E26: Three-Dimensional Modeling For Design

University of California, Berkeley - Mechanical Engineering Department
Professor Ken Youssefi

Wind Turbine Design Project

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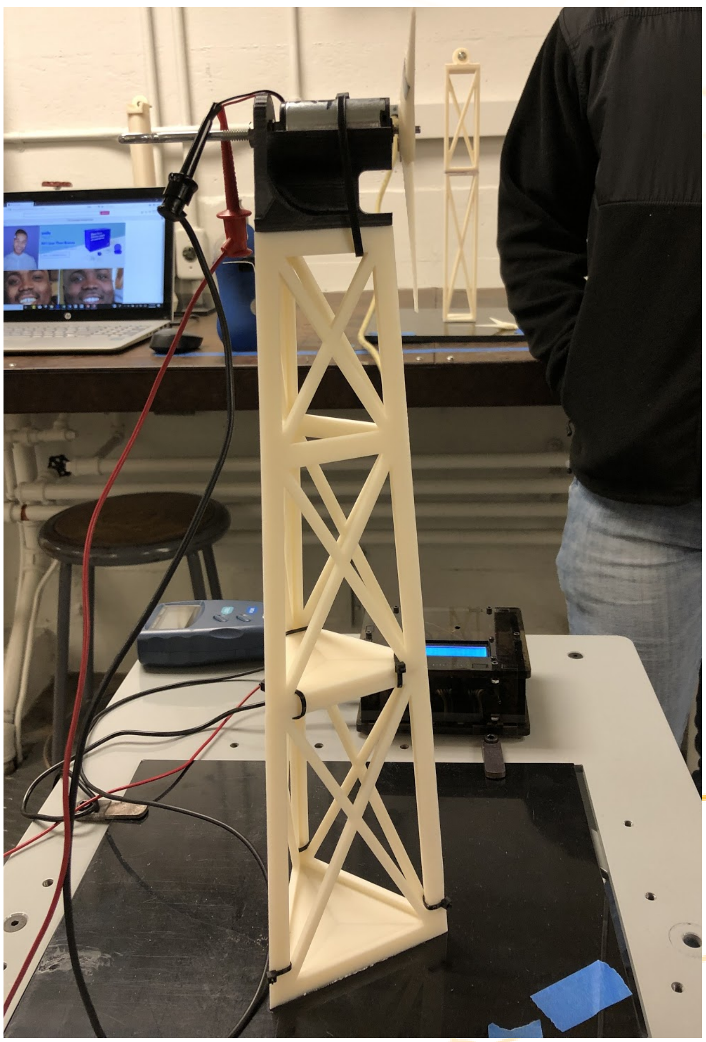


Project Summary

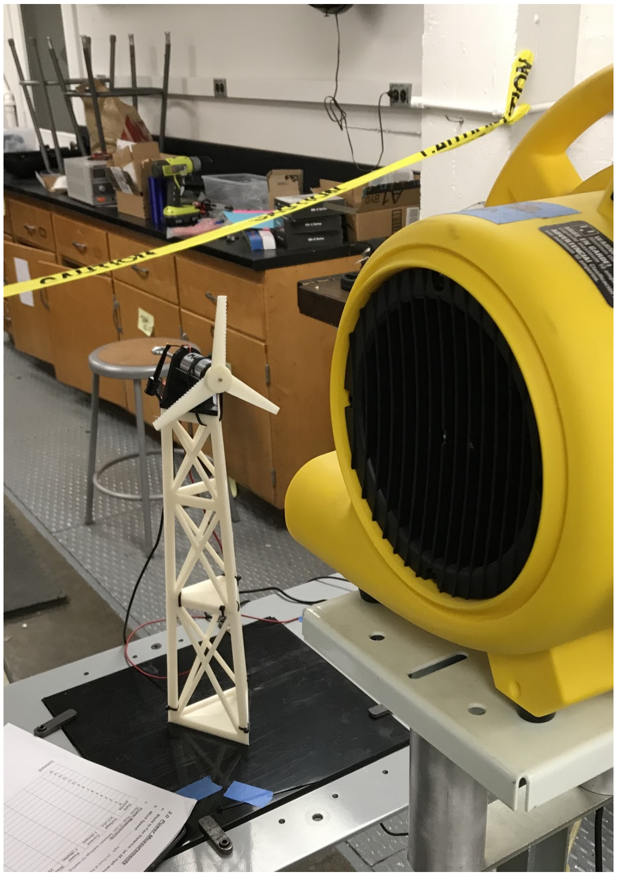
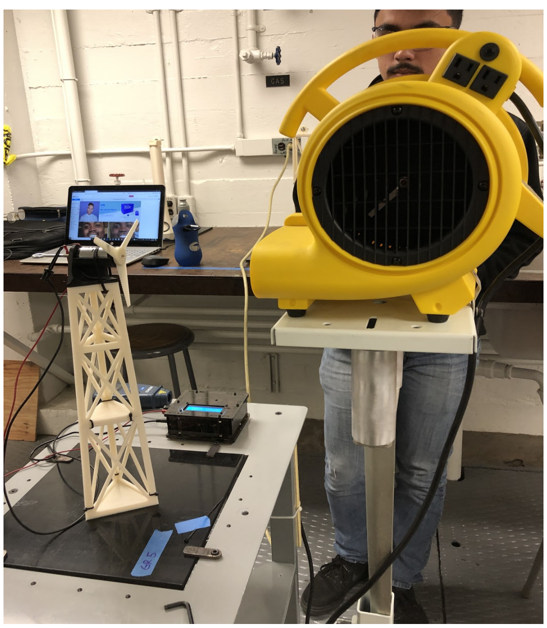


Figure I.1 Final tower design during testing.

The objectives of the Wind Turbine Design Project were to design a wind turbine tower that would be light and stiff and produce lots of power. Specifically, the aim was to design a tower with the least deflection per weight ratio and a blade with the highest power output possible. The goal for the blade was that it would be able to generate at least two watts of power. The design constraints were a 16 inch tower height at the motor, a maximum volume of 18 in^3 , and a maximum blade length of 2.5 inches.

Our tower design was light and that showed itself at the weigh in when our tower came in at 229.6 grams. Following the design constraints, the towers height at the motor mount was exactly 16 inches and its total height was 16 ½ inches. During the wind testing our blade managed to produce a peak power of 1.52 watts. The performance metric for stiffness was its deflection per unit weight ratio, which after testing we calculated to be 6.11 N/mm.

The performance of the tower and blade was less than what we had hoped for. Power generation fell short about ½ watt as our blade only produced approximately 1.5 watts. Although our tower was light, actually considerably lighter than most of the competition, it's stiffness was not up to par with the objective. The stiffness of our tower fell short by about 4 N/mm from the goal of having a tower with a stiffness coefficient of 10 N/mm. Although both of our performance figures fell short from the objective, neither can be considered a significant failure as both figures were on par with competing designs.



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I. Introduction

With increased demands for electricity as well as the shift towards renewable energy sources, wind energy has become one of the most popular options in power production. The wind turbine design project aims to present and test an miniature wind turbine in order to simulate and model a real-life turbine used in today's power generation. One goal of this project is to build an optimized wind blade such that it will generate maximum efficiency in power production. These turbine blades generates energy by converting wind kinetic energy into mechanical energy. Combined with the use of a generator, this mechanical energy is then converted to electricity (Figure 1). However, in order to maximize this power generation, many factors must be considered in the blade's design; this includes maximizing lift, minimizing drag as well as the best angle of attack (Figure 2). Outside of the blade's design, the structure must also be taken into consideration. The structure provides the support for both the motor and blade such that it allows the blade to be at a high enough attitude to reach desired wind speeds. In addition, it must be designed to withstand certain forces (maximum stiffness) while keeping weight and volume at a minimum.

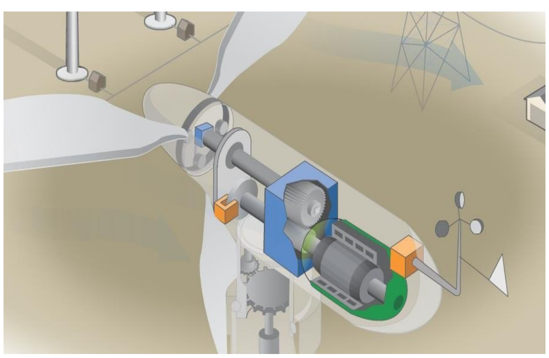


Figure 1: Power Generation (energy.gov)

Figure 2: Wind Blade Designs (energy.gov)

For this project, the design of the wind blade and structure is created using SolidWorks, a Computer-Aided Design (CAD) software. Through SolidWorks, the blade is designed with the constraint that the swept area should not exceed 6 inches and that the blade length must be within 2.5 inches. The blade is created by extruding a sketch from the cross-section of the turbine hub to another sketch at blade length. It is also extruded such that there is a smooth transition throughout to maximize wind flow.

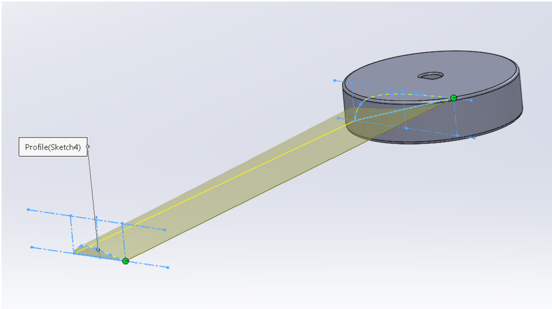


Figure 3: Wind Blade Profile

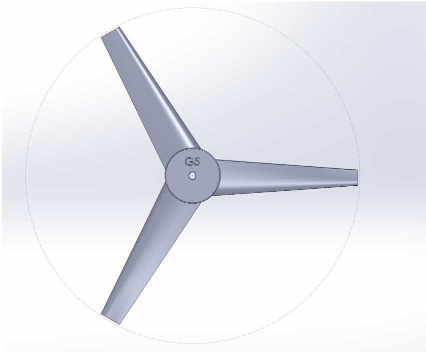


Figure 4: Wind Blade with Hub

The wind turbine project is tested for weight, stiffness, and power output. Hence, the blade is optimized by choosing the best angle of attack for the design. This is done by finding the angle of attack that will maximize lift and minimize drag. Pictures below is the implemented blade design (Figure 5) and its respective coefficient of lift to drag ratio which is highest at angle of attack around 10 degrees (Figure 6).

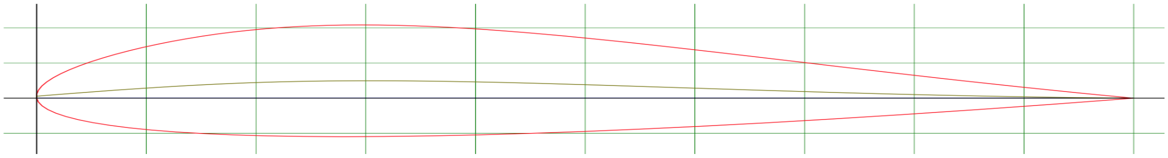


Figure 5: Wind Blade Profile

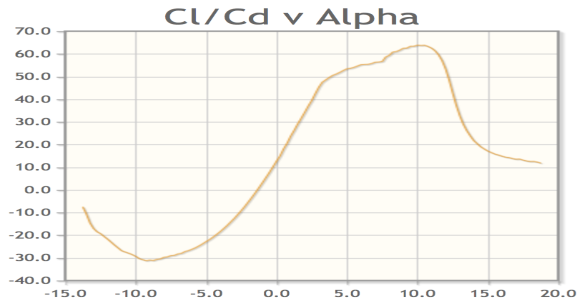


Figure 6: Graph of Cl/Cd vs Angle of Attack

The structure, itself, is designed utilizing two different sections, each containing three symmetrical parts such that it reaches a height of 16 inches. The goal of this structure's design is to maximize stiffness with as little volume as possible. Hence, the structure is designed using a triangular support where the two legs would withstand the most force on the tower. Since area moment of inertia is proportional to stiffness, trusses similar to I-beams are inserted between structure supports to increase load area while maintaining a low volume. The motor mount is also designed through SolidWorks with heavy consideration on weight and volume.

The design is then 3D printed using Fused-Deposition Modeling (FDM). FDM creates parts by building layers of thermoplastic material over previous layers from base the upwards. Separate printed parts are then glued together in order to form the wind turbine.

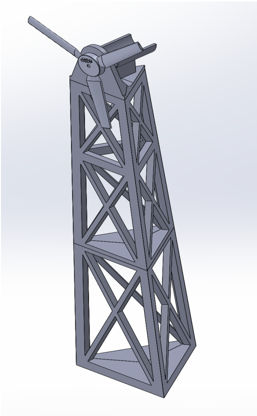


Figure 7: Assembly View(CAD)

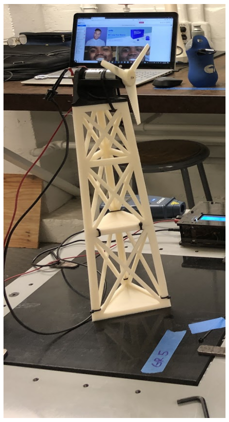


Figure 8: Wind Turbine Model

II. Theory:

To choose the right aerofoil for our blade design, we use the Lift Force equation from NASA website:

$$L = C_l \frac{rV^2A}{2}$$

where: L is the lift force

C_l is the lift coefficient

r is the air density

V is the wind speed

A is the blade area

To achieve highest efficiency, according to the equation above, we need to maximize the lift force. To do that we need to design the blade with high lift coefficient. We use the website airfoiltool.com to choose the airfoil that has high lift coefficient.

The fraction of lift coefficient over drag coefficient is also very important. Our targeted angle of attack is 10 degrees. We want to maximize lift and minimize drag, so the higher the result of lift coefficient over drag coefficient in this range of angle of attack, the better performance we will get on our wind turbine.

As for number of blades, choosing the even number of blades will decrease the stability of the wind turbine because it will produce uneven forces on the rotor shaft and rotor blade. Also, after three blades, increasing more blades will not increase the power efficiency by a significant amount. In addition, the cost for manufacturing, material is not worth for adding more blades to the rotor.

The blades on the rotor are twisted to catch the wind at different angles. This will allow the wind turbine to work at different wind directions.

As for tower design structure, the goal is to design a structure that has low weight and high stiffness. First, by decreasing the weight of the tower, we can save a lot of money in material, manufacturing and transportation processes. Second, by having high stiffness, our tower will survive harsh conditions such as: storms, small earthquakes, high wind, etc.

Based on the known parameters and the wind speed we can calculate the theoretical power generation from the our wind turbine.

$$P_{theoretical} = \frac{1}{2} * (\rho) * (A) * (V)^3, \text{ where}$$

ρ = Density of Air

A = Swept area = πr^2

V = Wind speed

In testing, we can collect the experimental or actual power generation by connecting the turbine to the power meter. Having experimental power generation, we can calculate the efficiency of our wind turbine.

$$Efficiency = \frac{P_{theoretical}}{P_{actual}} \times 100\%$$

To calculate the stiffness of the structure, we use this equation:

$$k = \frac{Load}{Deflection}$$

where: -k is the stiffness of the structure

-Load is the total force applied to the tower

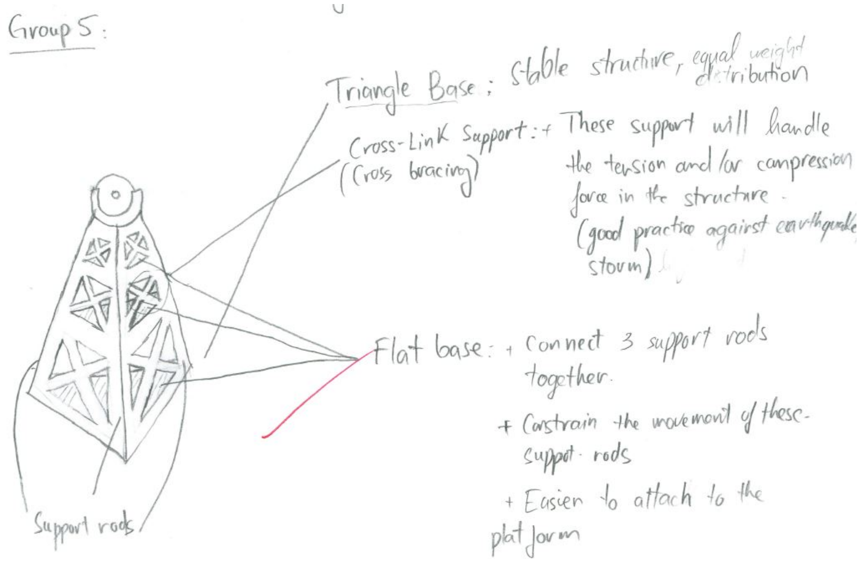
-Deflection is the total displacement of the tower under load

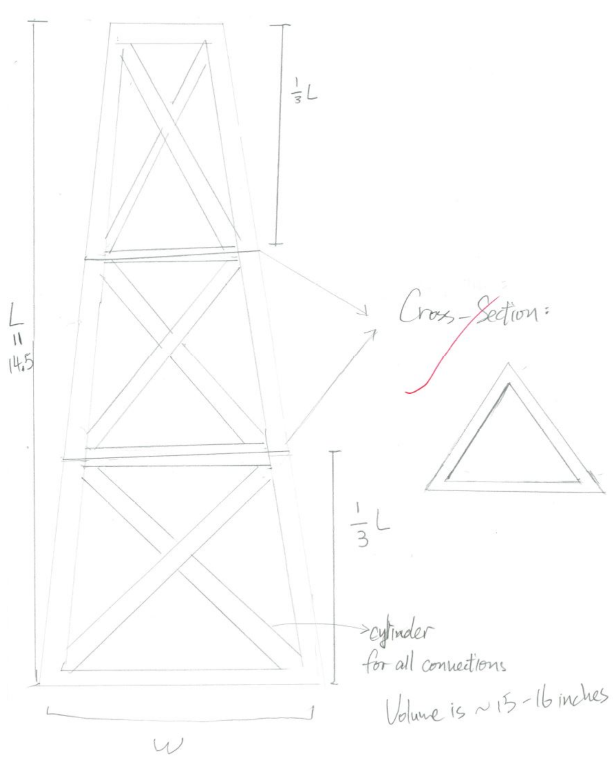
Having high stiffness means our tower will have small displacement under high load, which is an indication of strong structure.

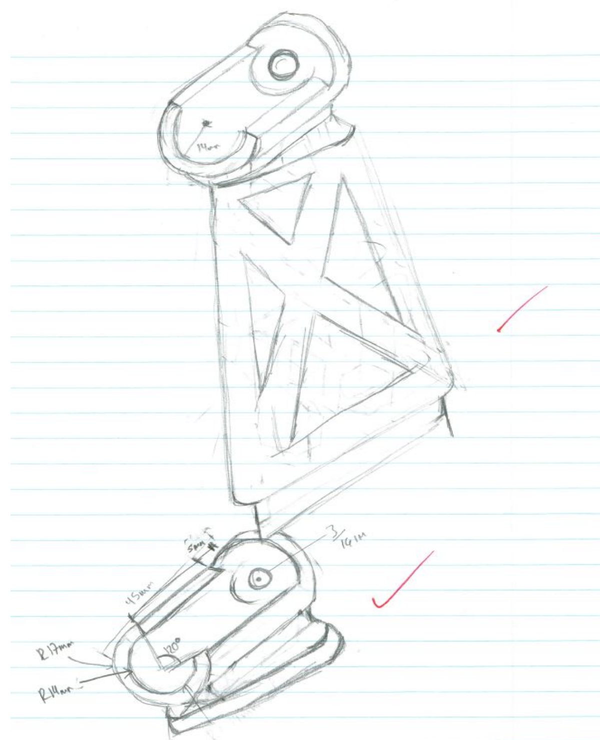
III. Design- Build-Test

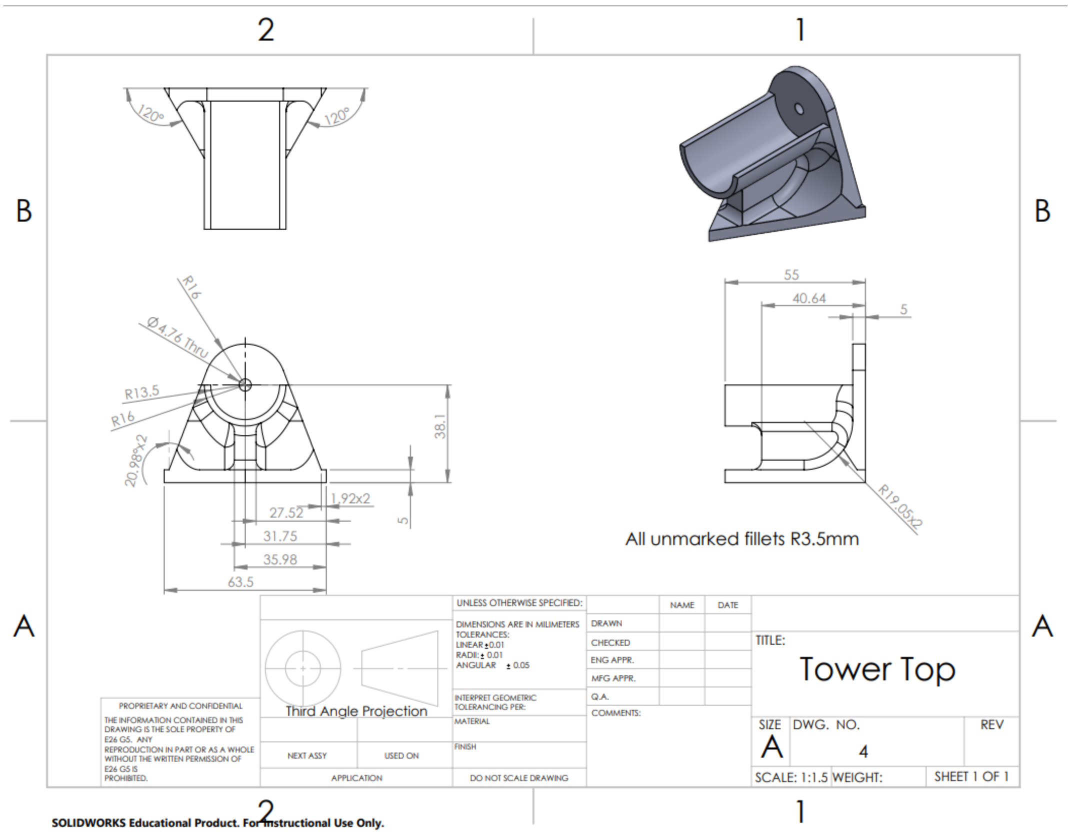
1. Blade Design Sketches:

2. Tower Design Sketches:





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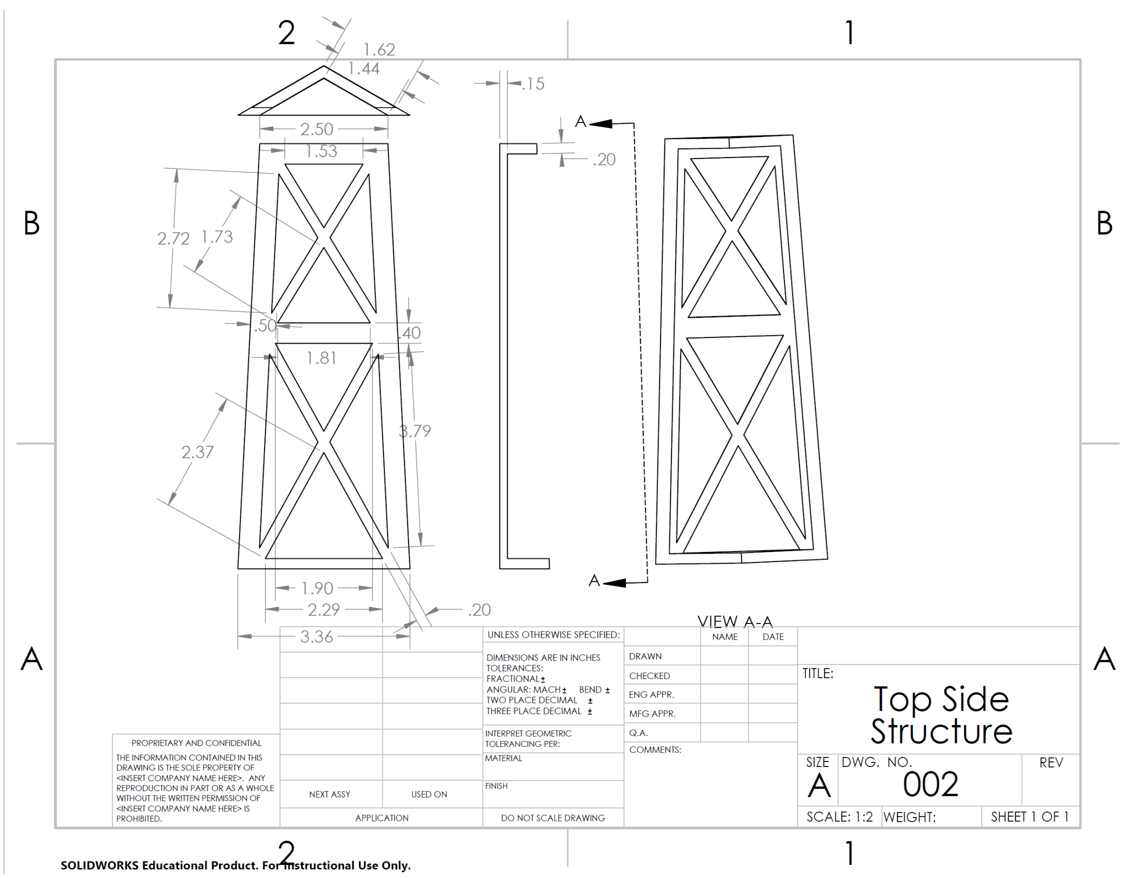
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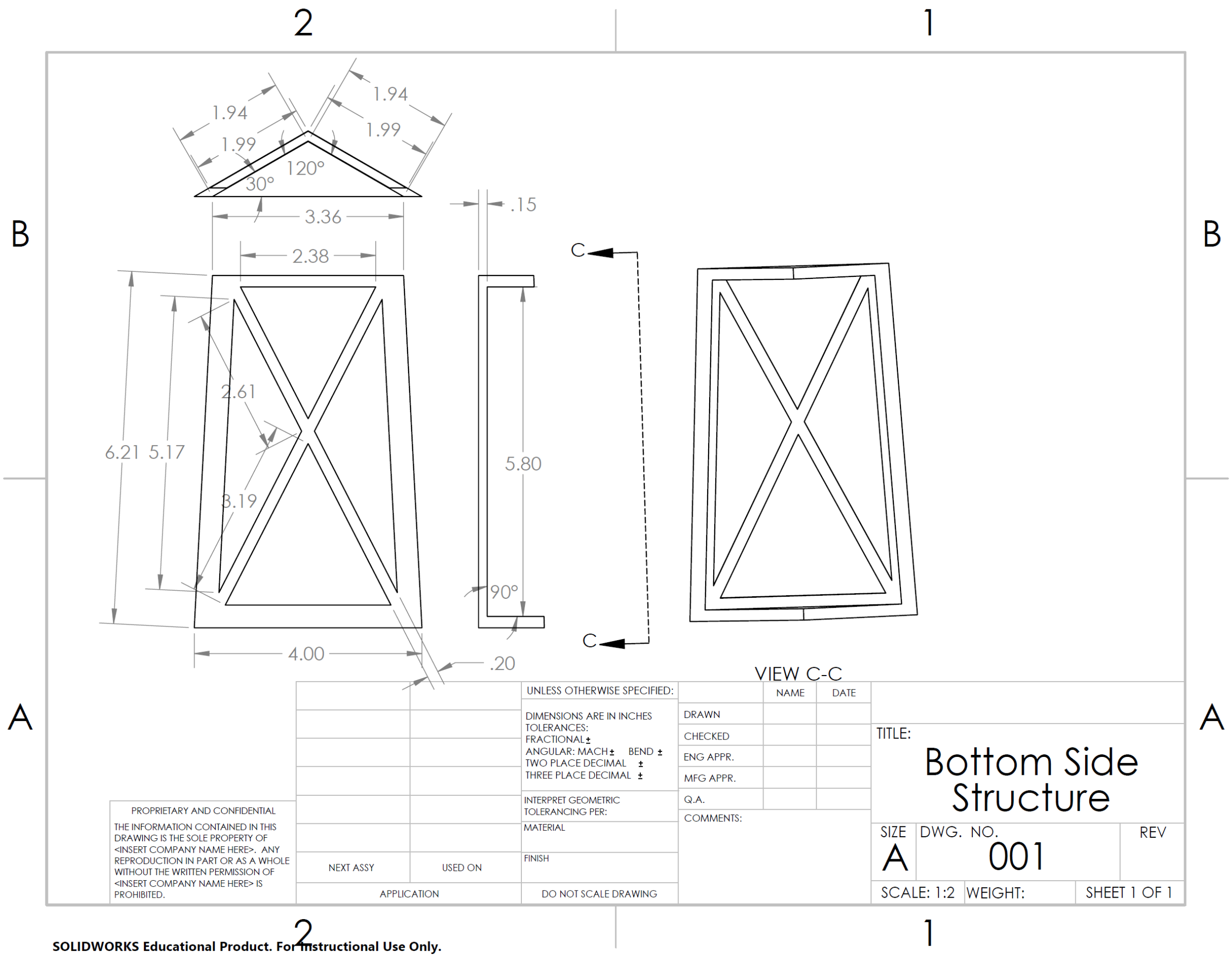


3. Material Specs (Type, Shape, Materials):

For the tower model it was critical to select materials with properties that would help us optimize performance. The important properties about the materials used were their weight and their modulus of elasticity or Young's modulus. For an optimal project we wanted materials with lower density since they will weigh less (mass=density x volume). Additionally we want to look for materials with a higher Young's modulus. This is because we know that the maximum deflection will be described by a formula similar to the formula for the deflection of a beam $\delta = WL^3/3EI$. In the aforementioned formula, W is the load placed on the edge, L is the distance between the load and the base, E is Young's modulus, and I is the moment of inertia. Because the Young modulus always goes on the denominator of a deflection formula, we know that a larger Young modulus will give us a lesser deflection.

The tower design utilized two main materials in its conception. One was ABS^+ plastic and the other was PLA plastic. The ABS^+ plastic has a Young modulus of 2.2 GPa and a density of 1036.9 kg/m^3. We used ABS^+ plastic for most of the tower because the 3D printers with finer tolerances use this material. It was important to have precise parts for our tower because the parts have to interlock together with a good fit so that our tower will be more rigid. We also used this material for our blade because the blade required precise detail, which these 3D printers could provide. The one downside to using this material was that it's somewhat expensive, coming in at around 5 dollars per cubic inch. We ended up using about 14 in^3 of this material.

The other material used, PLA, was used mainly as for cost reduction purposes. We used PLA on the top of our tower because there was only one surface where that part had to be attached. In other words, some inaccuracy was allowable. The PLA has a Young modulus of 3.5 GPA and a density of 1250 kg/m^3. Therefore it's a stronger material than ABS as can be seen from the Young modulus, but it's also a heavier material. The second advantage to using PLA is that it is freely for Jacobs makerpass holders. We used a total of 2.54 in^3 of this material.

4. Fabrication tools:

The building of our tower took advantage of the 3D printing processes that have been popularized in the last decade. The portion of our tower printed in ABS^+ was printed using the Stratasys Dimension 1200es 3D printer in the Etcheverry machine shop. This type of printer offers soluble supports which resulted in very clean parts. The g-code for these printers is created using Catalyst software. The second type of 3D printer we used was the Ultimaker 3D printer in Jacobs hall which prints using PLA. This printer does offer soluble support but we chose to use breakaway since the part that we were going to print didn't need much support. This type of printer runs on g-code created by Cura software.

After the 3D printing process was complete, the last step in the fabrication of our tower was the assembly of the parts. We assembled our tower using Loctite clear adhesive for plastics. We applied a generous amount of glue to all of the surfaces that would be in contact with each other before joining them and holding them together for a few minutes while the glue bonded. We did this part by part, first joining the bottom 3 sections of the tower with each other, then joining the top 3 sections of the tower with each other. Afterwards the upper portion of the tower was glued to the lower portion of the tower. To finish we glued the motor mount to the tower and then glued the tower to the base plate, making sure that the back of the tower faced one of the sides of the base plate. We also used zip ties to hold the corners together while the glue dried.

5. Testing (Setup/Procedure):

Our first test was power output measurement. The purpose of this test was to find the maximum power out of our wind turbine generator. We used a power meter to measure the power (mW), current (mA), and voltage (V) generated by the motor and blade. A load box was also attached to measure the maximum power that could be drawn. The tower was clamped down, with the front of the turbine facing the wind generator, which was set to 24.1 mph, as close as we could get to 25 mph. Then the wind generator was turned off and load box attached to the power meter and motor, We zeroed the load at 0W (turned potentiometer all the way counterclockwise), turned the wind on, and measured voltage, current, power, and blade speed. We ramped up the load in roughly 0.2W increments until we reached our max load. To measure blade speed, we attached some tape to the blade and held a wind speed measuring meter steady, pointing the laser at its outline. One person held the device while another read off the number. Our maximum power output peaked at 1.520W with a blade speed of 4860 rpm. Increasing the load caused power output and wind speed to drop.

Our second test was the stiffness measurement test, to see how much the tower deflects under load in the form of measured masses. We secured the wind turbine to the testing platform with clamps and attached a string to the back of the top support plate using a provided eyebolt, pulling it over the pulley. Next, we positioned the dial indicator to face the turbine and zeroed it. Then, we added weight in increments of .1 kg and measured the displacement with the dial indicator. After 1 kg (with displacement of 1.67 mm), our tower did not break so we continued adding weight in 1 kg increments until 5 kg, which had a displacement of 9.80 mm. After plotting and fitting it with a curve with 99.5% correlation factor, our stiffness k was 6.117 N/mm.

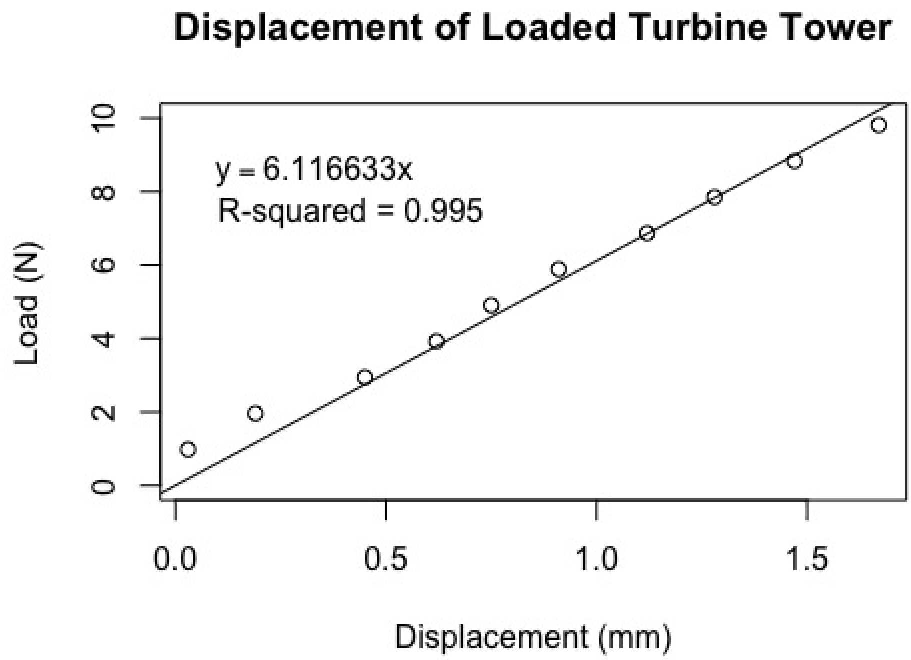
6. Testing Instruments:

The power measurement mainly involved three types of instruments. The first type was used to generate wind, which included a fan and a wind speed measuring meter. The second type was used to measure the output power. This consisted of a small brushless motor that was attached to our rotor blade, a power meter that was connected to the motor, and a load that was used to measure the power output. Finally, we placed a piece of reflective tape on our blade and used a tachometer to measure the speed of the rotor.

The instruments involved in the tower stiffness measurement were simpler: the dial indicator that was used to measure the scale of displacement and ten 100g weight blocks that were added to string attached to the tower one by one.

7. Data Plots:

a. Turbine Tower Stiffness Measurement



Loads range from 0.1kg to 1kg, increasing with 0.1 interval, are applied to the towel. The related displacements were recorded (See **Appendix** for the complete data sheet). Our turbine tower deflected a total of 1.67 mm under 1.0 kg of load.

We plot load vs. displacement according to the recorded data and use linear regression to fit a line with zero intercepts to the data. The regression line has the equation y = 6.12x, which means that the stiffness of the wind tower is 6.12 (N/mm), and the correlation factor, R^2, is 0.995 under this curve.

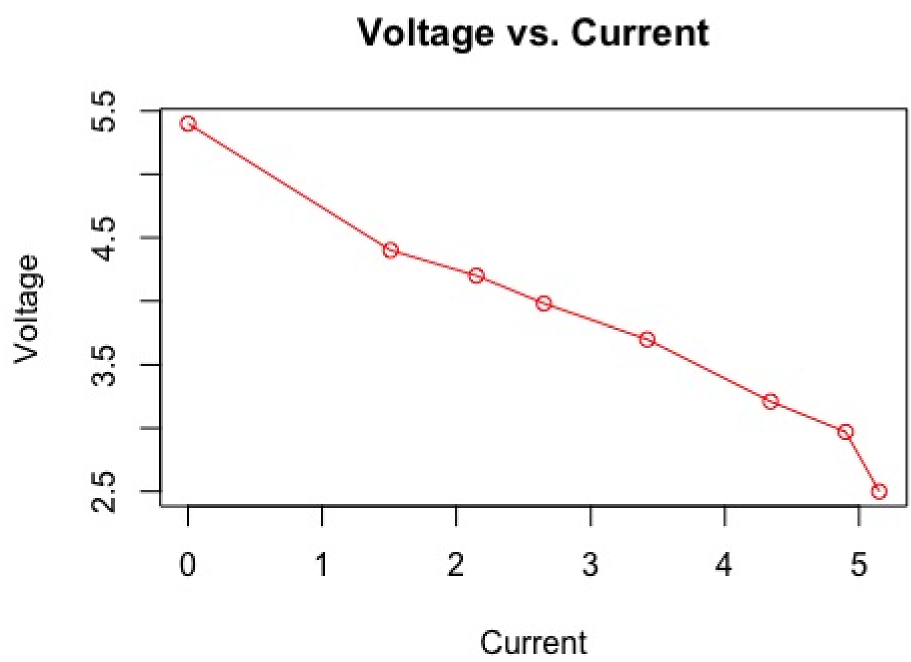
This stiffness seems to be about average compared to the towers from other groups. We likely could have increased the stiffness value by altering the design of our truss structure in order to decrease deflection.

b. Voltage, Power, and Current Measurements

The power generated by our wind turbine is also measured under a wind speed of 24.1 mph. Below is the summary table of power data under different voltage and current values. The complete data sheet can be found in the **Appendix**.

Data Points	Voltage V (Volts)	Current I (Amps)	Power P (Watts)	Blade Speed (rpm)
0	5.4	0	0	7460
1	4.4	1.51	0.675	6600
2	4.2	2.15	0.890	6350
3	3.98	2.65	1.060	6120
4	3.70	3.42	1.250	5800
5	3.21	4.34	1.450	5250
6	**2.97**	**4.90**	**1.520**	**4860**
7	2.5	5.15	1.250	3900

Our wind turbine produced a maximum value of 1.520 watts of power at 2.97 volts and 4.90 amperes, with the blade speed at 4860 rpm. As evident in the below Power vs. Current figure, the power output increased in value with the current until it maxed out at just under 5 amps. From testing, we observed that increasing the current past 5 amps only caused the power to decrease. From the Voltage vs. Current graph, an increase in current is seen to correlate with a decrease in voltage.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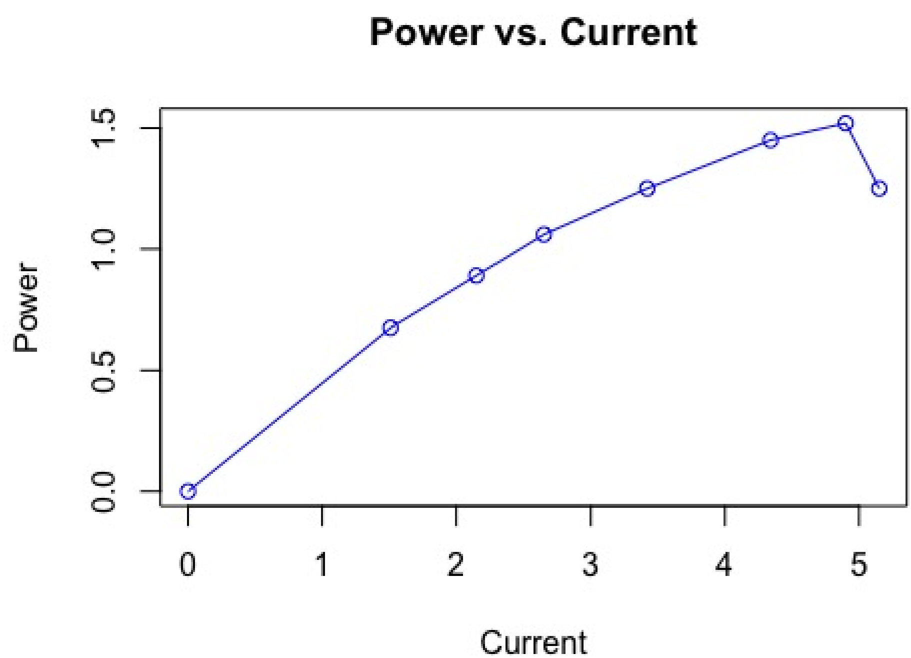
Power vs. Current
Power
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Current

8. Power Generation

The theoretical power generated by the wind turbine is calculated using the following formula:

$$P_{theoretical} = \frac{1}{2} * (\rho) * (A) * (V)^3, \text{ where}$$

ρ = Density of Air = 1.2 kg/m^3,

A = swept area = πr^2 = 3.14*(0.0762)^2 = 0.0182 m^2

V = 24.1 mph = 10.774 m/s

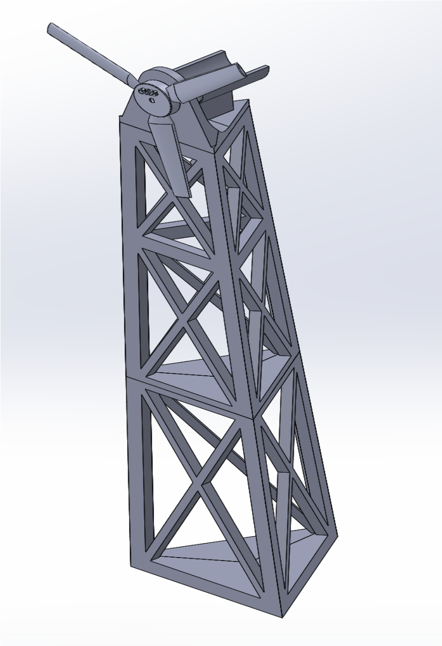
So $P_{theoretical}$ calculated by the above formula is 13.66 Watts when the maximum power generated by our wind turbine is P_{actual} = 1.52 Watts.

Therefore, the efficiency of our wind turbine is $\frac{P\,actual}{P\,theoretical} = \frac{1.52}{13.66} = 11.13\%$

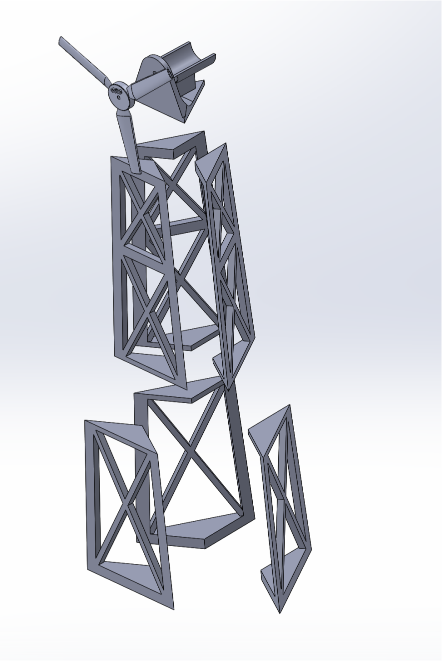
To conclude, our turbine produced 1.52 Watts of power at maximum, which when compared to the theoretical power output of 13.66 Watts, results in an efficiency of 11.13%. For comparison, commercial turbines often have an efficiency of around 40%. In this respect, then, our turbine did not perform as well as it ideally should have.

IV. CAD Drawing

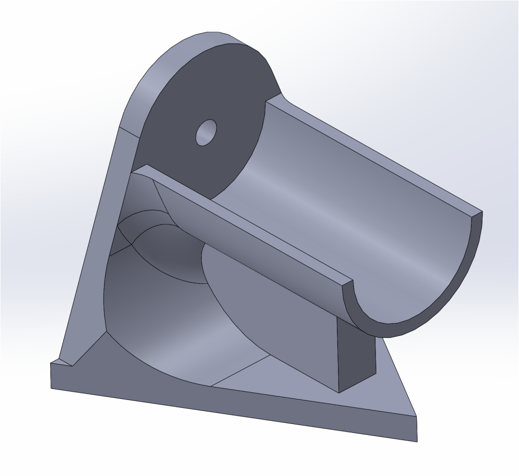
Assembly



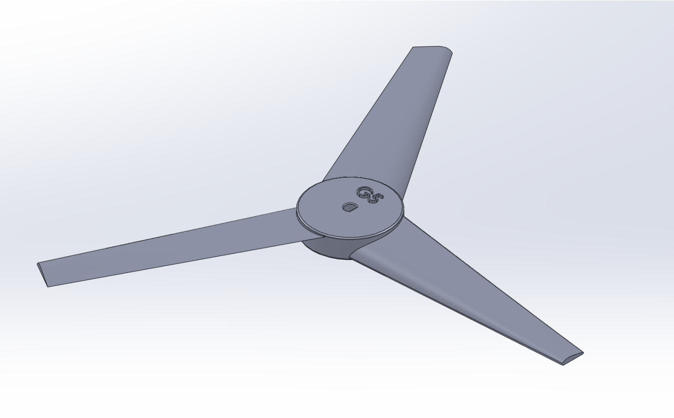
Exploded View



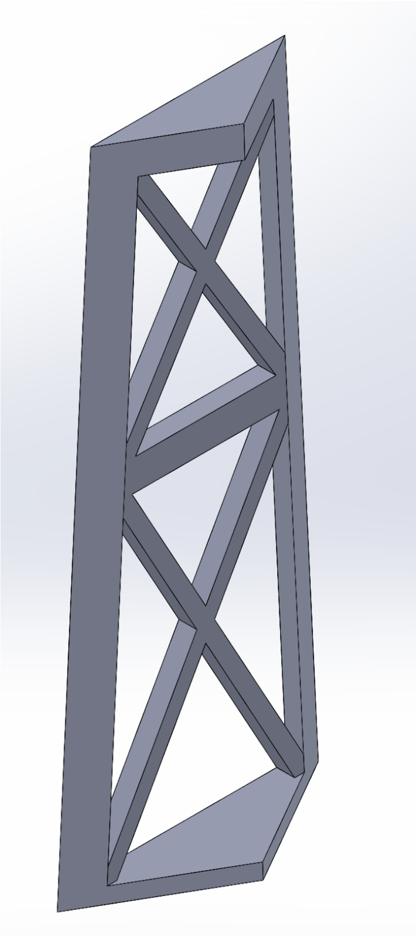
Motor Mount



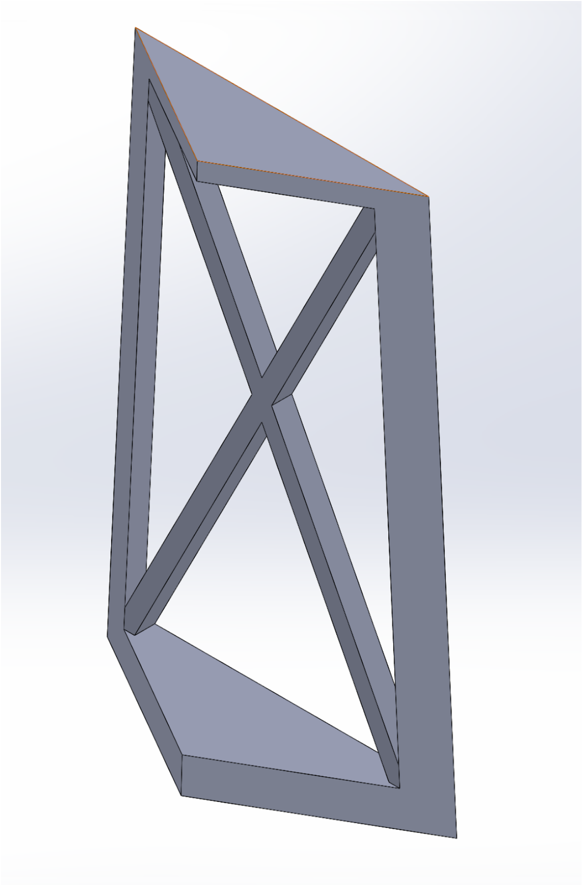
Wind Turbine Blade



Top Structure



Bottom Structure



V. Conclusions

The design of the blade was chosen to optimize power generation through principles in fluid dynamics as well as an angle of attack that maximizes coefficient of lift and minimizes coefficient of drag. The tower structure was designed with trusses to reduce as much volume and weight while still keeping its stiffness. These designs are created in SolidWorks and 3D printed using Stratasys Dimension 1200es printers.

Each of our members learned to apply theory when creating 3D models and had a chance to present their own ideas and designs throughout the duration of project. As a team, we looked at each other's approach to designing and combined them to model the final product.

Overall, compared to our competitors and specifications, our tower performed well. Getting our total volume under 18 inches cubed made us have to shave off some material from the insides, which made our weight (229.9 g) well under what we needed, which was good. It performed well in the stiffness tests, not breaking even under the full load of 5 kg. The blade design worked sufficiently well with a 1.52 Watt power output. We learned that during the printing process, the bottom of our tower, when glued, was not completely flat. Some manufacturing processes can change what was intended so we needed to account for it by using sandpaper to flatten the base. The efficiency of the turbine was 11.13% while the industry is around 40%, so compared to that, it is definitely subpar, and could definitely be improved with more research next time.

VI. Future work

For the power test, our highest power generated reading was 1.520 W, this is acceptable and we found that there are much more room for upgrades. First in the blade design, if we increase the area of the blade by making wider, we will have higher lift. During the testing, we did not decrease the interval of the potentiometer near the peak value. This is call quantization error due to human factor. Instead of changing the potentiometer at the same large interval, we should decrease the interval in the region when the power starts to drop. That way we don't miss the peak power by setting the small intervals.

For the deflection test, we got the stiffness of 6.12 N/mm. Our structure is very strong. One reason that keeps it from getting higher stiffness is the contact area of the tower to the platform. We realized that our tower was not completely in the contact with the flatform surface. This is caused by the uneven alignment when we fastened the parts of the tower together. In the future, we will spend more time to align the component so that they will perfectly align and hence yield the highest performance.

With these testing data and better understanding of wind turbines, further optimization can definitely be made on future tries.

VII. References

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VIII. Appendix

1. Complete Data Sheet for Power Measurements

Blade to Fan Distance: 7.5 in

Wind Speed: 24.1 mph

Data Points	Voltage V (Volts)	Current I (Amps)	Power P (Watts)	Blade Speed (rpm)
0	5.40	0	0	7460
1	4.80	0.93	0.440	6900
2	4.55	1.18	0.545	6760
3	4.40	1.51	0.675	6600
4	4.35	1.76	0.770	6520
5	4.20	2.15	0.890	6350
6	4.08	2.40	0.985	6300
7	3.98	2.65	1.060	6120
8	3.85	2.94	1.130	6020
9	3.70	3.42	1.250	5800
10	3.50	3.85	1.335	5540
11	3.21	4.34	1.450	5250
12	2.97	4.90	1.520	4860
13	2.5	5.15	1.250	3900
14	1.9	4.50	1.000	3500

2. **Complete Data Sheet for Deflection Measurements**

Tower height: 16 in

Tower Net Weight: 229.9 grams

Data Points	Load (Kg)	Load (N)	Displacement (mm)
1	0.1	0.981	0.03
2	0.2	1.962	0.19
3	0.3	2.943	0.45
4	0.4	3.924	0.62
5	0.5	4.905	0.75
6	0.6	5.886	0.91
7	0.7	6.867	1.12
8	0.8	7.848	1.28
9	0.9	8.829	1.47
10	1.0	9.810	1.67
11	2.0	19.62	3.76
12	3.0	29.43	5.49
13	4.0	39.24	7.62
14	5.0	49.05	9.80