Optimal Wind Turbine Design

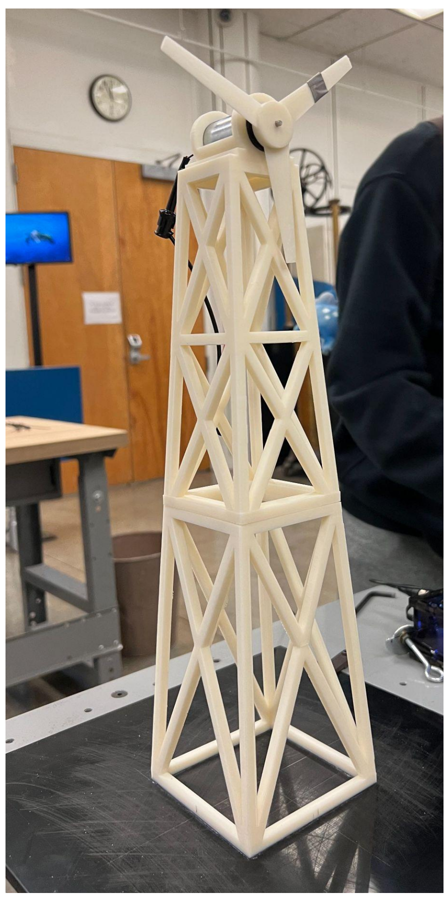
University of California- Berkeley

Mechanical Engineering Department

Engineering 26- Group 23

Masoma Naseri, Jack Galetti, Joy Zhang,

Amber Le, Catherine Lee, Thian Callanan, Brandon Lou



PROJECT SUMMARY

Our objective of our project is to successfully implement the CAD skills we have developed over the semester to follow the guidelines of creating a windmill along with exercising creativity, creating a real prototype that we can observe, test, compare to our SolidWorks version.

In the beginning of the project, we each delve deeply into researching windmills, inquiring about how we could optimize the blades and tower. The angle of twist, angle of attack, pitch angle, number of blades, and tower structure stability were all details we had to compare and choose in order to start the CAD of our designs. After deliberation, we decided with an angle of twist of 35 degrees, angle of attack of 15 degrees, and a pitch angle of 10 degrees. We ended up creating a 3-bladed design with a 4-sided pyramid with inner triangular open structures between for additional support.

During the CAD process, it was crucial to follow the guidelines of the project. Some considerations were that we had to decide on how to effectively split the tower into 2 parts due to the limitation of the 3D printer. We also had to adjust the angle of our pyramid structure according to the volume limitation, as our wide design overestimated how much bigger the tower was actually going to be in real life.

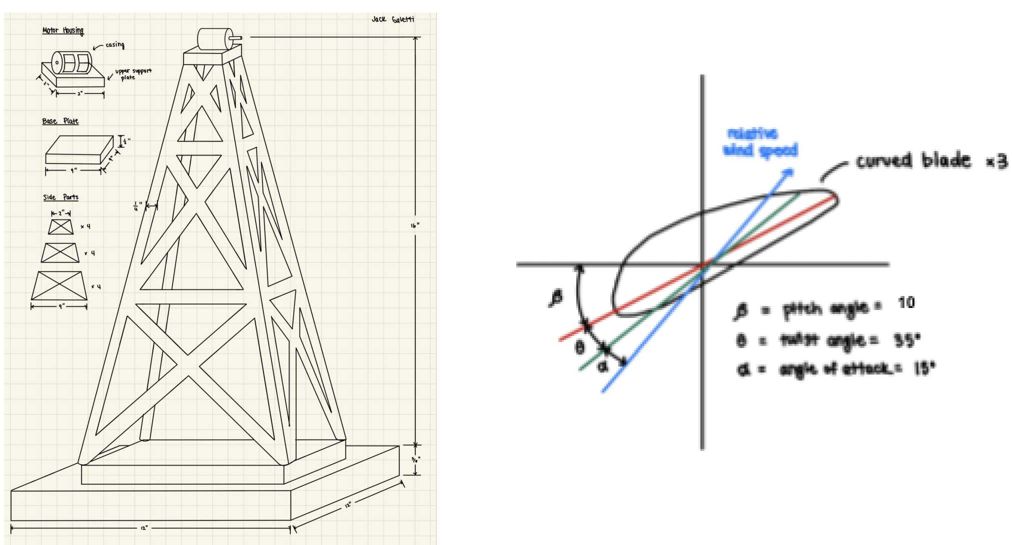


Figure 1: tower and blade structure design on paper

After all our parts were printed out, two members of our group had took charge to glue our structure together since it was printed out in two parts. After letting it dry for a week, our whole team went back to the lab to complete our final testing.

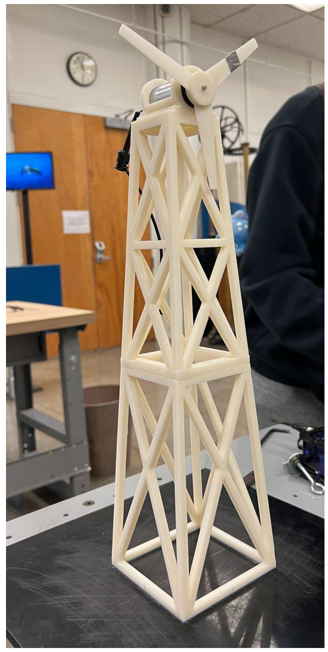


Figure 2: Final 3D printed tower

The testing mainly consisted of completing measurements, testing the differences in the fluctuations of voltage, current, power, and blade speed to get the max power value. We collected around 12 data points by changing the resistance by increments of 100g and 5g, which corresponded to changes to the variables we were observing. From there, we also performed tests to measure the deflection (stiffness) and weight.

We measured our weight to be 276.4 grams after subtracting the weight of the squared base that was attached for testing purposes. To measure stiffness, we collected 10 data points and measured the deflection when we added on 100g increments for each new data test we performed. Our final deflection measured at 1kg was 0.75mm.

Table of Contents

INTRODUCTION

To introduce our project scope, we explored various design iterations of a wind turbine model based on engineering principles and previous background research. As a brief history of the wind turbine structure, the ideation of the wind turbine dates back to ancient eras. Initially used to power machines like water pumps, wind was a strong source of power and natural energy. While wind turbines first originated in Scotland by engineer James Blyth for electricity generation, the surge of interest in renewable energy during the 1970s led to increased development of wind turbines with increased efficiency. Today, wind turbines are highly common sources of energy, and are found powering homes and businesses from wind farms around the world. With the increased importance of lowering greenhouse gas emissions, wind turbines are an essential factor to promoting sustainable energy production.

For more background information on the wind turbine structure, a wind turbine functions by converting kinetic energy into mechanical energy through its subparts — the rotor, the shaft, the generator, and the control system. After the rotor captures the wind, the blades on the wind turbine rotate around the rotor hub, allowing the shaft to transform the mechanical energy from the blades into the generator. From there, the generator converts the mechanical energy into electrical energy. This highly sustainable system generates energy from the wind, providing another energy source that reduces dependence on fossil fuels.

Therefore, knowing these engineering principles, we then conducted individual research to understand the optimal metrics for the following components of the wind turbine — number of blades, angle of attack, angle of twist, blade length and pitch, and blade shape. From our findings, we found the ideal number of blades to optimize both stability and energy output is 3 blades. Furthermore, with proper understanding of blade function, we found that "curved blades are generally more useful for energy production. Air moves faster over the blade's curved side than the flat side, which in turn increases the blade's rotational speed. Curved blades can turn quickly, which also increases energy product potential" (Most Effective Wind and Blade Turbine Design). From these findings, we can deduce that our design should involve rounded edges in order to maximize energy product potential, as this shape will increase the rotational speed. To further elaborate these findings, the scientific article Aerodynamics of Wind Turbine Blades explores the specific shape that has previously been the most successful in maximizing the lift of the blade design, called the airfoil profile: “The airfoil profile (shape) of a turbine blade will actually change as you move down the length of the blade, generally getting flatter and narrower towards the tips of the blades. This is to optimize the lift and minimize the drag.”

For angle of attack, we found that while increasing the angle of attack increases lift, the angle of attack should not be over 20 degrees; therefore, the optimal angle of attack lies around 10-15 degrees. For angle of twist, we found that most wind turbines feature a twist towards the end of their blade in order to ensure the wind hits them at an optimal angle of attack along the entire length of the resulting, in maximum efficiency of the wind turbine as a whole. “The angle is adjusted in radians and seems to indicate maximum value at approximately 0.62 radian, or roughly 35.5 degrees… Therefore, the blades should be tilted at an angle of roughly 35.5 degrees from the oncoming air stream to obtain the optimal amount of energy using the flat blade windmills” (Optimized Blade Design for Homemade Windmills).

Therefore, knowing these engineering principles, we wanted to focus our final wind turbine design to provide structure and optimize energy production throughout the entire length of the blade. From these objectives, we each created individual sketch designs (as pictured below). Afterwards, we came together to compare and select the most ideal tower structure design.

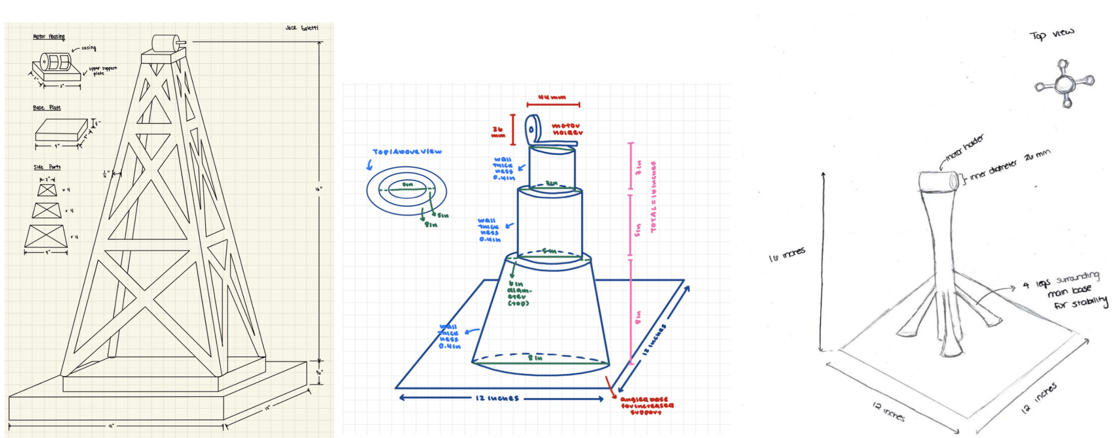
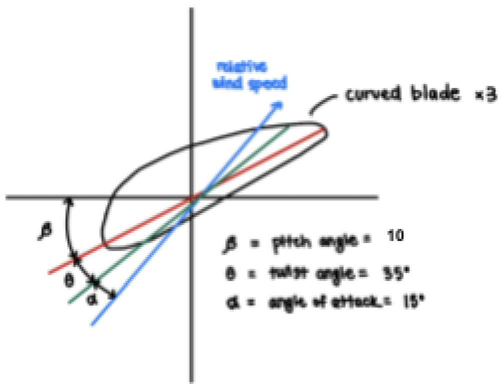


Figure 3: examples of wind turbine idea design sketches

DESIGN

SKETCHES

Through our research, we decided on the following characteristics of our turbine blades: angle of twist of 35 degrees, angle of attack of 15 degrees, a pitch angle of 10 degrees, and 3-blades in total. We also decided on Jack's tower design since it looked the sturdiest – the triangular cross trusses provide extra support because the weight is distributed evenly on all sides of the tower.



DESIGN TOOL

To create our designs, we used SolidWorks. SolidWorks is a Computer Aided Design platform where individuals can create 2D and 3D models of real-life items on a digital platform. A lot of the time, CAD is used before creating a real life model to allow individuals to visualize and test their design. This can be helpful because creating a design in real life can be time intensive and expensive. CAD can also export files to 3D printers to bring the designs to life, which is what we did during this project.

In addition to SolidWorks, we also used a 3D printer to print our CAD models. 3D printers take melted plastic (oftentimes PLA, ABS) and use the exported file to print the design layer by layer. It is oftentimes a long process, but the flexibility it provides with designs is very valuable! (ie. much easier to 3D print a wind turbine than to manufacture a creative design).

DESIGN SPECIFICATIONS

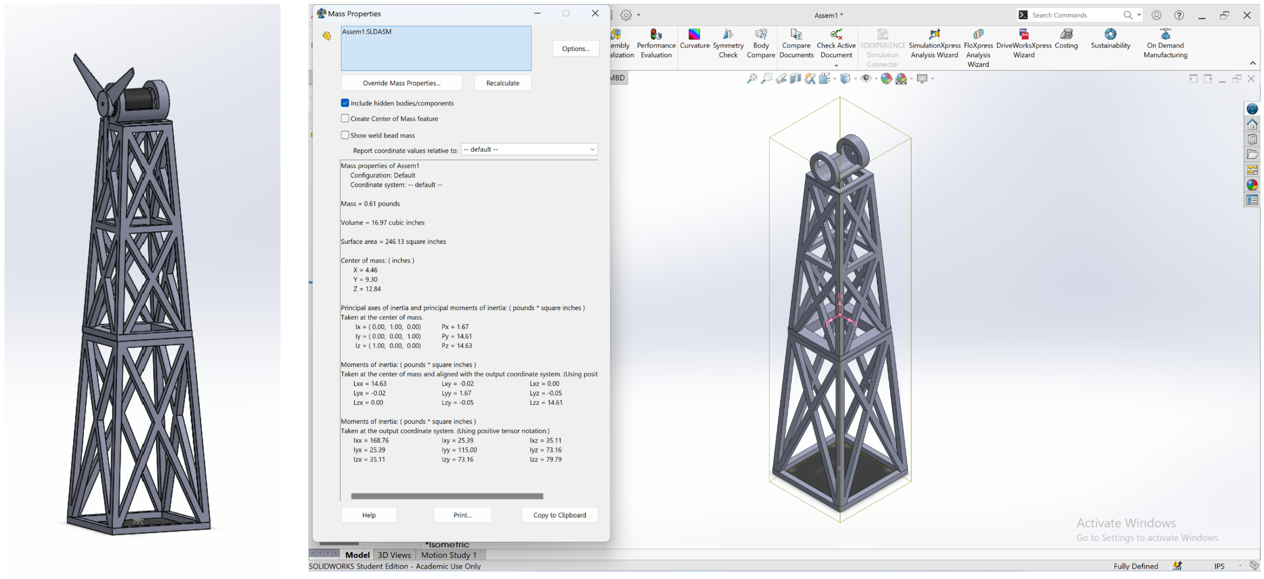


Figure 3: Final Turbine Design with tower volume in SolidWorks.

Considering the project requirements and limitations (i.e. total volume of the tower, structural design experience, and artistic creativity to name a few), Jack's tower design, Figure 1, was selected to be composed into SolidWorks. From the original drawing, few adjustments were made to accommodate the maximum tower volume of 17 cubic inches and increase structural support of the tower due to the printing height requirements. These alterations reduced the size of the tower's printed base plate, increased surface contact between the two pieces of the tower, and removed parts of the motor support as shown in Figures 3, 5 & 6.

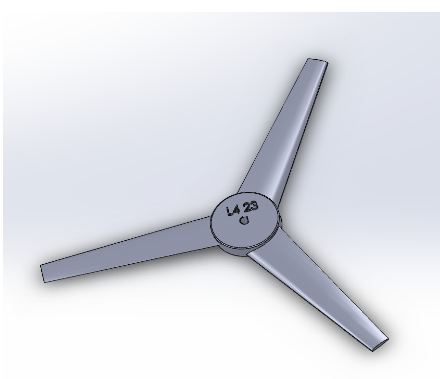


Figure 4: Blade Design in SolidWorks.

From its original inception, the blade design was not altered, Figure 4. This was because the design proved to be sufficient when considering that our angle of attack met the optimal criterion, 15º. Three blades were used in the design because it has been agreed that a three blade design yields the best energy to stability and durability ratio that is sought out in wind turbines (Adeyeye).

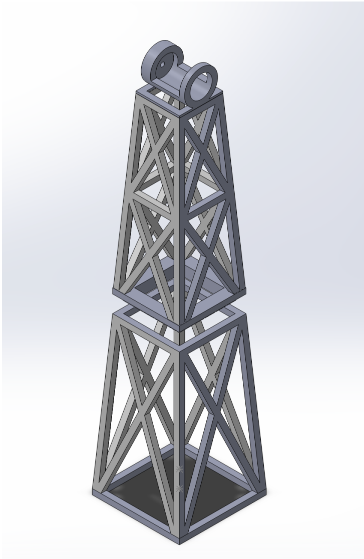


Figure 5: Exploded view of the tower in SolidWorks.

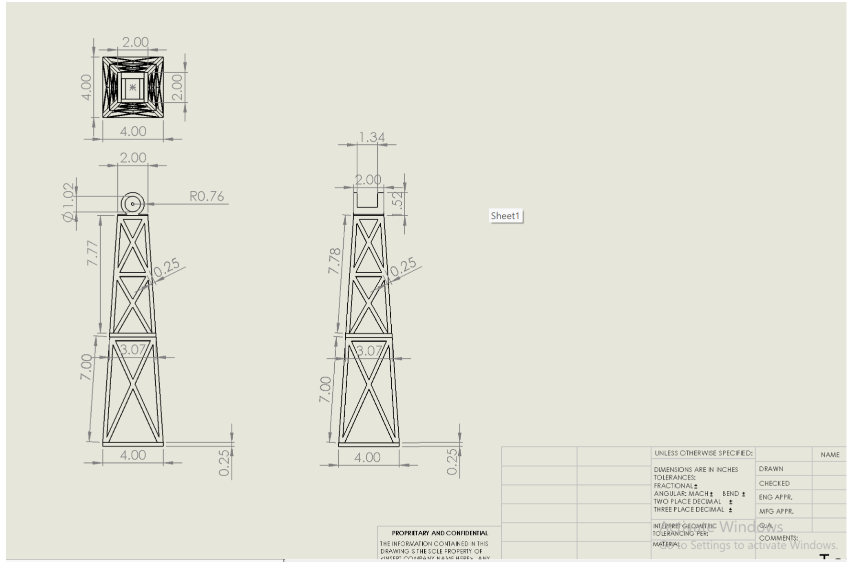


Figure 6: 2D Drawing of Final Tower Design, Final Volume of 16.97 in^3.

As a team, we used SolidWorks to build the tower in CAD. We continued with the use of trusses because they are a reliable structural support that is both lightweight and high in strength. Other iterations of the tower included parallel planes with the base normal to the vertical axis of the tower, but in an effort to reduce volume, those designs were unused. The method used to print the tower was considered into the design of the tower, and it was agreed that the FDM printer was suitable for optimal performance of the tower given the ABS+ filament. Although no printing parameters were available to manipulate, the components were printed without any visual defects such as ghosting, stringing, sagging, or under-extrusion.

Three Finite Element Analysis (FEA) simulations (i.e. displacement, strain, and stress) were performed on the CAD tower design and are depicted in Figure 7. A load of 10 kg was applied as a circular load into the socket of the motor cage. From the simulations, there were no clear indications of structural failure because the stress on the model was evenly dispersed onto the upright beams of the tower. The points with the largest stress were located along the bottom corners of the tower, however, there were no indications of failure because the material strength was well within the allowable limits of design. This would suggest that the gluing process of the tower to the base plate was an important factor of the final product. The displacement of the tower, Figure 7b, can explain this occurrence because of the boundary conditions that were set on the tower upon application of the load; fixed position of the bottom surface on the tower. These conditions cause the corners of the tower to be the most rigid features and therefore assume the most stress under the described load. The boundaries also account for the increased displacement along the upright direction. Since the strain is directly proportional to the stress of a material, Equation 1, it is reasonable to see that the beams with the most strain, Figure 7c, are in line with those that had the most stress.

$$\sigma = E\varepsilon$$

Equation 1: Hooke's Law. Stress is equal to the strain multiplied by the Young's elastic constant of the material.

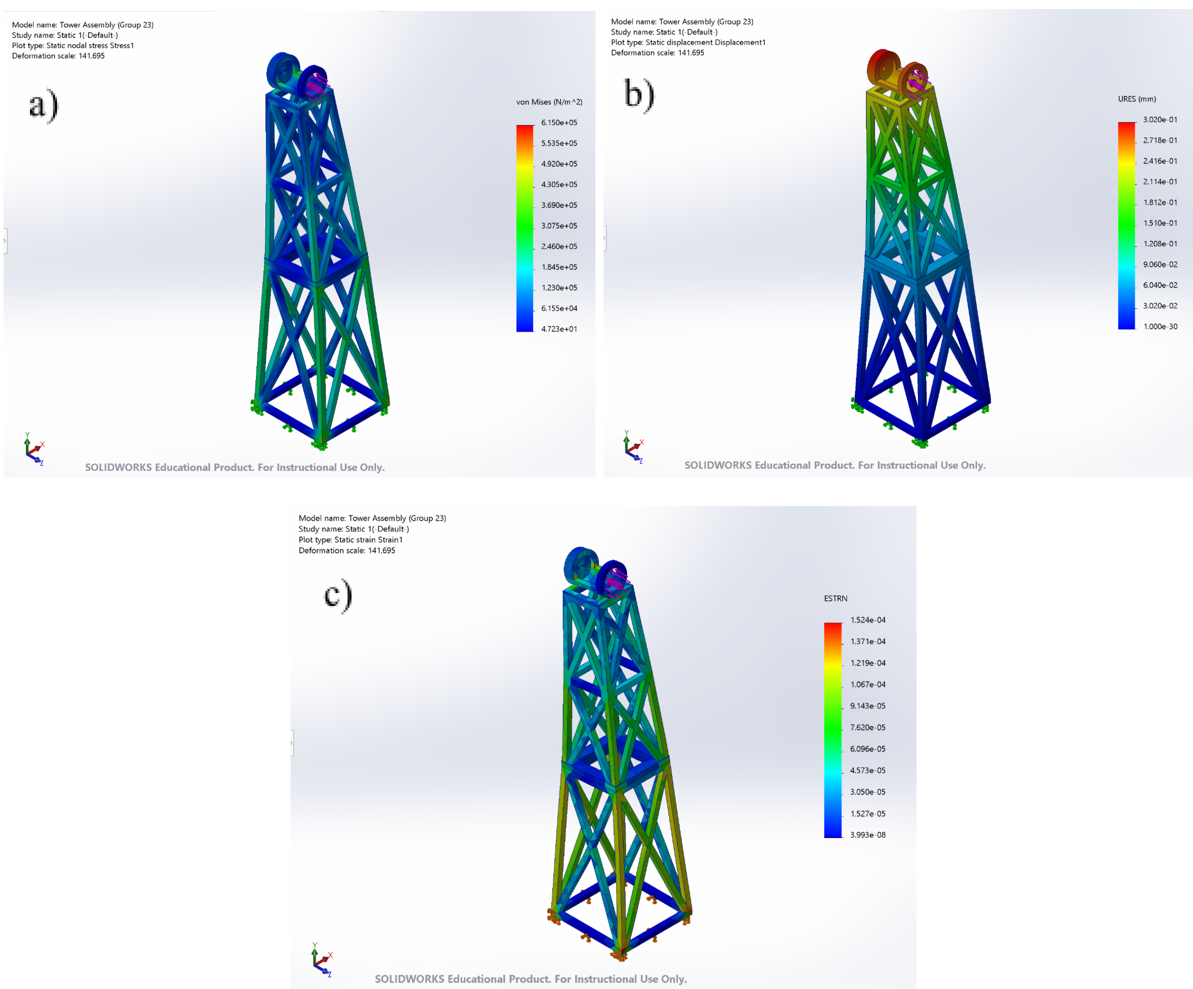


Figure 7: FEA Simulations on the Final Tower Design under 1 kg of load against the cage of the motor. a) Stress plot. b) Displacement plot. The maximum displacement recorded was 0.000301985 m. c) Strain plot.

The load applied onto the FEA simulation was added in increments of 100g to mimic the environment of the laboratory experiment. The displacement is plotted against the load of the simulation, Figure 8, and displays the linear relationship we expected to see in a rigid body structure. Since it was a computer generated simulation, there was an expectation that the simulation would have provided linear results as described by the R^2 value of 1. The slope of the data then suggests a stiffness coefficient of 341 N/m. Contrary to the slope indicated in Figure 8, the slope was calculated by measuring the displacement over the mass of the load applied. Since the load is applied to as free weights, the load has to be multiplied by the gravitational acceleration.

DEFLECTION & POWER DATA PLOTS

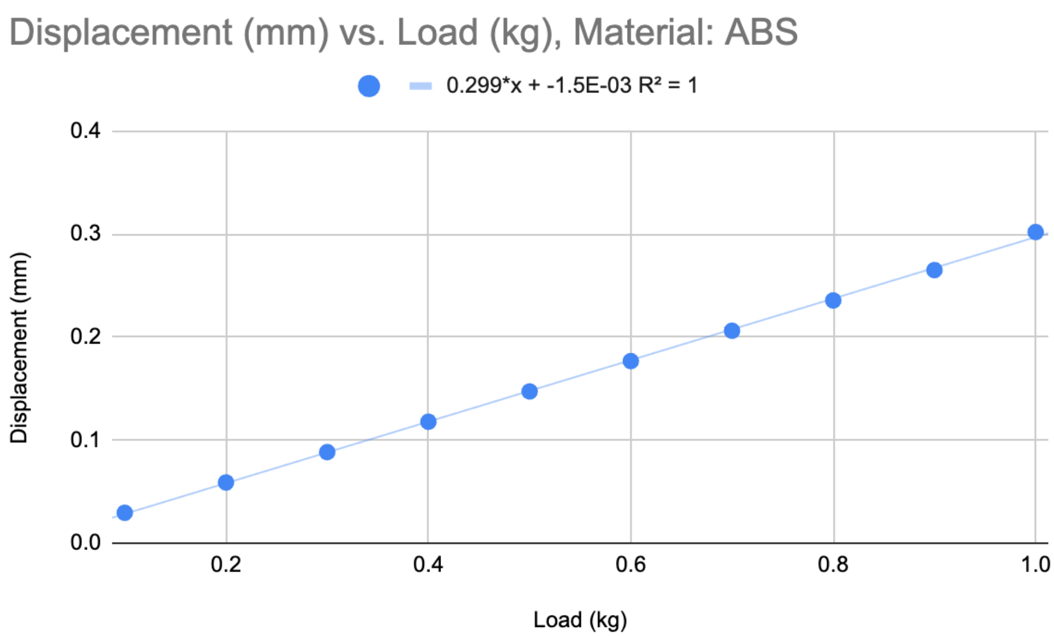


Figure 8: Displacement vs Load (FEA). The line of best fit does not accurately represent the stiffness coefficient. By applying the gravitational acceleration to the load and changing the units of displacement to (m), a stiffness coefficient of 341 N/m is obtained.

TESTING

TESTING PROCESS - POWER

The first thing we tested was the **power** of our wind turbine. To do so, we used the following set up and materials:

- Table – We put the wind turbine on a table that provided a flat surface. We positioned the wind turbine so the blade was facing the blower.
- Washers and Allen Key – There were 4 rectangular washers that we screwed down using an allen key to prevent any movement of the platform while the wind was blowing at the wind turbine.
- Blower – In front of the wind turbine was a blower. The blower was placed directly in front of the blade, 15.5 inches away.
- Motor – A motor was attached to the top of our 3D printed base and to the blade to allow the blade to rotate.
- Power Box – We hooked this up to the motor to measure the power output of the wind turbine. This power box also had potentiometer knobs that allowed us to record different currents, voltages and powers.
- Anemometer – We used this at the very beginning to measure the wind speed of the blower. To do so, we placed it directly in front of the air coming from the blower and recorded the wind speed in MPH.
- Tachometer – We used this device to measure the rotational speed of the blades (rpm). This was placed right next to the wind blower and the laser was aimed at a piece of tape on the blade, which allowed for accurate measurements of the rotational speed.
- Measuring Tape – Used to measure the distance between the blade and the blower.

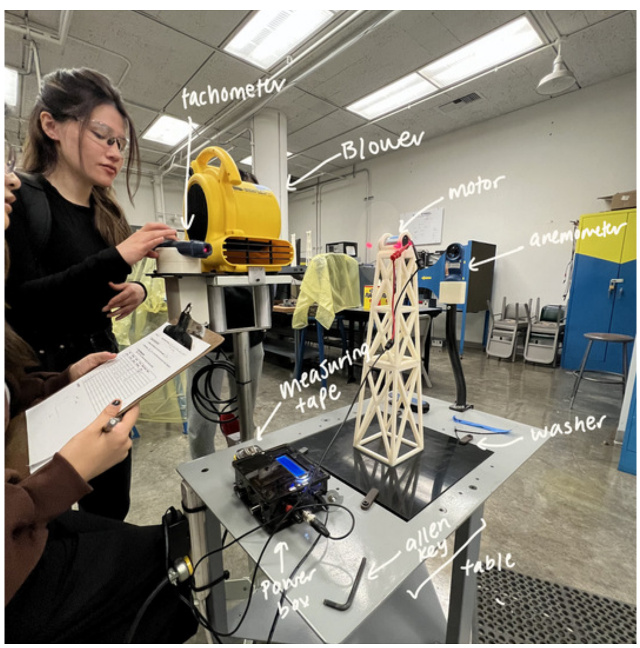


Figure 8: labels of all the testing equipment used

After setting up the wind turbine, we began testing! To test the peak power of our wind turbine, we first had to record some preliminary points. Using the measuring tape, we measured the distance between the blade and fan, which ended up being 15.5 inches. We also placed the anemometer in front of the blower to measure the wind speed, which ended up being 26.2 mph.

Next, we utilized the potentiometer knobs on the power box to adjust the current. The power box allowed us to record different values of voltage, amps and watts. We first measured the current at 0 amps as a baseline point. Following that, we used the potentiometer knobs to adjust the amps to 0.1611 amps. We then recorded voltage, power and blade speed (RPM) at 0.2155, 0.2201, 0.2705, 0.2711, 0.3305, 0.3533, 0.3746, 0.3748, 0.3785, and 0.3867 amps to figure out the plateau point.

Through plotting these values, we were able to produce two plots: Current vs. Voltage and Current vs. Power. This process allowed us to find the conditions that maximize power for our specific wind turbine. While testing power, we had to ensure at least 5 seconds of wait time between readings to allow the values to stabilize. In addition to the power box values, at every data point, we also recorded the blade speed in RPM using the tachometer tool.

<u>TESTING PROCESS - STIFFNESS</u>

After measuring the power, we proceeded to measure the **stiffness**. To do so, we utilized the following materials:

- Clamps (x4) – used to hold down the base of the wind turbine during testing.
- Cylinder insert – we put this cylinder insert into the motor holder to allow us to measure displacement.
- Dial indicator – the tip of the indicator was placed against the face of the cylinder insert to measure the displacement of the tower after putting load on the tower.
- Eye bolt – this was attached to the back side of the tower and was hooked up to a string that was placed over a pulley.
- Pulley – the string was fed over the pulley to allow for weights to be attached.
- Load (ten 100g hook masses) – these masses were hooked onto the end of string

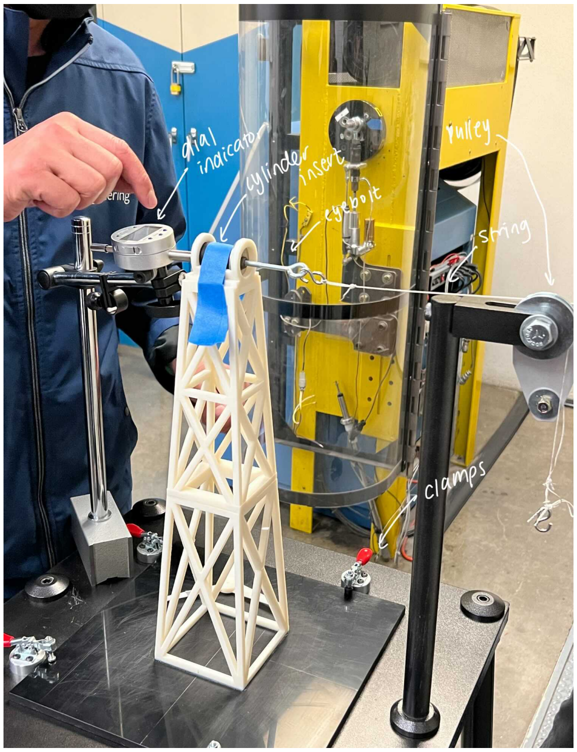


Figure 9: labels of equipment used to measure deflection of tower

To set up the stiffness test, we first clamped down the base of our wind turbine. Then, we placed the cylinder insert into our tower's motor holder. Next, we set up the dial indicator. To do so, we placed the tip of the indicator against the cylinder and zeroed out the indicator. Lastly, we attached the hooks on the string to the eyebolt and allowed the string to dangle over the pulley.

After setting up our wind turbine, we proceeded to the testing part. We began by placing one 100 gram mass to the end of the string. Then, we recorded the displacement value on the screen of the dial indicator. Next, we added another weight to the end of the 100 gram mass, totaling 200 grams as a whole. We repeated this process 10 times until we reached ten 100 gram masses attached to the tower.

<u>TESTING PROCESS - WEIGHT</u>

Along with stiffness and power, we also recorded the **weight** of the tower. To do so, we placed the tower on a zeroed mass scale and recorded the value. We got a value of 1172.4 grams. This value includes the weight of the base board, so we had to subtract 896 grams (weight of the base board) to get a total of 276.4 grams.

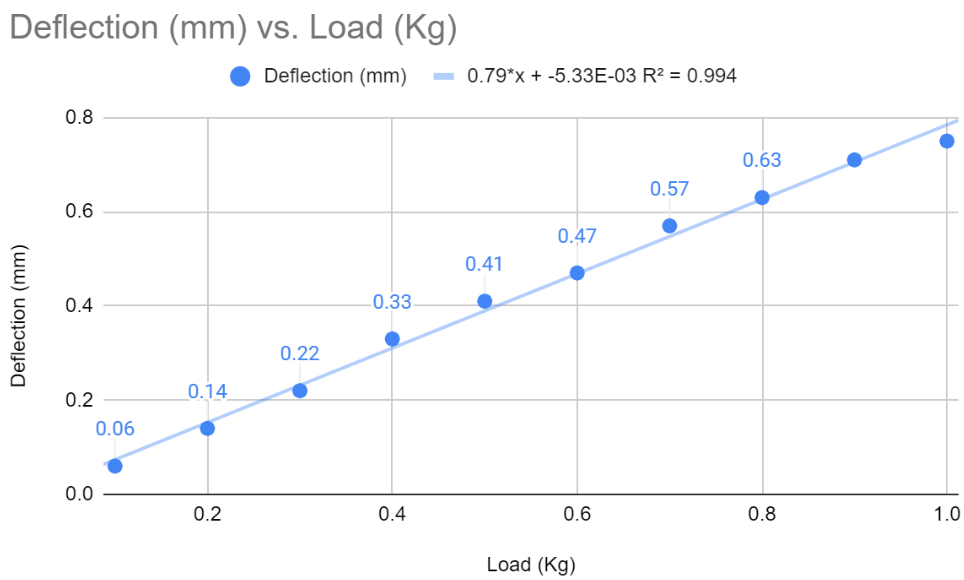
DATA TABLES

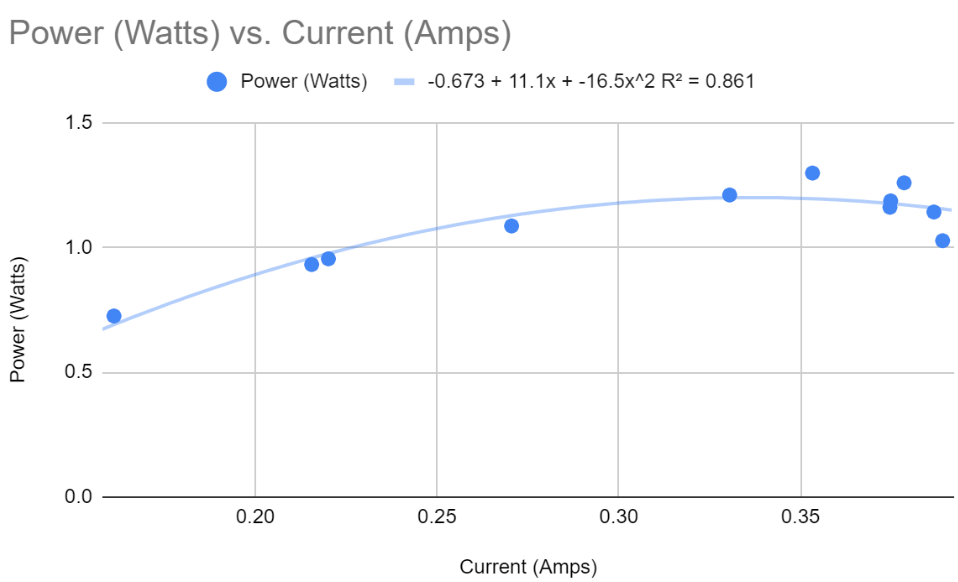
Power Measurements				
Blade to Fan Distance: 15.5in			Wind Speed: 26.2 mph	
Voltage (Volts)	Current (Amps)	Power (Watts)	Theoretical Power (Watts)	Blade Speed (RPM)
4.51	0.1611	0.7254	0.726561	6512
4.32	0.2155	0.9316	0.93096	6360
4.28	0.2201	0.9545	0.942028	6330
4.05	0.2705	1.086	1.095525	6130
3.68	0.3305	1.2101	1.21624	5690
3.59	0.3533	1.298	1.268347	5550
3.16	0.3746	1.161	1.183736	5036
3.19	0.3748	1.1865	1.195612	5106
3.28	0.3785	1.259	1.24148	5251
2.99	0.3867	1.142	1.156233	4805
2.78	0.3891	1.027	1.081698	4350

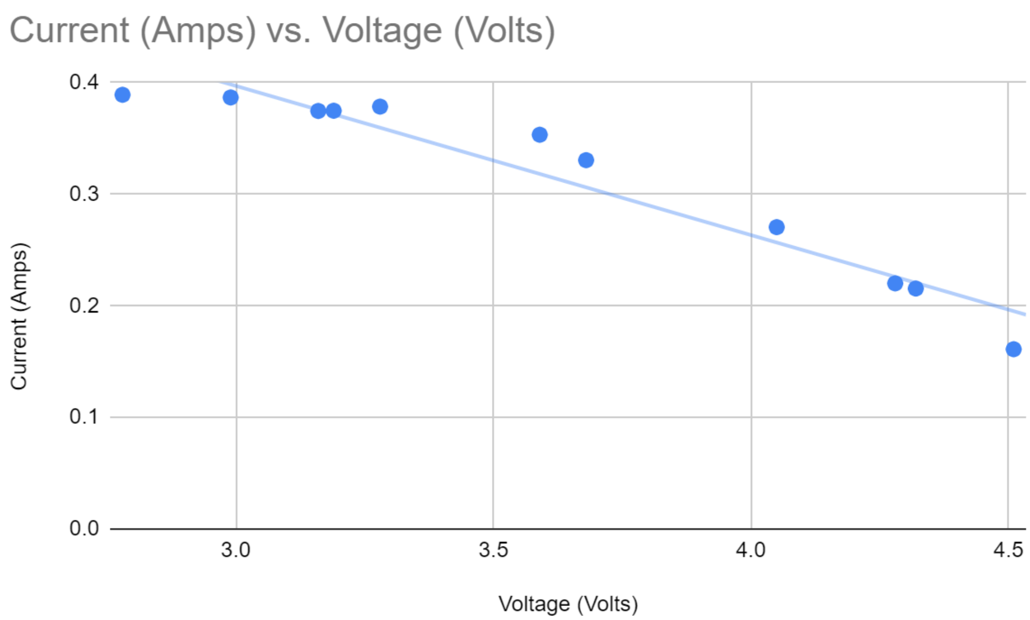
Deflection Measurements		
Tower Net Weight = 276.4 grams		
Tower Height = 15.52 in		
Load (Kg)	Load (N)	Deflection (mm)
0.1	0.981	0.06
0.2	1.962	0.14
0.3	2.943	0.22
0.4	3.924	0.33
0.5	4.905	0.41
0.6	5.886	0.47
0.7	6.867	0.57
0.8	7.848	0.63
0.9	8.829	0.71
1	9.81	0.75

PLOTS

The overall stiffness of this tower is 0.79 (the slope of the line).



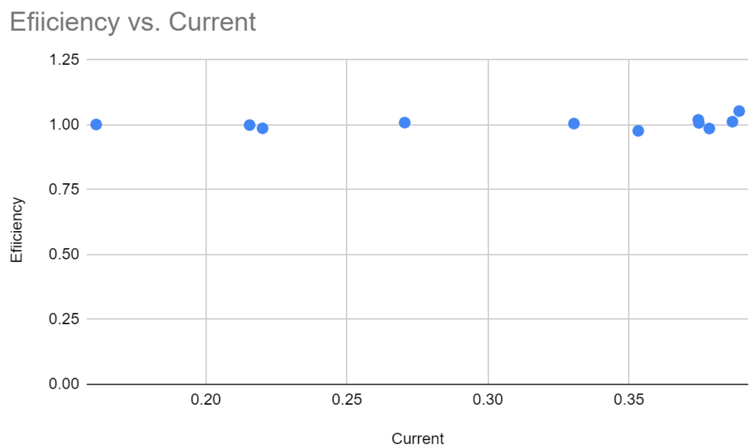




THEORETICAL POWER

To calculate theoretical power, we used the formula Volts*Current = Power. Then, we calculated efficiency by taking the theoretical power and dividing it by experimental power. The efficiency was thoroughly high throughout, with no value less than 0.975.

Experimental Power (Watts)	Theoretical Power (Watts)	Efficiency
0.7254	0.726561	1.001600496
0.9316	0.93096	0.9993130099
0.9545	0.942028	0.986933473
1.086	1.095525	1.008770718
1.2101	1.21624	1.005073961
1.298	1.268347	0.9771548536
1.161	1.183736	1.019583118
1.1865	1.195612	1.00767973
1.259	1.24148	0.9860841938
1.142	1.156233	1.012463222
1.027	1.081698	1.053259981



CONCLUSION

Our approach to the project contained several steps to ensure that we designed a wind turbine with the best method in mind. The fundamental core for this project was the research segment that was conducted by all members of the group. This step included finding design concepts for a wind turbine and understanding each element that contributed to the overall power performance. Each member then designed a turbine based on their prospective research and the final group design was picked through a group vote for most optimal performance. Once the final revision of the turbine was established, we began the CAD process.

Our wind turbine was designed with many factors in mind- we wanted it to be efficient in power production yet sturdy to resonate with natural forces. The CAD design was completed by making small iterations in the design to best fit the printing process. The tower was split into two and the beams were made thicker to fit the 3D printing limitation. The tower was later glued together and assembled for the testing section of the project. During our CAD component, we ensured that we used Finite Element Analysis to observe a simulation of real-life application before the actual testing. The turbine blades were created based on research that would optimize wind production. Through our research, we found that a 15 degree angle attack, 35 degree angle of twist and 10 degree pitch angle would be ideal.

After performing the final testing to determine power performance and durability, we concluded that our design performed well in generating power and remaining stiff with increased load. Our highest power generation amount was 1.298 amps, which was a bit lower compared to other turbine designs so our blade designs weren't optimized. On the other hand, our deflection was 0.75mm, which was on the lower side indicating a well designed tower that can withstand natural forces.

During our power generation testing, we came to realize that our battery holder was small which made it difficult to input the battery but it was still achievable with more manpower. We learned a key step in designing, that we must make the input larger than the battery's diameter. We designed it at 26 mm which was the battery's diameter but in real-life it almost prevented the power performance test from taking place. Our Finite Element Analysis varied from our testing outcome for load which showed us the difference between real-life testing and simulation. Although simulations can be helpful, it does not give accurate results. It is important to note that our own design varied from industrial wind turbines through material so we would not have been able to produce the same power efficiency as steel turbines or fiberglass designs. Overall, this was a great learning opportunity for our group to bring our simulation to real-life.

RECOMMENDATION FOR FUTURE WORK

Given the data we collected and the skills we learned during testing, there are some things that we would do differently next time. First, we would have increased the size for the motor mounting. Our diameter to insert the motor was 26 mm while the diameter of the motor was also 26 mm. This size made the fit very tight and it was hard to insert the battery into the mount. By increasing the size by even one mm, we would have had a better fit for the motor. We would have also taken more time to research the lattice structure of our tower to ensure the least amount of deflection as possible. Maybe adding a support beam in the middle of our tower would have helped alleviate some of the stress from the load. We could have performed numerous FEA's to find the best design before printing out our final iteration.

As for power generation, our team should have conducted more research about how to increase power generation by prototyping with differ numbers of blades or even different angles of twist to see if ideas like a four-blade design or increasing the angle of twist would lead to increased power generation. It would have also been a good idea to simulate our blade to check test rpm. Although the simulation might not have given us the correct answer, it would have given us insight to where the trajectory was towards. Although our power generation was not incredibly low, it was low compared to some other groups so, by testing blade versions, we would have been able to increase our power output.

REFERENCES

Adeyeye1, K. A., Ijumba1, N., & Colton1, J. (2021, June 1). *IOPscience*. IOP Conference Series: Earth and Environmental Science. Retrieved May 5, 2023, from https://iopscience.iop.org/article/10.1088/1755-1315/801/1/012020

Aerodynamics of wind turbine blades - nm Mesa. nm Mesa. (2004). Retrieved May 6, 2023, from https://www.nmmesa.org/wp-content/uploads/2019/10/Aerodynamics-of-Wind-Turbine-Blades.pdf

Greco, B. (2012, April 3). *EK 130 wind*. EK 130 Wind Wind Turbine Blade Design and Testing Project Comments. Retrieved May 5, 2023, from https://blogs.bu.edu/ek130wind/2012/10/03/wind-turbine-blade-design-and-testing-project/

Kehinde Adeseye Adeyeye *et. al.* IOP Conf. Ser.: Earth Environ. Sci. (2021) **801** 012020

Tutorials, A. E. (2022, January 7). *Wind turbine blade design, flat, bent or curved*. Alternative Energy Tutorials. Retrieved May 5, 2023, from https://www.alternative-energy-tutorials.com/wind-energy/wind-turbine-blade-design.html

APPENDIX

Reference graphs:

https://blogs.bu.edu/ek130wind/files/2012/10/Calibration.jpg

https://blogs.bu.edu/ek130wind/files/2012/10/5deg.jpg

https://blogs.bu.edu/ek130wind/files/2012/10/15deg.jpg

https://blogs.bu.edu/ek130wind/files/2012/10/30deg.jpg

https://blogs.bu.edu/ek130wind/files/2012/10/7in.jpg

https://blogs.bu.edu/ek130wind/files/2012/10/9in.jpg

PEER EVALUATIONS

We all split the work together and accordingly.