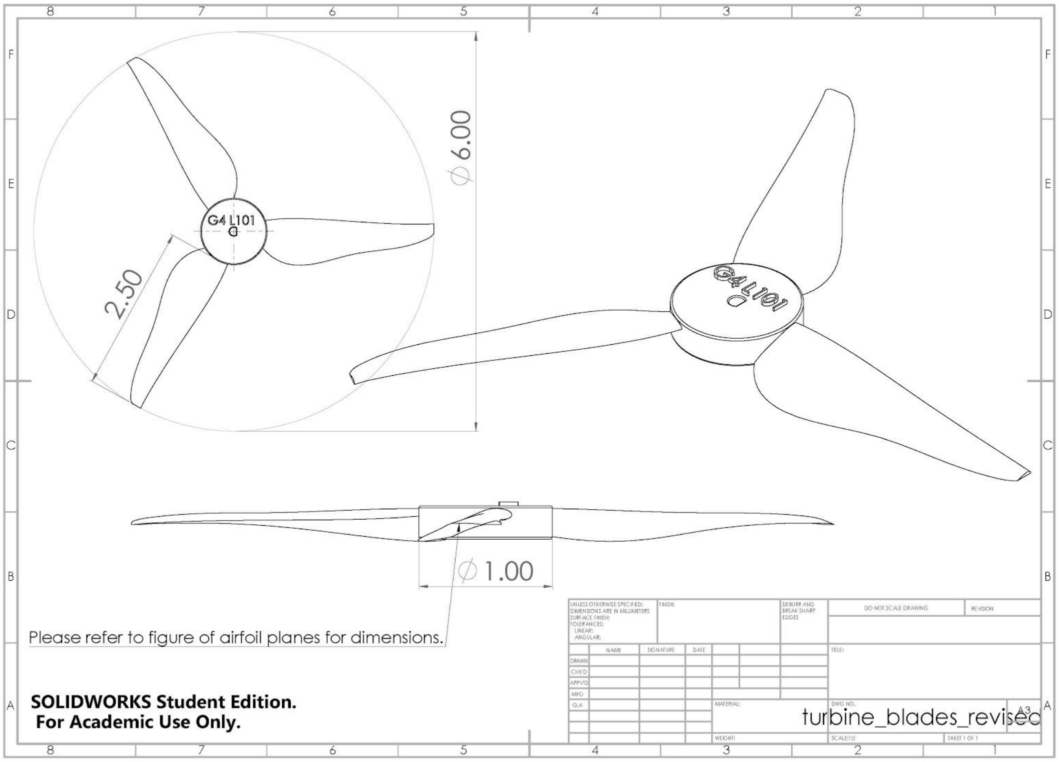



Figure 14: 2-D drawing of turbine blades

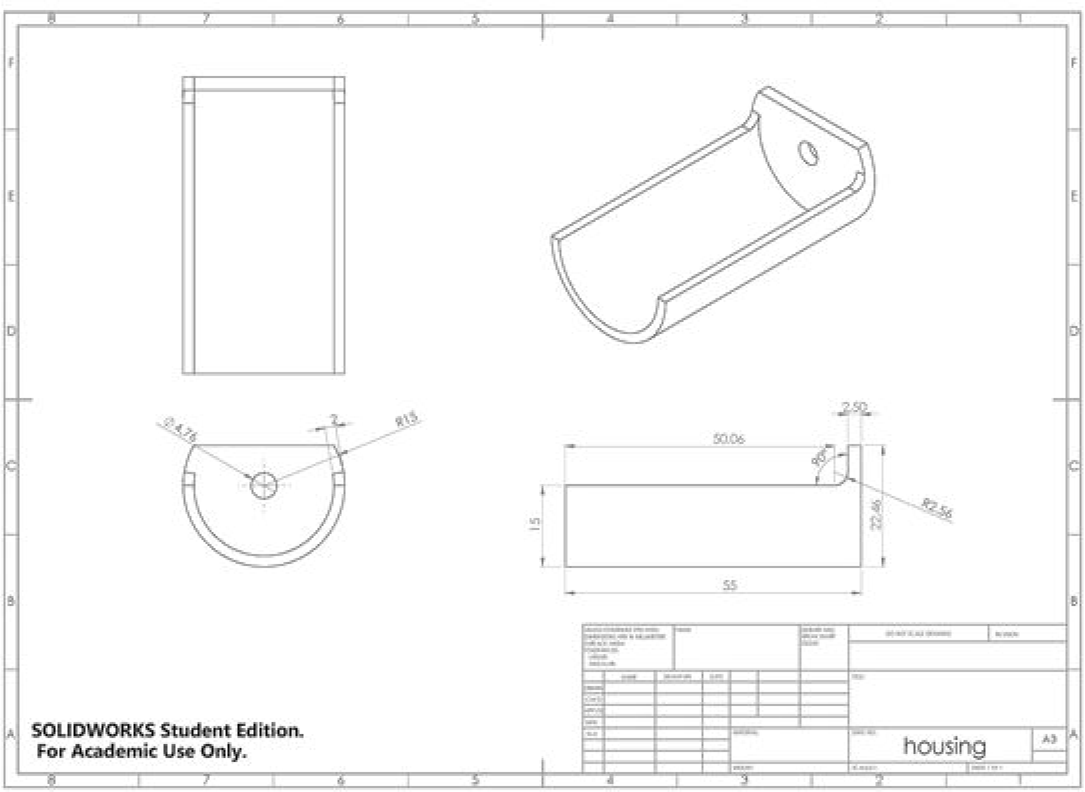
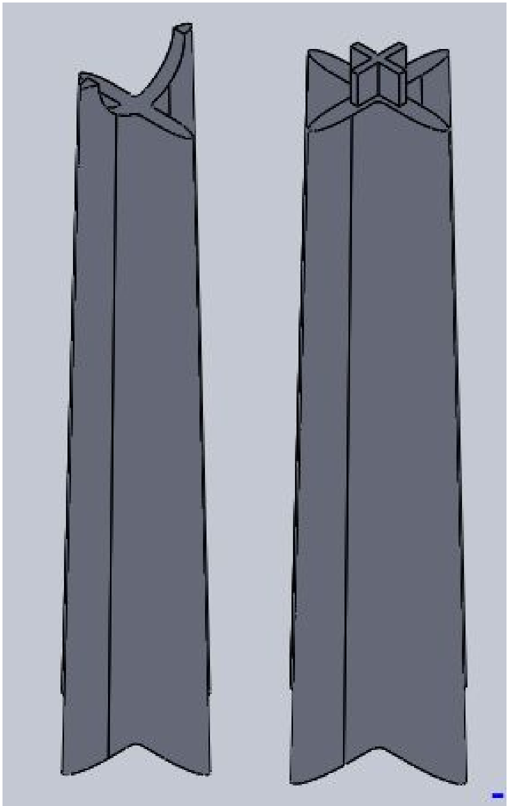



Figure 15: 2-D drawing of motor housing



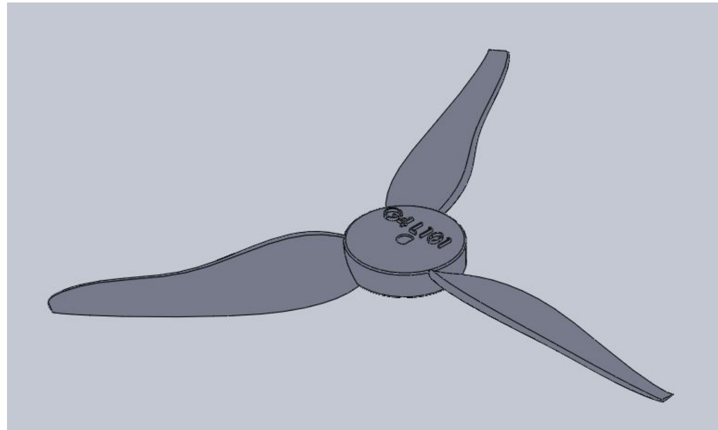


Figure 17: Isometric view of turbine blades

Figure 16: Isometric view of top and bottom of tower structure

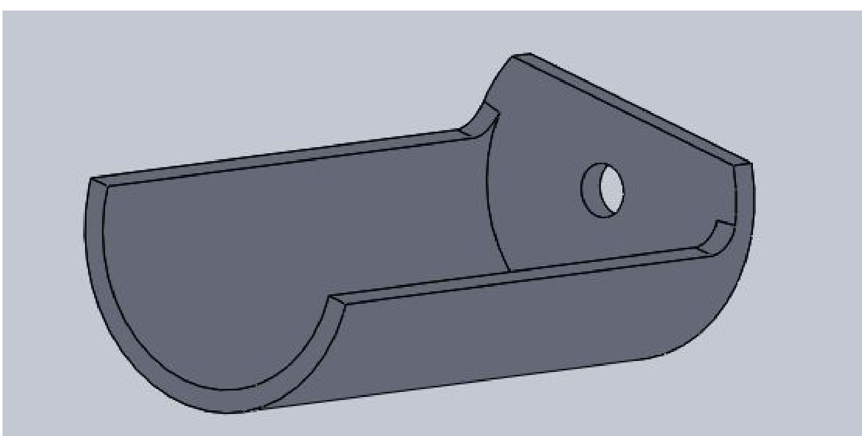


Figure 18: Isometric view of motor housing

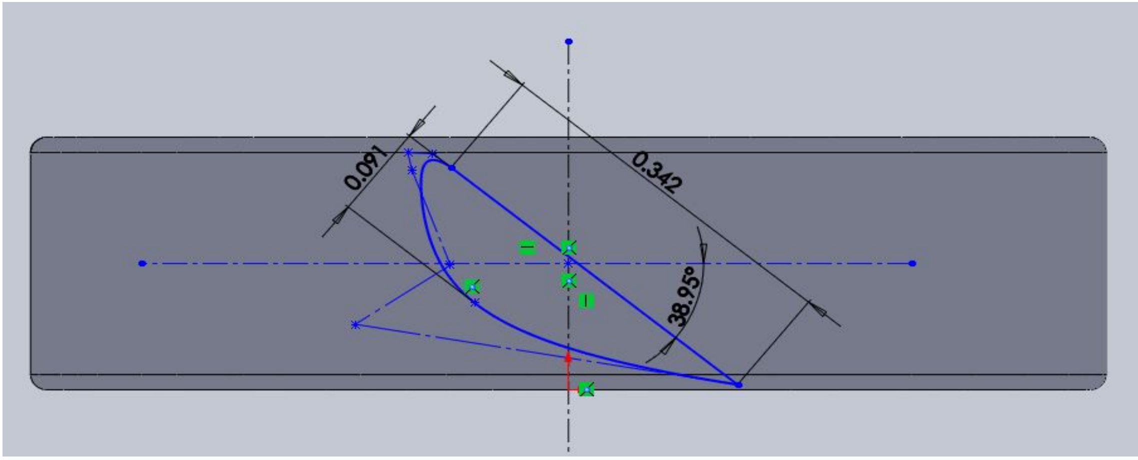



Figure 19: First plane of airfoil blade

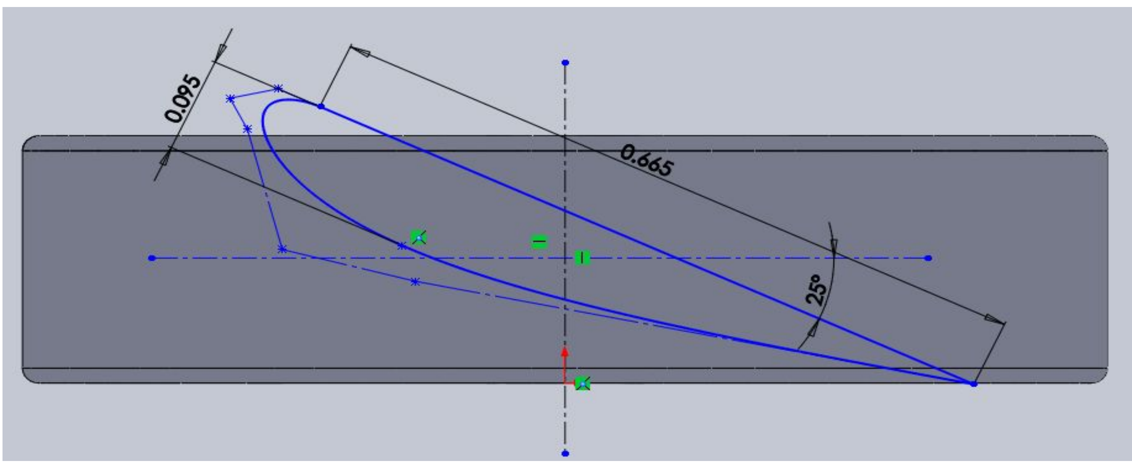



Figure 20: Second plane of airfoil blade

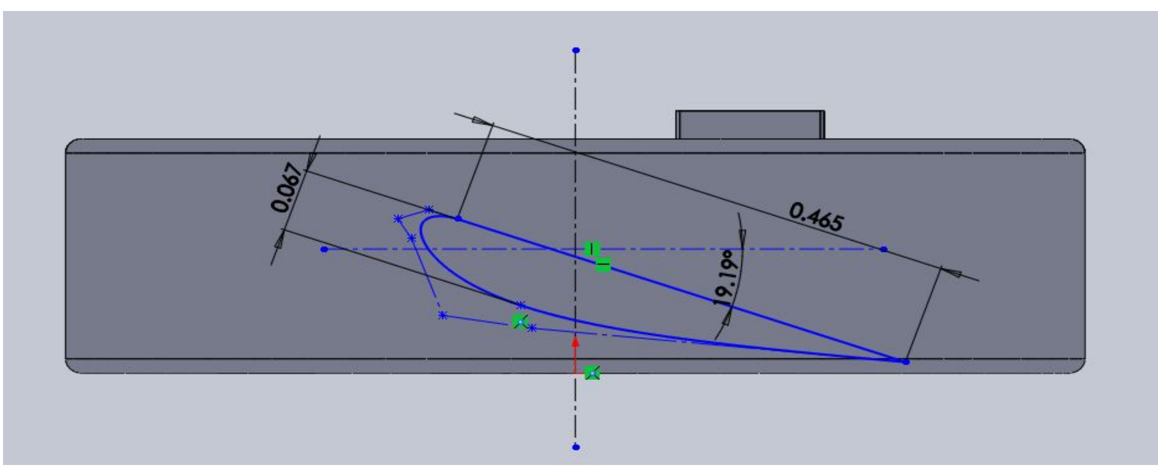



Figure 21: Third plane of airfoil blade

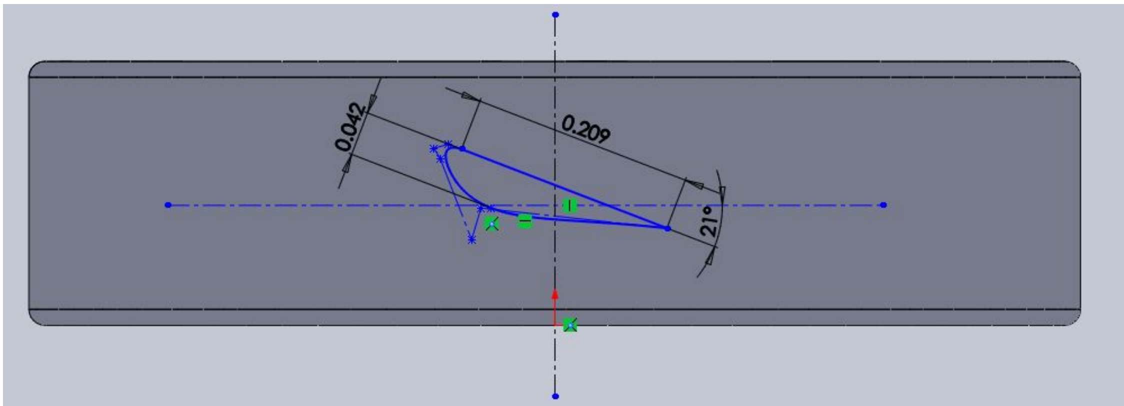



Figure 22: Fourth plane of airfoil blade

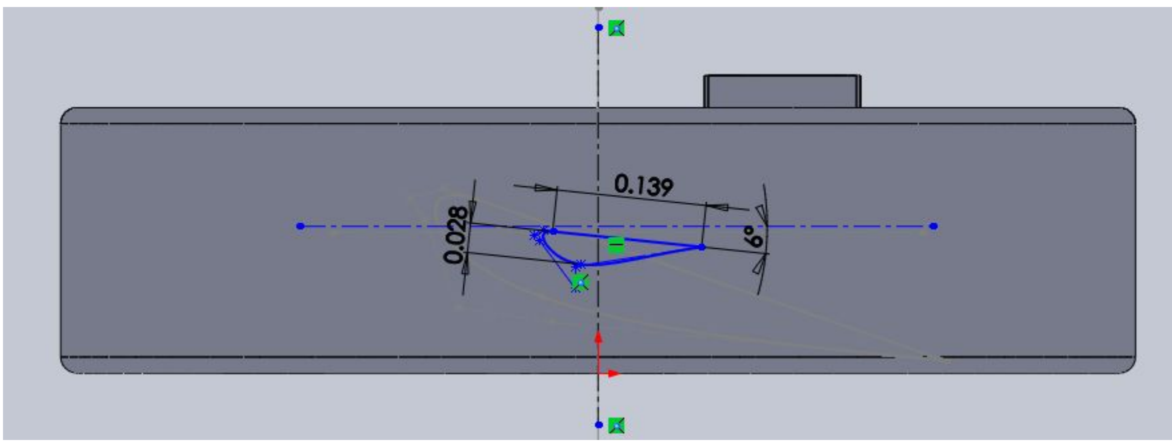



Figure 23: Fifth plane of airfoil blade

## Test

The wind turbine structure was tested in two ways as mentioned. The first test was efficiency measurement. The blade was subject to rotation under a  constant speed of wind generated by a fan. The speed of wind (mph) was initially measured using potentiometer and distance from the fan to the blade was measured as well. After than, rotational speed of the blade (rpm),  voltage (V), current (A)  and the power (W) were recorded under 14 different loads points connected to the circuit.

Secondly, we tested the stiffness of the tower measurement.The net weight and height of tower were initially measured. Then we connected an eyebolt to the housing, applied a load on the eyebolt which gradually increased by 0.1 kg from 0 to 1.4 kg. This was done by attaching a wire with the weights horizontally to the eyebolt much like a simple pulley. The deflection of the tower (mm) under the weight (kg) was measured with spring-loaded dial gauge and then plotted.

The initial measurements for the power generated by the blades was consistent with what we expected more or less. Voltage would exponentially decay as we increased the current, and power would exponentially rise and then drop off with increasing current. However, for higher current values, we noticed increased variability for both voltage and power. The graphs followed a smooth trend until about 0.3 to 0.4 amps, and then became significantly more unpredictable. Nevertheless, we went with this data and found our max power generated to be 1.27 watts at a current of about 0.351 A. Using the Equation 1 from the Theory section, $P_w$ comes to 9.77W. Therefore, the % efficiency of the turbine is P/Pw *100% = 16.6%. In comparison to 40% of commercial wind turbine, the value is approximately less than half.

For the stiffness experiment, we measured fairly reliable results. The linear least-squares regression line was extremely straight with a R^2 coefficient of 0.99754. The stiffness value was the slope of the graph plotted with load (N) on the y-axis and displacement (mm) on the x-axis. Even though load was the dependent variable, the axes were set this way to quickly tell the stiffness value which was 3.4645 N/mm. Eventually with enough load, the displacement would begin to stop increasing and the structure would break. We decided as a group we did not want to risk breaking our structure, so we stopped testing after around 1.4 kg. However, the straightness of the line suggests our structure could have potentially held more weight.

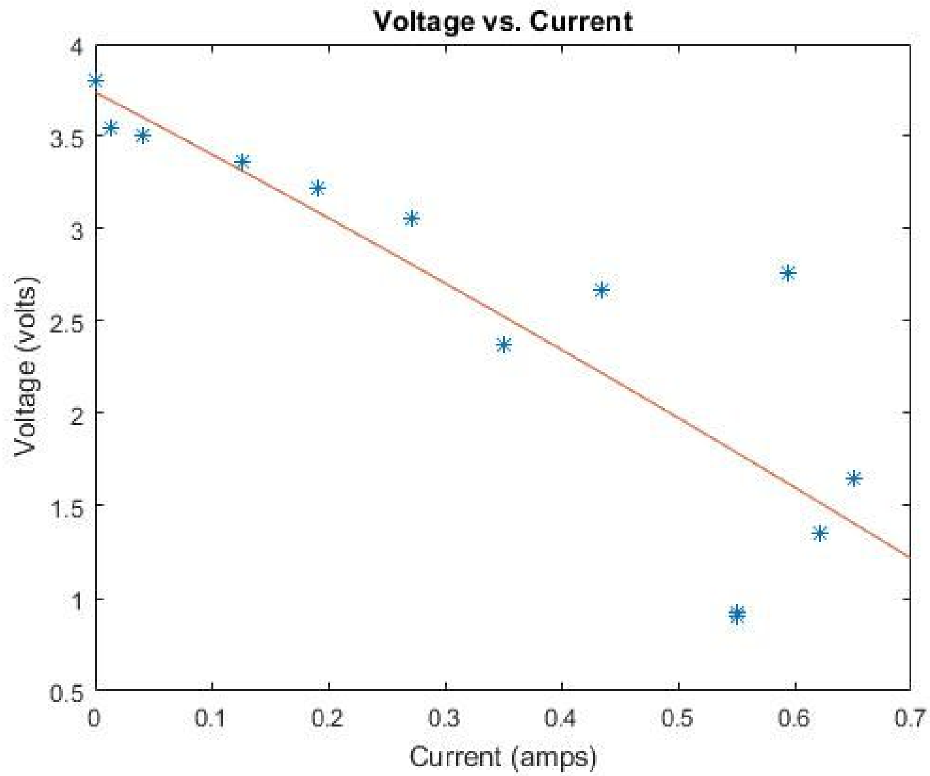



Figure 24: Voltage vs. Current plot

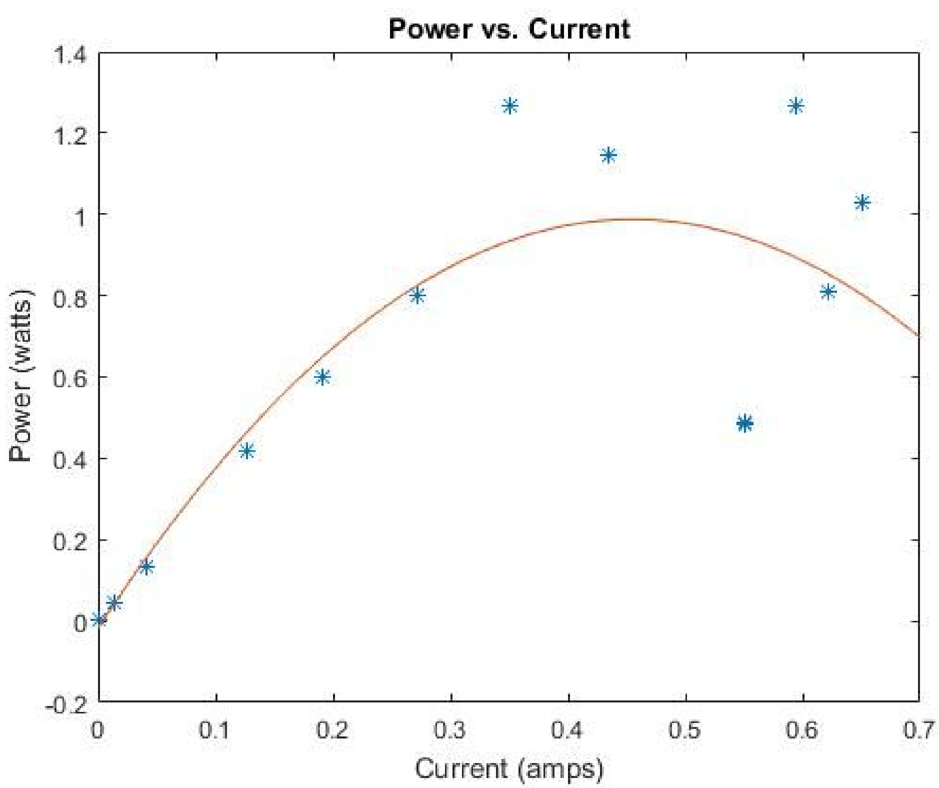



Figure 25: Power vs. Current plot

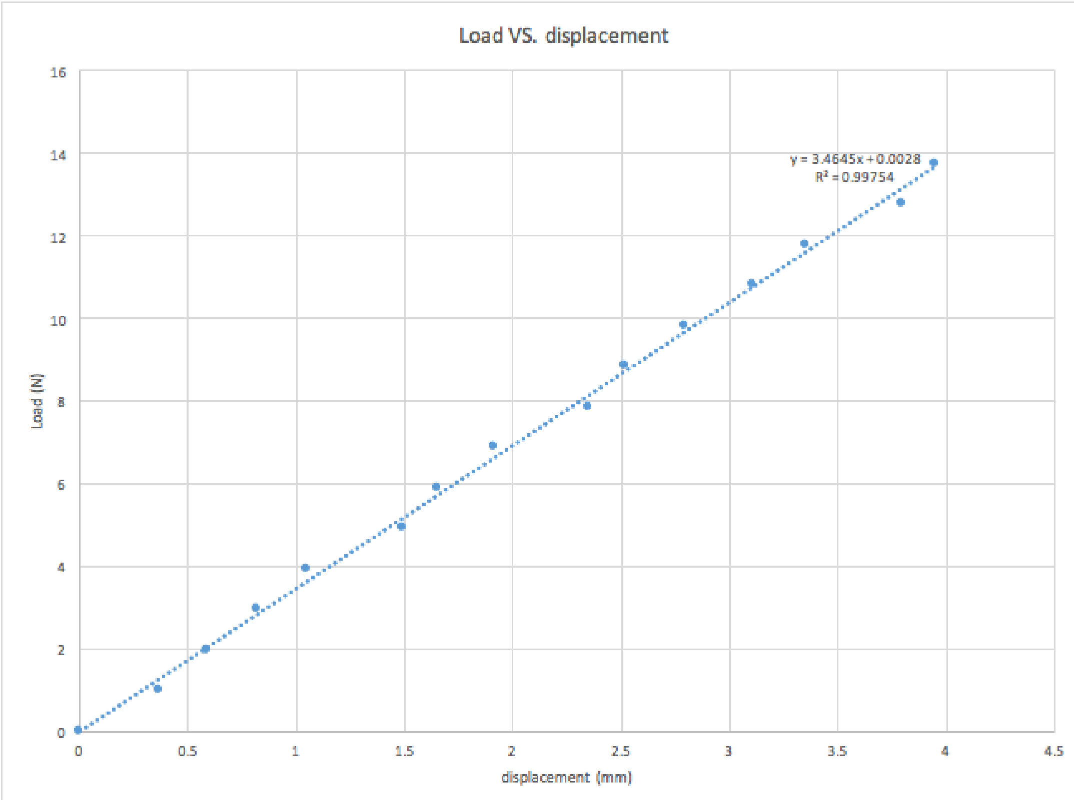



Figure 26: Stiffness plot

## Conclusion

The purpose of the project was to design the wind turbine using Solidworks, 3-D print it, and test the efficiency of the blade and rigidity of the tower structure. The radius of blades and minimum tower structure was constrained, so the optimization was needed. For blades, optimum we  found an angle of twist from reference, and a tapered shaped blade was designed. The stiffness of the tower over the total weight was to be calculated so consideration of the strength and volume of design was necessary. Using basic solid mechanics knowledge, we reached the conclusion that I-Beam was the best candidate. Upon testing the power generation of the turbine blades, the maximum power was generated at an equivalent load as the rest of the circuit. The maximum power created under constant 25.5 mph wind was 1.267 watt, which was competitive compared to others. However, the deflection was significant even though the volume of the tower was small. The reason was that the tower structure was solid with small cross section area, but other teams use larger moments of inertia and made the structure hollow to cut down the total volume.

Theoretical power of the wind is calculated to be 9.77 W, whereas our maximum power generation was 1.267 W, which yielded 16 % of efficiency. Commercial wind turbines have approximately a theoretical maximum power efficiency of 40%. This result was mildly successful.

As a result of this project our group learned how to communicate better, become more punctual, and were able to create something from the ground up. With this type of experience we were given, we had the opportunity to understand what it is like to work together as engineers with given physical constraints and resources.

## Recommendation for Future Work

Our group's recommendation for this project's future work is to mainly change our overall tower structure that it allows for less deflection. We noticed that our structure was deflecting more than previous groups during the load testing. Upon asking the assistant, he informed us that most of the structures with lower deflections implemented tripod support. If we given more time for the project and allowed to do it again, would definitely incorporated some sort of supporting legs. In addition, we could have minimized the volume of our structure by utilizing a density fill, instead of a solid fill to perhaps increase the moment of inertia. For the efficiency of the turbine blade, our biggest weakness was the blade width. Our blades were relatively narrow compared to the rest of the groups, and for a small scale test, wider blades are perhaps essential to catch the most wind. More research should have went into studying similar scale designs instead of industry standards because there are varying constraints for both scopes. With wider blades, we would have to increase the angle of attack even further to prevent less drag from the apparent wind felt by the tips of the blade. Ultimately, it a question of trade offs, and we felt out group took the middle route.

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[6] *Wind Energy Foundation | Wind Energy FAQs.* (n.d.). Retrieved May 10, 2016, from http://windenergyfoundation.org/about-wind-energy/faqs/

[7] Youssefi, Ken | Photos taken from E26 bCourses website.

# Appendix

## Blade Speed - Power measurements

| Data Points | Voltage V(volts) | Current I(Amps) | Power P(Watts) | Blade Speed(rpm) |
|---|---|---|---|---|
| 0 | 3.80 | 0.001 | 0.002 | 5260 |
| 1 | 3.55 | 0.014 | 0.043 | 5230 |
| 2 | 3.50 | 0.041 | 0.135 | 5190 |
| 3 | 3.36 | 0.127 | 0.416 | 5046 |
| 4 | 3.22 | 0.191 | 0.598 | 4900 |
| 5 | 3.06 | 0.271 | 0.802 | 4770 |
| 6 | 2.67 | 0.435 | 1.145 | 4400 |
| 7 | 2.37 | 0.351 | 1.267 | 4070 |
| 8 | 2.76 | 0.595 | 1.265 | 3825 |
| 9 | 1.65 | 0.651 | 1.029 | 3120 |
| 10 | 1.35 | 0.621 | 0.808 | 2620 |
| 11 | 0.92 | 0.550 | 0.490 | 2000 |
| 12 | 0.90 | 0.550 | 0.483 | 1900 |

**Tower - Deflection measurements**

| Data Points | Load(kg) | Displacement(mm) |
|---|---|---|
| 1 | 0 | 0 |
| 2 | 0.1 | 0.37 |
| 3 | 0.2 | 0.59 |
| 4 | 0.3 | 0.82 |
| 5 | 0.4 | 1.05 |
| 6 | 0.5 | 1.49 |
| 7 | 0.6 | 1.65 |
| 8 | 0.7 | 1.91 |
| 9 | 0.8 | 2.35 |
| 10 | 0.9 | 2.52 |
| 11 | 1.0 | 2.79 |
| 12 | 1.1 | 3.11 |
| 13 | 1.2 | 3.35 |
| 14 | 1.3 | 3.80 |
| 15 | 1.4 | 3.95 |