Design and Testing of a 3D Printed Wind Turbine for Optimizing Power Generation and Stiffness

University of California, Berkeley Mechanical Engineering Dept. E26

Justin Kim, Jasmine Gupta, Dixun Cui, Joseph Pena, Dom Souto

Group 22

Professor Youssefi || GSI Jackie First

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Project Summary

The objective of the wind turbine project was to design, manufacture, and test a wind turbine that would maximize power generation and stiffness within the constraints of weight, volume, and height. The aim was for the tower to generate two watts of power and have a stiffness ratio of 10 N/mm, all while weighing under 400 grams and being 16 inches in height. The project began with blade research and hand-drawn sketches of a model, followed by the creation of a 3D blade model. Next, several tower designs were sketched out and a 3D model was made for 3D printing. Finally, testing was performed to gather data for analysis used in the final report.

The final wind turbine had a mass of 387.2g with a height of 16 inches. At its peak, it produced 0.72 watts of power, while deflecting 1.71mm under a 1kg load and 9.17 mm under a 5 kg load. This resulted in a stiffness ratio of 5.27 N/mm. When compared to theoretical power calculated, the efficiency of the tower was found to be 21%.

In comparison to the guidelines, the tower slightly underperformed. The power generated was 36% of the target power, but the stiffness of the tower was average in comparison to the target guideline, with the maximum goal being 10 N/mm. The efficiency was also lower than the typical industry efficiency of 35% - 45%, which can be attributed to the relatively low strength of ABS plastic, compared to steel used in real-life turbines.

Overall, the project was mildly successful with lots of room for improvement. The design of the tower succeeded in meeting the constraints but it was found that the de2sign, particularly of the blade, could be greatly improved in regards to power generation. Because the objectives of the project were partially met, there were no total design failures but many weak areas in design.

Figure 1: Finished Tower

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Introduction

The wind turbine project aimed to design and build a wind turbine system that modeled a real-life, power generating turbine. The goal was to create a design that maximized stiffness and power generation in order to better understand the design factors that go into the construction of such a system. Throughout the process, experience was also gained in 3D printing and assembly, as well as different experimental testing and data analysis techniques.

In the real world, wind turbines are one of many renewable energy sources that convert kinetic energy from nature into useful electrical energy. Wind turbines comprise of a rotor that catches wind, which is attached to a generator, which converts the rotational energy to useful electrical energy. These turbines are typically seen in clusters. Built out of materials such as steel, they are made to last as long as possible in order to increase the return on investment. These towers are tall in order to access winds of higher velocity, and the blades are optimized to generate lift force which leads to energy production. The towers themselves typically feature a gradually thinning cylindrical shape and the rotor can commonly be seen to have three radially symmetrical blades.

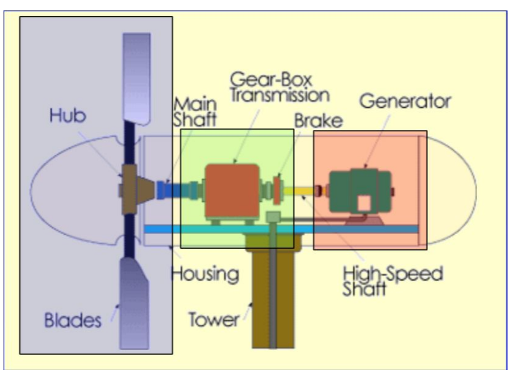


Figure 2: Turbine Power System (Youssefi,2018)

Figure 3: Wind Turbine (RawFilm,2017)

In the scope of the project, many modifications had to be made when translating wind turbine concepts from the real-world into a model that could be designed and built with the resources available. For the project, the tower and the blade were designed in Solidworks. The blade was built from a given hub, while the tower was designed from scratch. Also, instead of metal manufacturing, the towers were 3D printed with ABS plastic.

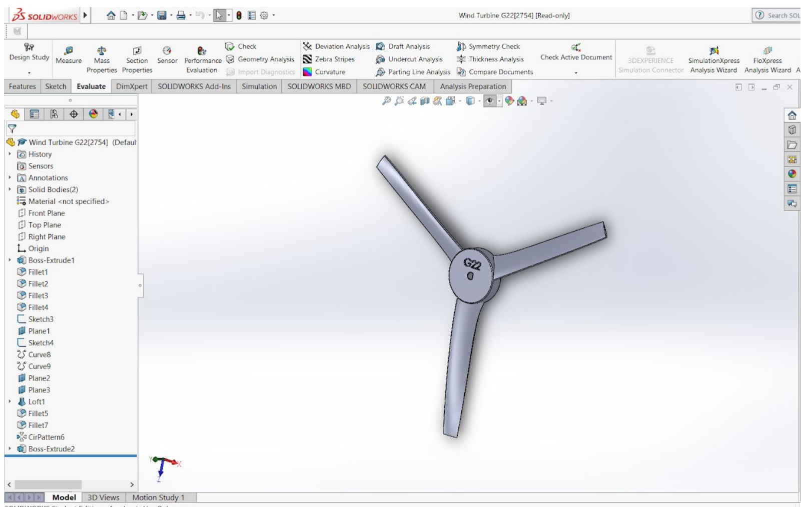


Figure 4: Solidworks Design Screen

The project has several specific objectives as well as parameters and constraints. The goal was to generate 2 watts of power and to have a stiffness ratio of 10 N/mm. The constraints were that the tower had to be 16 inches tall, with a maximum mass of 400 g with a maximum volume of inches^3. The tower would be placed on a 12 in x 12 in platform. The blade had a maximum swept diameter of 6 inches and the entire tower and blade would be printed with ABS plastic. The top of the tower also had to accomodate a specific motor size specification and had to have a 3/16 inch hole to allow for stiffness testing.

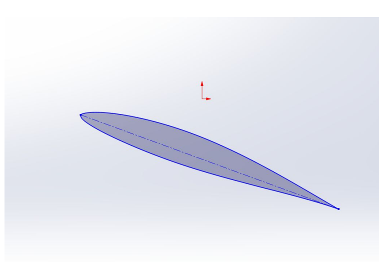


Figure 5: Internal Blade Profile

Figure 6: Required Motor Specification

In generating the design of the tower and blade, the team worked together to optimize power and stiffness while working within the constraints. Ultimately, it was decided that the goal was to use inspiration from real-life towers to create an efficient model that eased manufacturing. The tower took a hollow-body cylinder concept from real-life turbines, which aimed to reduce weight while maintaining structural stability from having a relatively wide tube thickness. The rotor was chosen to have three blades to reduce weight while still generating a high power and the motor mount was chosen to be directly attached to the tower to increase stiffness, as fewer parts would have to be glued together. The tower was also built to meet all the requirements while being easily modified, in the case that specifications were changed. For example, weight could be reduced by thinning the tower, and an increase in height would not require a total redesign.

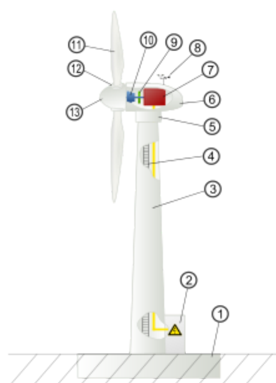


Figure 7: Hollow Body Turbine Inspiration
(Nordmann, 2007)

After the tower was 3D printed, testing occurred under standardized methods. Finally, data was collected and analyzed to generate results that would determine how effective the overall design was as well as to learn more about what could be improved.

Theory

Blade Considerations

Number of Blades – 3

Our group decided to have total three blades after conducting some research. Although one-bladed design may have the highest theoretical energy yield, It is likely to cause the turbine to become unbalanced. Two-bladed wind turbine results in wobbling which also threatens the stability of the turbine. Any number of blades more than three is going to cause too much drag that lowers the efficiency. Thus, our group decided to have three blades which is the most drag efficient without stability issues.

Length of the Blade – Max length of 6 inches

$\text{Power} = \frac{1}{2}(\rho)(A)(V)^3$	ρ = Density of air A = Swept area V = Wind velocity

In order to maximize the power generated, we settled with the maximum blade length of 6 inches which gave us a maximum swept area. This is because power is directly dependent on the swept area, thus maximum swept area would result in maximum power generation.

Angle of attack – 1.5°

In a real world application, the optimal angle of attack would be around 10°. However, considering that our tower is a miniature version, we concluded that applying an angle of attack for a actual wind turbine to our model would not benefit the efficiency of our turbine. Also, higher angle of attack leads to a larger drag force. Considering that our blade is created through fused deposition modeling (FDM) printing, which leads to rougher finish compared to real turbines, we chose a lower angle of attack to minimise these drag forces.

Efficiency

The Betz limit is the theoretical maximum efficiency for a wind turbine with the value of 59.3%, However, in real life the efficiency is known to range around 35 to 45%. We targeted our blades efficiency to fall in this practical range as our blades have a comparatively rough surface due to FDM printing.

Tower Considerations

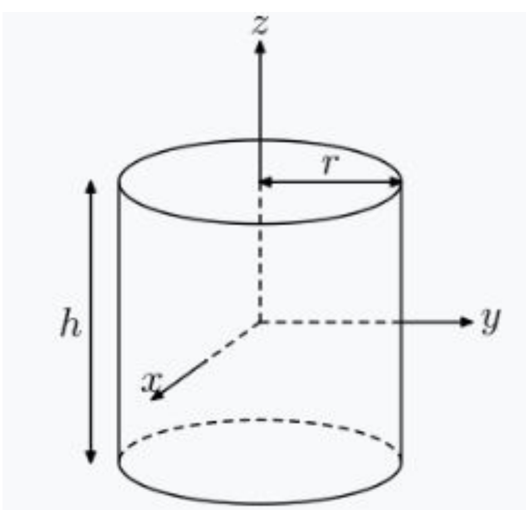
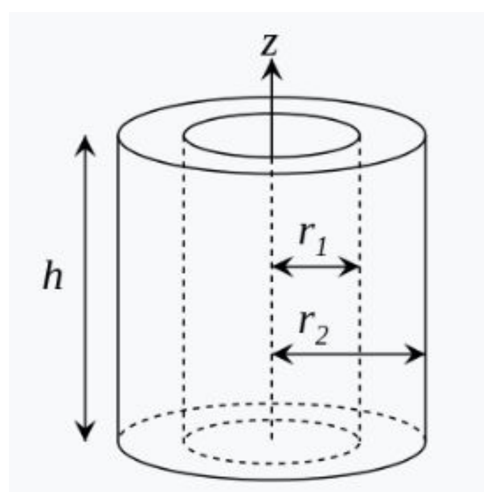
Aerodynamics

Although the wind blows only in one direction in the competition, wind blows from numerous direction in the real world. Considering such facts that the direction of the wind changes even from day and night, we designed our tower as a cylindrical shape so that the tower remains aerodynamic despite the direction of the wind.

Young's modulus

Y = deflection = $FL^3 / 3EI$	F = Force L = Length of tower E = Young's Modulus I = Moment of Inertia

In order to decrease the deflection value, we needed to maximize the moment of Inertia as it the only variable. F, L, and E are material properties and fixed values that we do not have control over during the design process.

Regular Cylinder	Hollow Cylinder
	
$I_z = \frac{1}{2}mr^2$	$I_z = \frac{1}{2}m\left(r_2^2 + r_1^2\right)$

Comparing a regular solid cylinder with a hollow cylinder, the hollow cylinder has a greater moment of inertia which makes it most plausible for a wind tower among the candidate shapes, therefore, we moved on to designing the cylindrical tower to be hollow. By doing so, our group was also able to effectively reduce the weight of the tower without compromising the exterior structure.

Center of mass

$$\bar{x} = \frac{\sum_{n=1}^{N} m_n x_n}{\sum_{n=1}^{N} m_n}, \quad \bar{y} = \frac{\sum_{n=1}^{N} m_n y_n}{\sum_{n=1}^{N} m_n}$$

Considering the fact that our tower is a miniature prototypes for a real life wind turbine, our group considered factors including the structural strength of the tower. With the tower being to light, the drag that the blades create might exceed the maximum counteracting torque that the tower can withstand and thus fall. In order to prevent the tower from falling, we designed our tower to have decent weight and focus the mass on the bottom half of the tower in order to lower the center of mass along the vertical axis(y). This enables the tower and the blades to endure more drag forces which would contribute to building an efficient wind turbine.

Tolerancing – Translation Fit

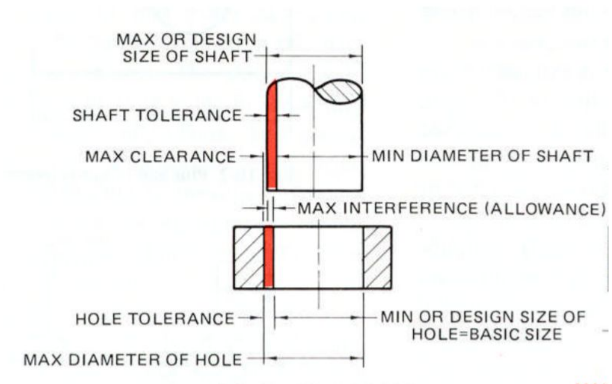


Figure 8: Translation Fit tolerancing diagram

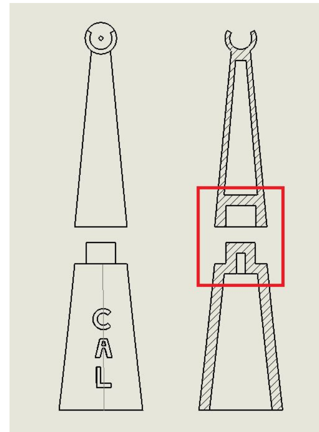


Figure 9: Tower Section View

In order to effectively glue the top half of the tower with the bottom half without significant deflection, our group designed a hole and shaft on the tower that are compatible to each other. This particular design, which is highlighted in red in Figure 9, is designed so that it would have a translation fit that enables the shaft to easily slide in, but also have slight interference that restricts the movement once the tower is assembled. The tolerancing was designed through Solidworks by measuring the nominal size of the inner cylinder and finding the corresponding fit form the ANSI tolerance chart and dimensioning the upper insert accordingly.

Design/Build

Blade design

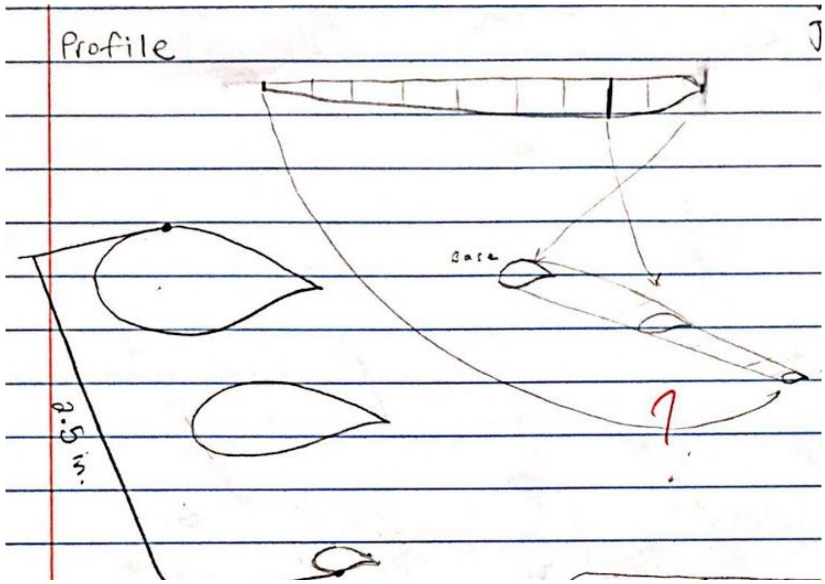


Figure 10: Initial blade brainstorming sketch

For designing the blade, we designed the blade to be wide near the hub but narrow near the end to lower the moment of inertia. This enables the blade to spin with minimal resistance but also produce enough momentum from the airflow. The three number of blades provide maximum efficiency without compromising the stability of the wind turbine, and the tear-drop shaped cross-section provides a lift and momentum to the wings. The blades were 3D printed on a Stratasys Fortus 360mc fused deposition modeling printer. The angle of attack of the blades were aimed towards a low value of 1.5° considering the limitations of a non-ideal miniature prototype model. Ultimately, the blades tapered from 0.49 inch wide to 0.29 inch wide due to the consideration of efficient momentum with low moment of inertia. The first offset profile was created 2.72 inches away from the profile and the second offset/end profile was 3.36 inches away from the first offset profile. These two distances enables the blade to have a wide to gradually narrow geometry.

Tower design

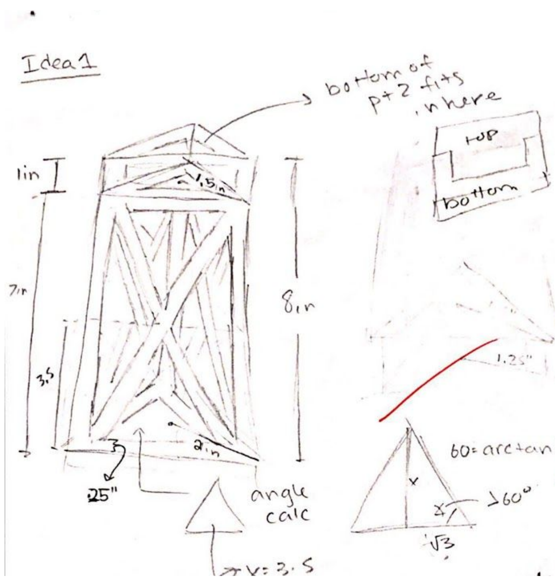


Figure 11: Tower Design 1 – Lower Half

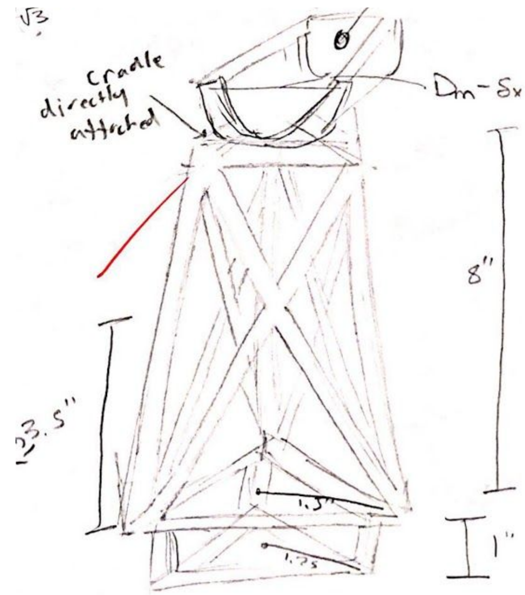


Figure 12: Tower Design 1 – Upper Half

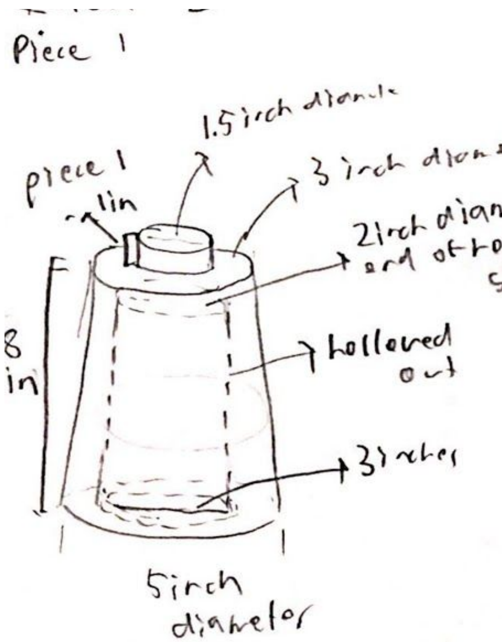


Figure 13: Tower Design 2 – Lower Half

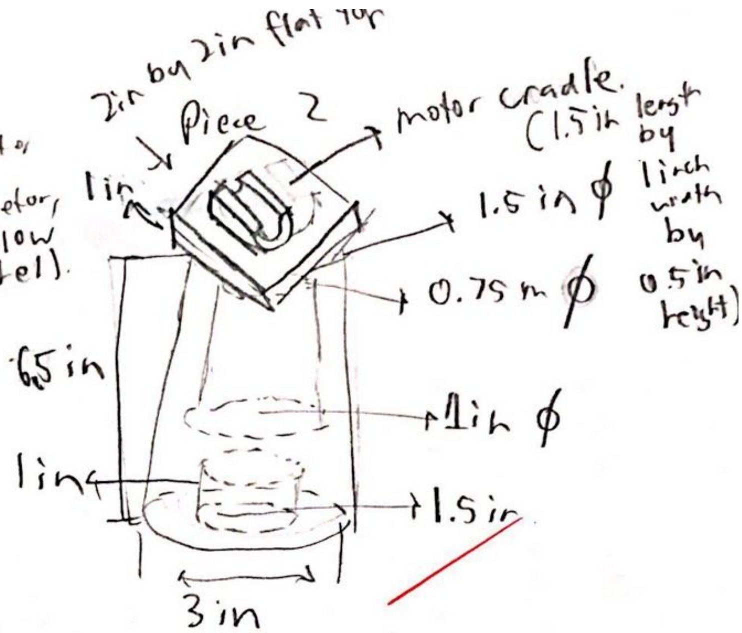


Figure 14: Tower Design 2 – Upper Half

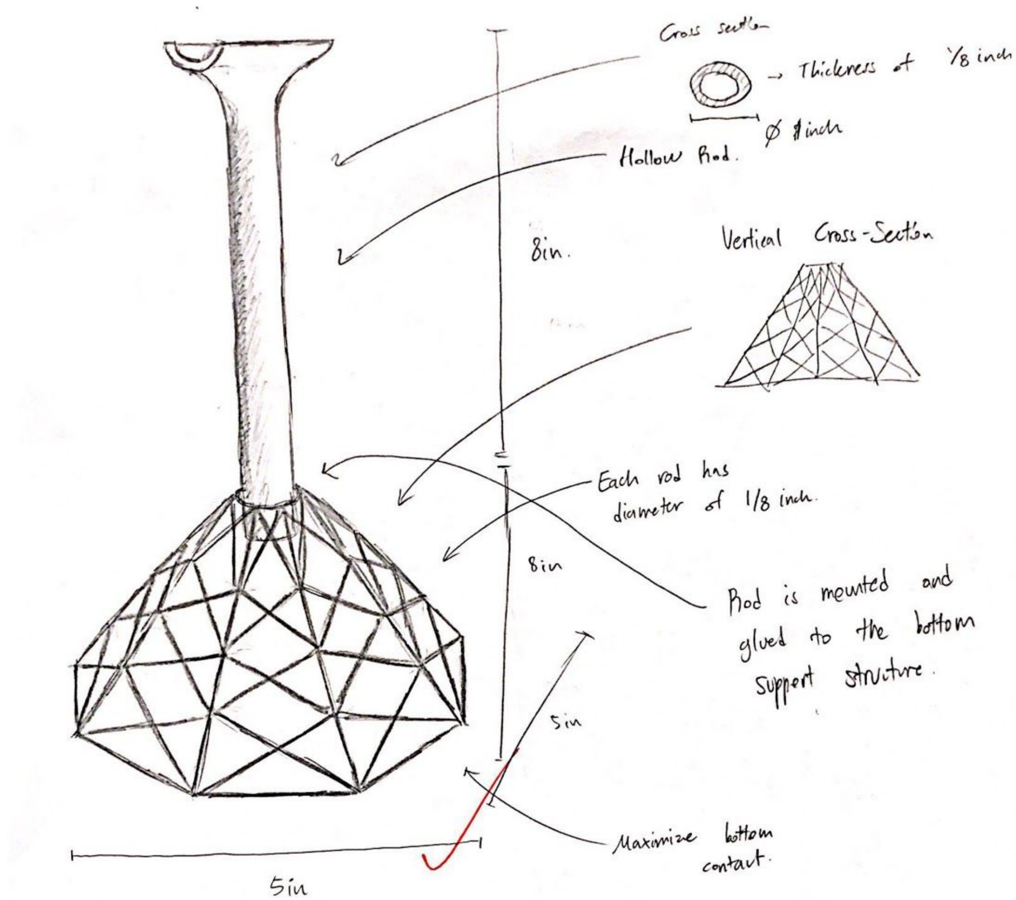


Figure 15: Tower Design 3

Our group initially had main three designs that we sought plausible. First design was implementing truss structures in order to effectively spread the mass over and increase endurance with minimum mass (Figure 11,12). Our second idea was a cylindrical tower that would ideally have great performance overall in multiple areas including stability, deflection, and weight(Figure 13,14). The third was a combination of both where truss structure would be used for the bottom half for support and the top half would be the cylindrical tower (Figure 15). We settled with our second idea after considering multiple critical factors. After designing from Solidworks, our tower was 3D printed on a Stratasys Fortus 360mc fused deposition modeling printer. Due to the dimensional limitation of the Fortus printer, our group had to design the tower into two pieces and glue them together in order to achieve that targeted height of 16 inches. Our tower was designed with a low center of mass in order to have stability and withstand the vibrations and turbulences that the tower would experience. For minimum deflection, we maximized the moment of inertia of our tower by making it a hollow cylinder. By enlarging the bottom surface proportionally larger than the top surface, we were able to significantly lower the center of mass and increase the stability of the tower.

Building

Tools

- Solidworks
  - 3D Modeling and designing of the parts and
  - Moment of Inertia analysis
- Stratasys Fortus 360mc
  - 3D printing of the tower and the blades
- Loctite Super Glue
  - Attaching the upper half of the tower with the bottom half

Assembly Procedure

1. Gather all materials including Loctite Super Glue, the Tower parts, and baseplate.
2. Wear safety glasses and latex gloves for protection.
3. Apply super glue onto the cylindrical shaft that was customized for gluing
4. Assemble the two towers together
5. Glue that bottom of the tower and glue it onto the baseplate.
6. Wait for the glue to cure.
7. Label group name.

Testing

Stiffness Test

Purpose: The purpose of this test is to measure the deflection of the tower by comparing the displacement of the structure to the load applied.

Equipment:

- Magnetic displacement measurement device
- Pulley structure + string
- 10 100g mass blocks
- 4 1 kg mass blocks

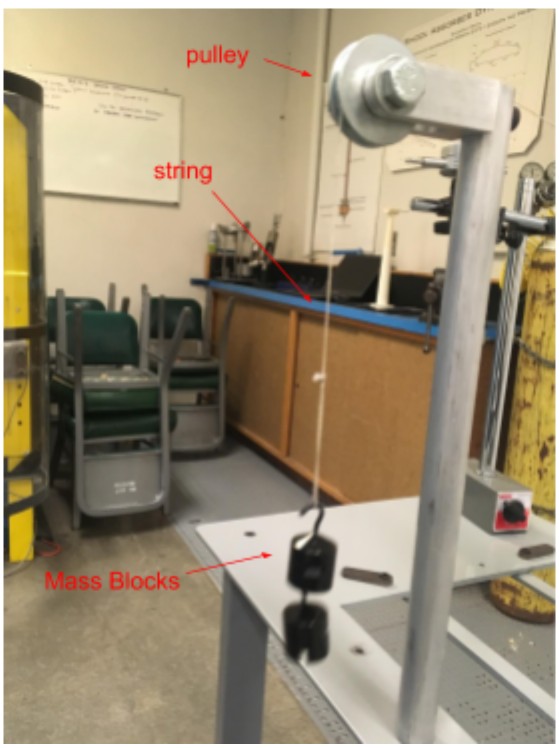


Figure 16: Mass Block addition process

Figure 17: Digital Displacement Meter

Procedure:

Secure the tower to the table with set up apparatus. Attach string to eye-screw in tower and align on pulley. Line up displacement measurement gauge to back of tower so it is touching with a displacement of 0. Then add 100g mass blocks one at a time recording displacement after each one is added. Attach each subsequent block to the bottom of the previous to minimize loading/unloading error. Once all 10 100g blocks are added start adding 1 kilogram mass blocks up to 5 kg total mass to original loop in string, once again recording displacement readout from gauge after each block.

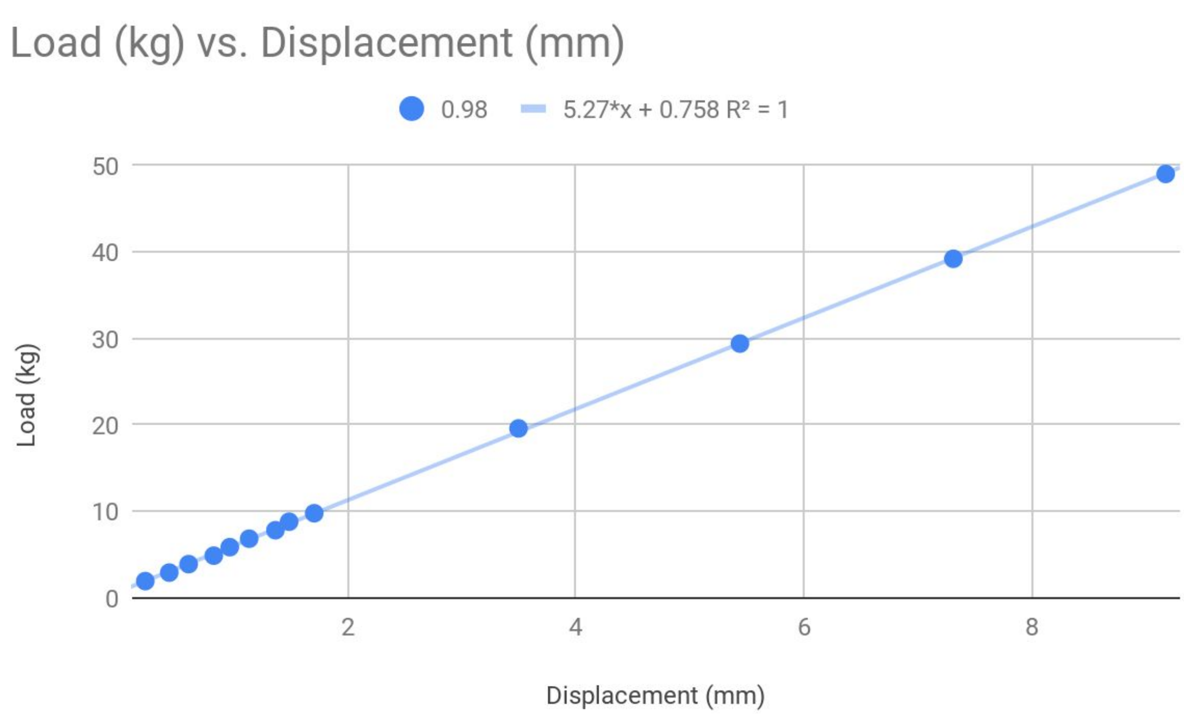
Results:

Our tower appears to have had a linear correlation between load applied and displacement. Based on our data, it looks like the tower went through only elastic deformation since the rate of displacement is fairly linear indicating no yield point. To graph the correlation, the measured load in kilograms was converted to Newtons by multiplying by 9.8, the gravitational acceleration. Based on the slope of the graph, the stiffness of our tower was 5.27 N/mm.

Table 1: Raw Data

Load (kg)	Displacement (mm)	Load (kg)	Displacement (mm)
.1	.04	.8	1.37
.2	.23	.9	1.49
.3	.44	1	1.71
.4	.61	2	3.5
.5	.83	3	5.44
.6	.97	4	7.31
.7	1.14	5	9.17

Graph 1: Deflection vs Load



Power Generation Test

Purpose: The purpose of this test is to measure the amount of energy that can be generated or converted by our tower from a given wind speed.

Equipment:

- Wind speed meter
- Tachometer
- Fan
- Power meter
- Reflective tape

Figure 18: Tachometer

Figure 19: Wind speed Meter

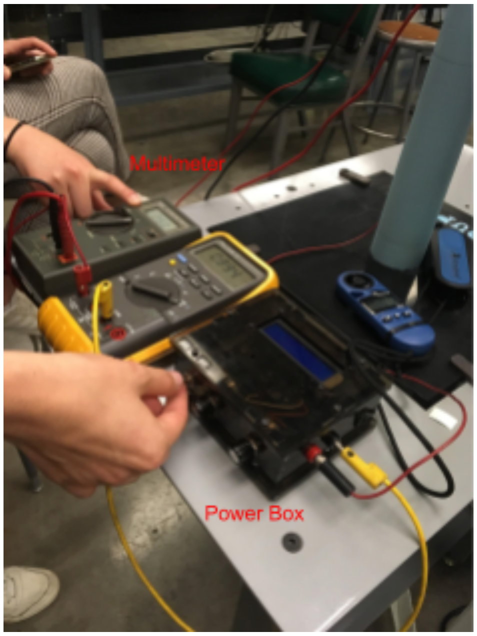


Figure 20: Power Box/Multimeter

Figure 21: Fan

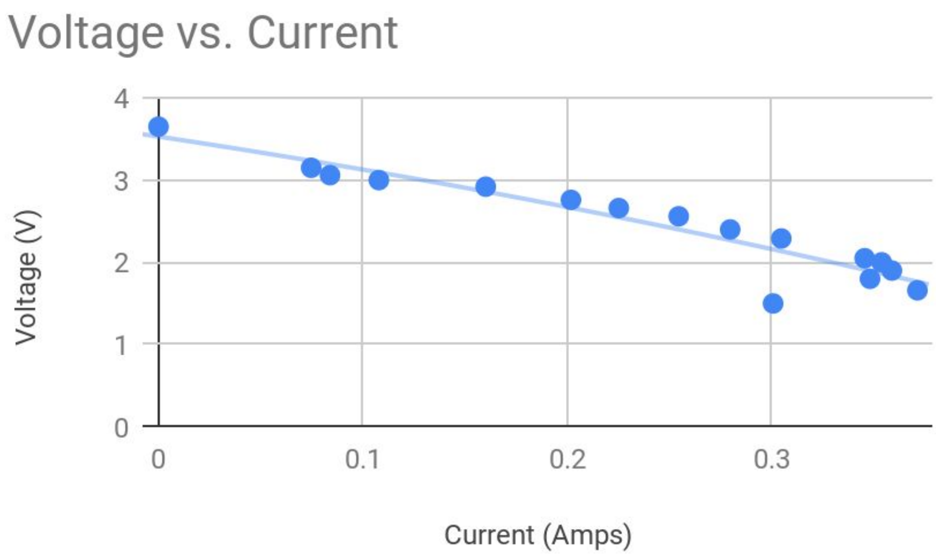
Procedure:

Turn on fan and use wind speed meter to adjust distance and ensure a wind speed around 21 mph. Attach small piece of reflective tape on one blade close to the hub. Connect tower to the power meter (load box + generator). Use power meter to find maximum power. Bring potentiometer to zero, turn blower on and slowly increase potentiometer, recoding voltage, current, power, and blade speed at each interval.

Results:

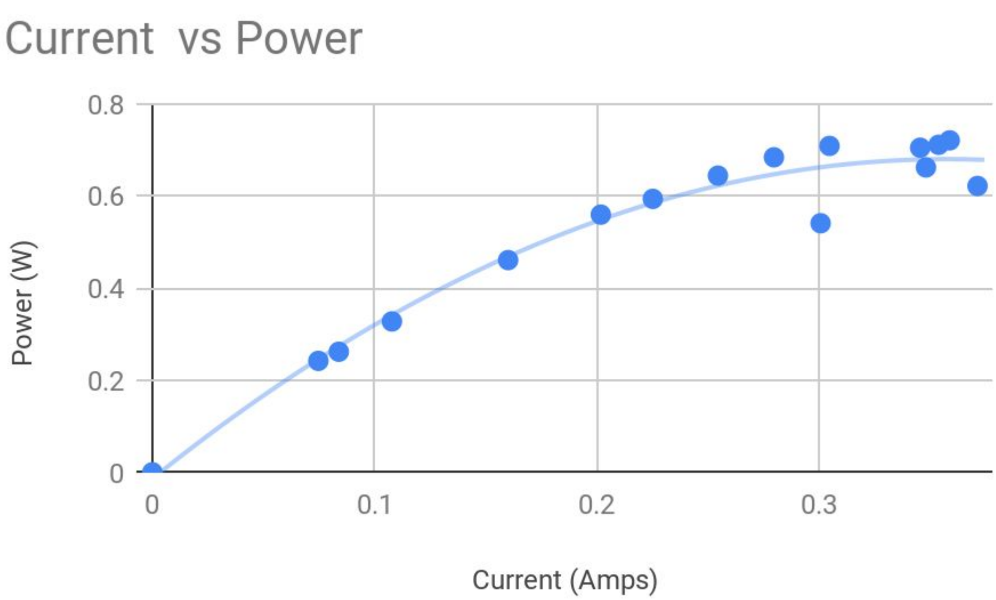
When setting up our test, we measured a distance to the fan from the tower of 7.85 inches reaching a wind speed of 22.9 mph. Initial readings of max power were measured to be around .8 Watts. As we went through testing, we noticed that there were fluctuations in the power generated, the longer we were testing of it we iterated over the same range multiple times we would get lower readings each time. The raw data from this test can be accessed in the appendix of this report.

Graph 2: Voltage vs. Current



It is seen that there is a fairly linear relationship between voltage and current. As the current increased, the voltage decreased. There was a bit of irregularity but that can be due mostly to the aforementioned variations in readings.

Graph 3: Power vs. Current



For the current vs power graph, it appears to be the first half of a polynomial curve. For the majority of the points, power increases with the increase in current. We do see a peak around

.36 Amps, though the low number of data point after we reach our max makes it hard to see the initial decline. It was also found in our data that the max power generated was 0.72 Watts.

Power Generated

Density of air = 1.2 kg/m^3

6 inch radius = .1524m

Area = π(.1524)^2 = 0.072966 m^2

V = 22.9 mph = 10.24 m/s

Theoretical power = $\frac{1}{2}\rho A v^3$

$= \frac{1}{2}(1.2\ kg/m^3)(0.07297\ m^2)(10.24\ m/s)^3$

= 3.43 Watts

Efficiency

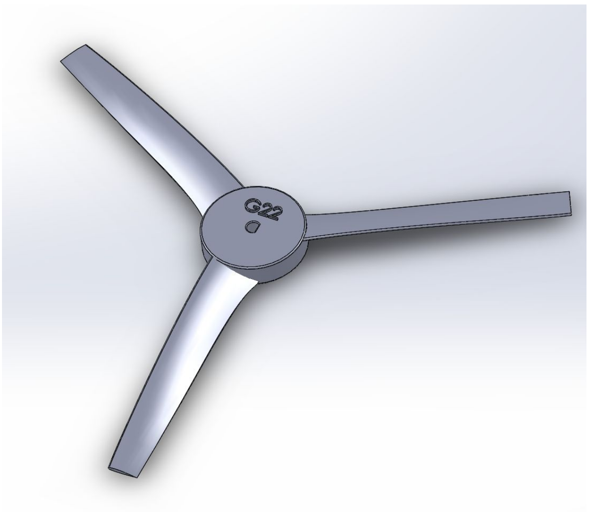
= P_e/P_t * 100%

= (0.72W/3.43W) * 100%

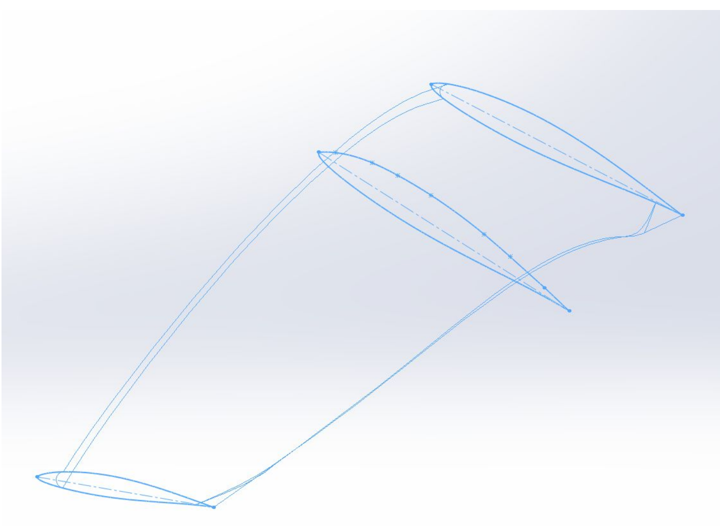
= 21%

CAD Drawings

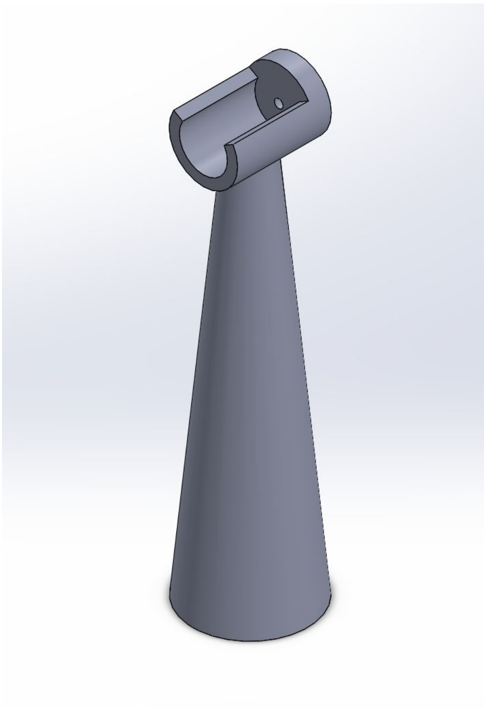
Blade



Blade Loft Profiles

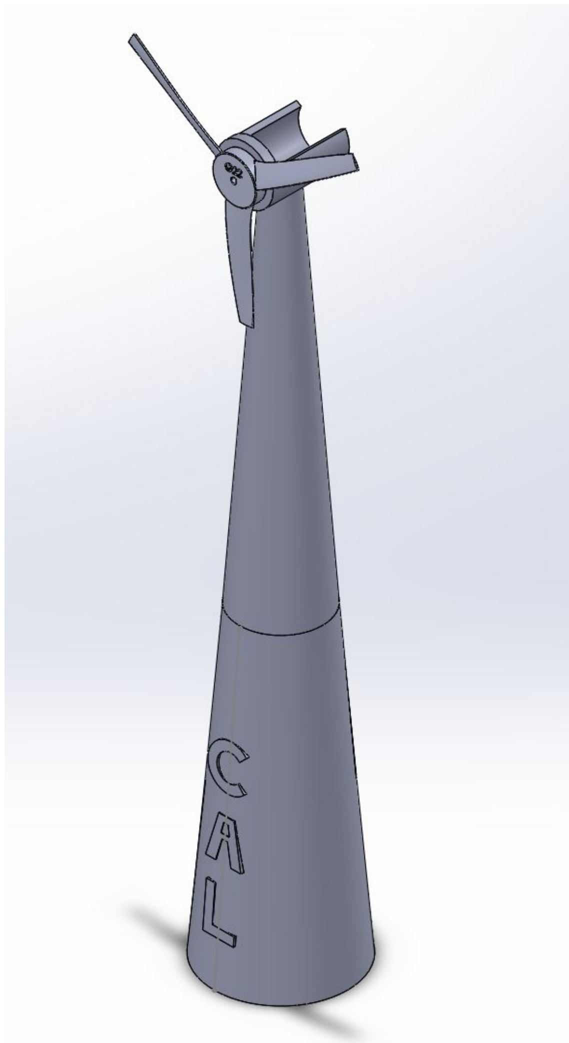


Tower Top Half

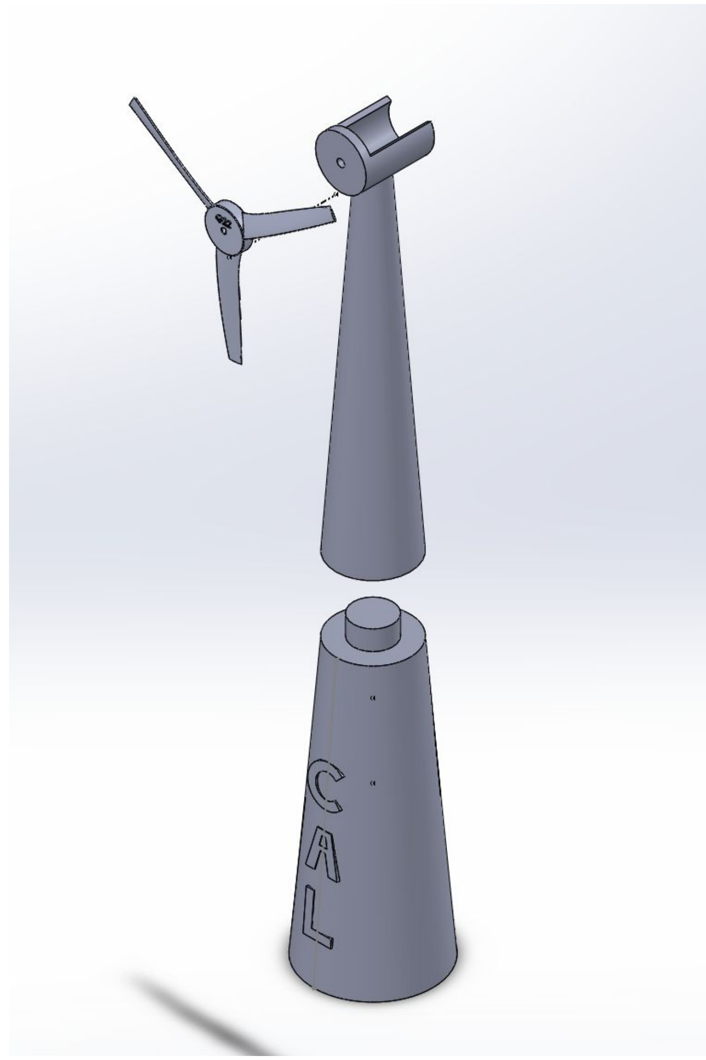


Tower Bottom Half

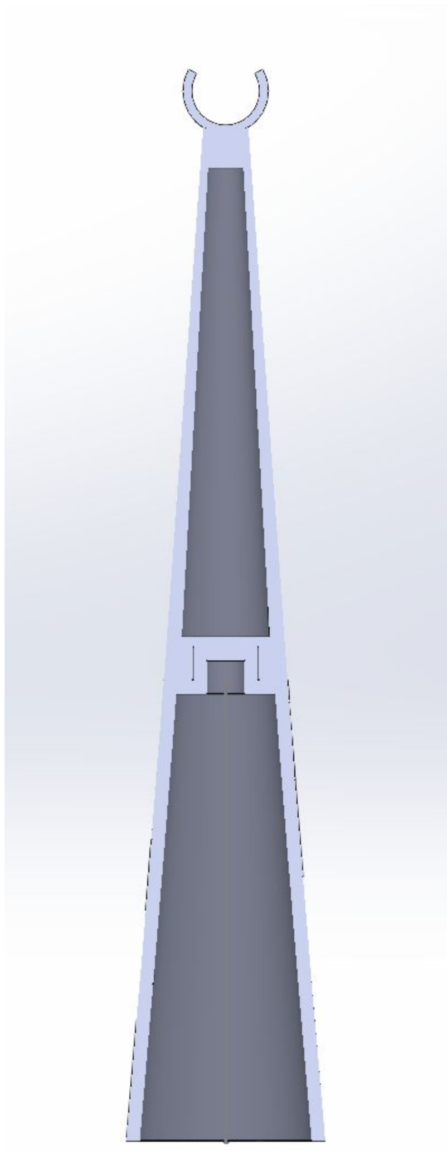
Assembly



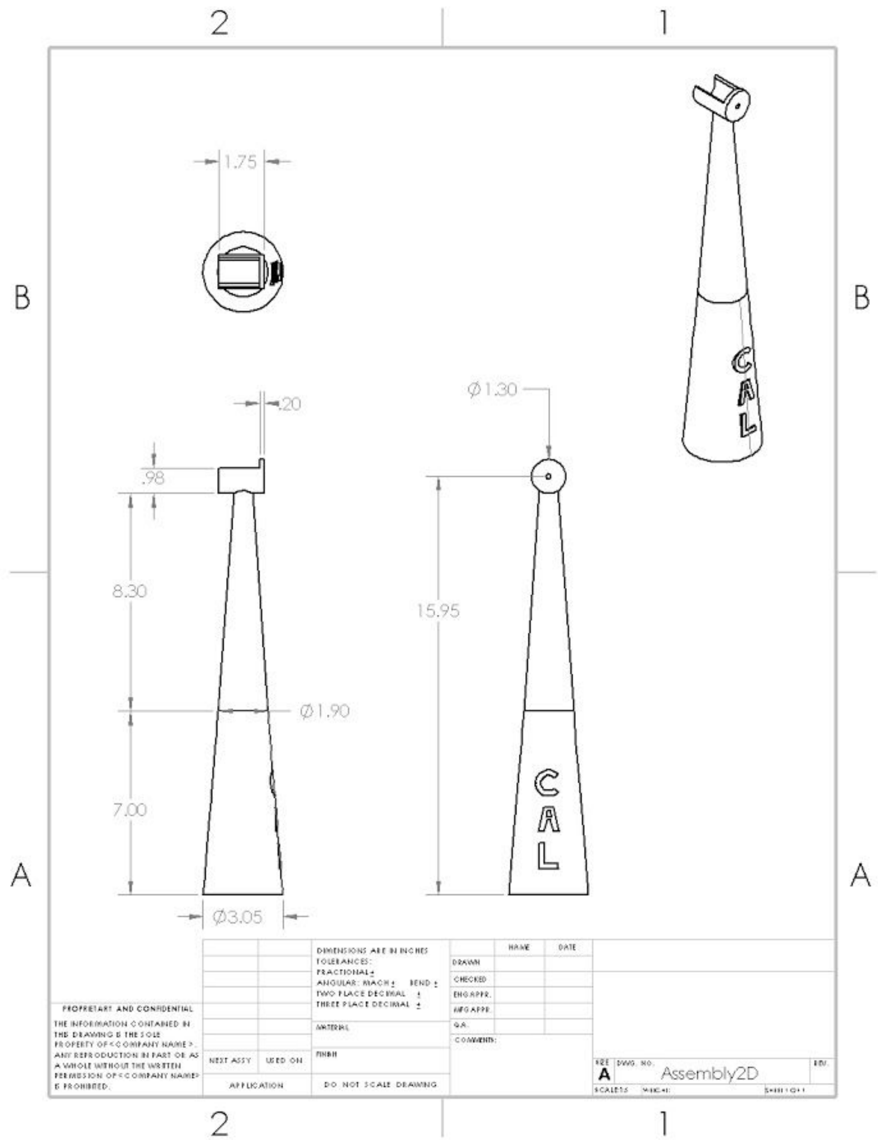
Exploded



Section View of Assembly



Tower Drawing



Conclusion

When designing our blade, we used Betz's pitch angle equation and the fluid mechanics principles to calculate our desired angle of attack of 1.5 degrees. After conducting some research, we concluded that three blades would give the best support while spinning as well as the best efficiency. Designing our blades to be light weight but decent surface area allowed us to produce the most power. If we had to do it again, we would make the blade dimensions slightly bigger, but the design and angle of attack performed outstandingly.

Our tower's design was inspired by couple designs that were commonly used in the real world, which has proven to be an easy way to equally and symmetrically distribute the weight while also maximizing strength. While designing our tower in Solidworks, we created two sections, cut a hole in one and extruded shaft on the other after measuring nominal size of the extruded shaft and figuring out the tolerances. We glued the top half and the bottom half of the tower together to help strengthen the stability and limit side to side movement. We also added CAL on the front to make ours unique and more creative as well as to show school spirit.

Once the wind turbine was glued and finished it was placed under multiple tests to measure the rpm, voltage output and stiffness. Our tower was 387.2 grams and 16 inches tall. When testing stiffness, at 1Kg our tower was displaced 1.71 mm, and when holding all the possible weights the turbine still held strong. At a wind speed of 22.9 mph, our wind turbine produced .720 watts of power. The turbine was rotating at 3409 rpm's while producing its max wattage.

Turbines will generate different outputs depending on the wind speed, but no matter the speed the real life turbine converts about 35 to 45% of the wind passing through the blades into energy. Our blade efficiency was 21%. Compared to industry equivalents, this was lower than what is typically seen. This can be attributed to design flaws in our blade that did not optimize power and it can also be attributed to the material. When compared to materials such as steel, ABS plastic is not as smooth or stiff which can reduce lift force generated.

Overall, our group members were able to learn how to apply 3D visualization skills and modeling techniques for designing an efficient wind turbine model. This project allowed us to explore wind turbine designs and the mathematics behind it, and creating a physical design on Solidworks. Although the tower's performance did not reach our targeted efficiency, we were able to establish a good understanding of the elements that we could have modified to enhance the functionality of our tower and maximize its capabilities.

Recommendations for Future Work

While our turbine performed well in the tests considering the material, time and budget, there are things we would change to increase performance and decrease cost.

To increase power production, we would do multiple tests and experiments beforehand to finalize the blade. The optimal angle of attack was found mathematically, so we would only need to change the blade dimension. If we changed the blade dimensions and tested each one we would be able to find which dimensions resulted in the maximum power production. In terms of overall weight and material cost, the most weight comes from the tower, so the extra weight added to the blade can easily be taken out of the tower through a reduction in thickness in certain areas.

In terms of the tower, our weight was measured to be a bit high, so we would want to make the inside slightly thinner. In the real world heavier means more expensive so we would want to make it lighter while still being sturdy. After the desired weight was found we would do the same stiffness test and record where the tower was bending. We would then go back and change the location of the hole and extrude to the location of the bend. This would make the tower sturdier and perform better on the stiffness test. We could also experiment with different profile shapes for the tower, which would let us keep the same general hollow-body concept which we felt was successful. We could experiment with ovals, or perhaps with an offset between the top of the tower and the base to increase the stability in the direction tested.

Ultimately, with more time and resources, many more iterations could be performed on the design to both test mathematically derived principles as well as different ideas for certain designs. These experiments would allow us to increase our efficiency and stiffness while decreasing tower mass.

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Appendix A: Raw Data

A1: Deflection Test

Wind Turbine Performance Data

Group#: 22 **Team members (Names):** ______________________

1.0 *Deflection Measurements*

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

b. **Tower Net Weight:** 387.2g gram. (Total Assembly – Bottom board)
1287.1g

Stiffness Measurements:

Data Points:	LOAD (Kg)	LOAD (N)	DISPLACEMENT (mm)	Observations
1	.1		-.04	
2	.2		.23	
3	.3		.44	
4	.4		.61	
5	.5		.83	
6	.6		.97	
7	.7		1.14	
8	.8		1.37	
9	.9		1.49	
10	1		1.71	
11	2		3.50	
12	3		5.44	
13	4		7.31	
14	5		9.17	
15				

Comment

Group22

2.0 Power Measurements

a. **Blade to Fan Distance: (at 25 mph wind speed):** 7.85 in.

b. **Wind Speed:** 22.9 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	3.65	0	0	5273	
1	3.15	74.4mA	241.9mW	4890	
2	3.06	83.9mA	261.6mW	4775	
3	3.00	107.8mA	327.4mW	4700	
4	2.92	160.1mA	460.5mW	4567	
5	2.76	201.8mA	559.2mW	4390	
6	2.66	225.2mA	593.4mW	4240	
7	2.56	254.5mA	643.8mW	4137	
8	2.40	279.7mA	683.6mW	4031	
9	2.29	304.7mA	708.3mW	3840	
10	2.05	345.5mA	704.4mW	3553	
11	2.00	353.8mA	710.8mW	3510	
12	1.90	358.8mA	720.4mW	3409	
13	1.80	348.1mA	661.6mW	3134	
14	1.66	371.3mA	621.4mW	2953	
15	1.50	300.7mA	540.5mW	2719	

Comment

prof max power → ~.8 mW