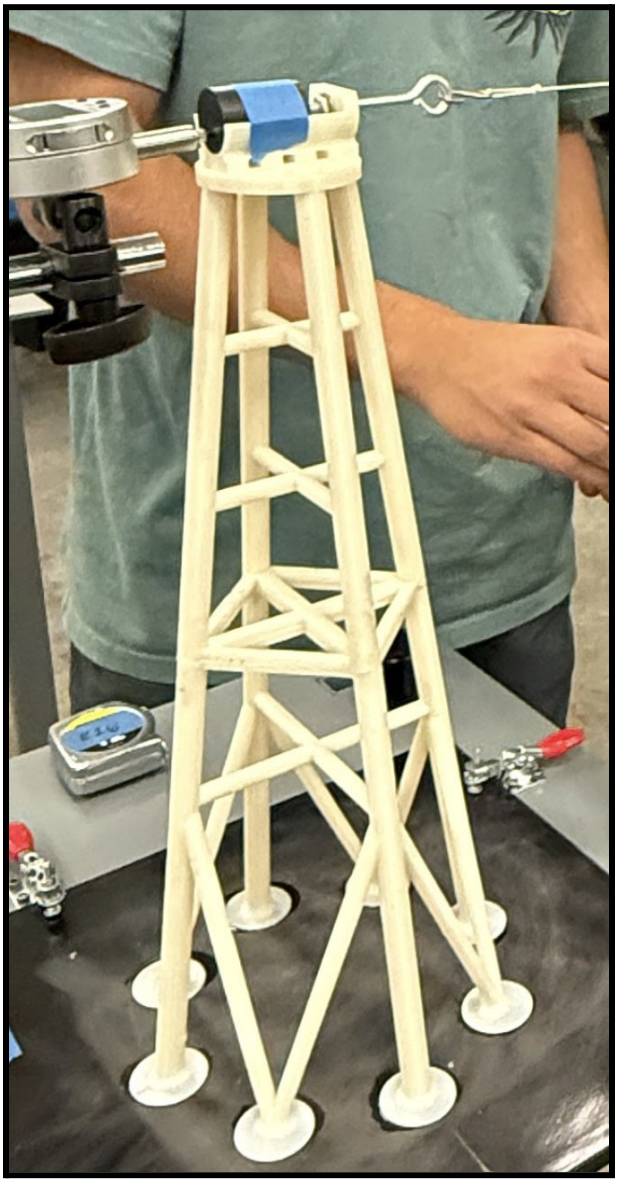
E26 Wind Turbine Final Report



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i. Project Summary

The purpose of this project was to design, 3D print, and test a small scale wind turbine capable of producing power whilst maintaining adequate stiffness and meeting other project constraints. To create this project using SolidWorks, we made a lightweight tower and a set of 3 curved blades designed to maximize power output whilst simultaneously staying inside guidelines of a swept radius limit of 3.0 inches. The final tower volume measured in at $16.996in^3$, staying in our constraint of the $17in^3$ limit, and the tower weight (excluding blade) was 140.7 g.

The turbine was tested in two different ways: power generation and overall structural stiffness. In the power test, we collected the following types of data: voltage(V), current (mAmp), power (mW), and blade rotation speed (rpm). Our turbine produced a maximum power of 1.242W (1242mW) at a wind speed of 24.6 mph. Now our displacement test introduced a few more variables such as displacement (mm) and load (N). Our turbine produced approximately 12.4 N/mm at loads from 0.98 N to 9.80 N with a tower weighing only 140.7g (excluding blade). The structure remained stable throughout further testing with a load of 19.6 N.

The turbine successfully met all the requirements and performed strongly in both tests, with clear potential to further improve blade performance and further structural reinforcement. We were able to find out what worked in our design and what was flawed through trial and error. Throughout our testing we only noticed one flaw, this being the blade instability causing a wobble at lower RPM but balancing itself back out at higher RPM. This could be fixed by adjusting the hole size for the motor to have a snug fit to ensure minimal movement and limit wobble.

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Introduction

Given current global energy demands, the need for sustainable clean energy is becoming more significant. One of the most popular sources of sustainable energy is wind energy due to its cleaner footprint and its ability to scale well compared to other energy sources. In conventional wind turbines, the main components of this system are the tower, the blades, a generator, and the mechanical parts that make up the smaller systems. For the wind turbine to function, the operation begins with wind blowing into the blades and creating lift for the rotor to revolve. Now, with the movement of this rotor, mechanical energy will be converted to electrical energy through the generator in the wind turbine. Finally, with this converted energy, it is sent into the power grid as usable energy. In essence, a wind turbine functions by converting the kinetic energy coming from the wind into mechanical energy, then changing that into electrical energy.

Because wind turbines are deployed in an outdoor environment, there will be guaranteed variation of conditions that engineers must account for. Without considerations and adjustments such as axis of rotation, number of blades on the rotor, the height of the tower, and individual blade shapes (Wind Energy-The Facts), the efficiency of these systems dramatically decreases. Therefore, every turbine must be created in order to meet the various logistical demands like cost, environment, and requirements of the design. In the instance of this project, the environment is controlled and therefore most variation for the design will be determined by the shape of the airfoil.

With this project, our goal was to create a blade design that could most effectively generate energy, and develop a tower construction that would be the most structurally sound as to reduce

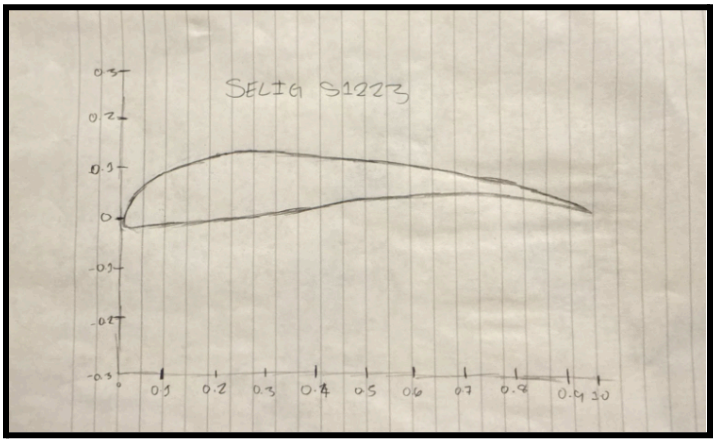


Figure 1. Depicts an early sketch of a singular blade cross-section design for the airfoil.

the vibration and ensure our blade had an adequate tower to sit on. The first step of the design process for the group was to research and find data about optimal blade cross-sections, angles of twist, angles of attack, and the amount of blades we would want on our rotor.

After brief deliberation, our group was able to come to a consensus of an outline that we wanted to follow for our design. In these early stages, our team immediately decided that a 3-blade rotor design would be the most optimal as it would ensure stability in our turbine. The possibility of a 2-blade rotor design was phased out due to it being more prone to vibration and instability issues. With a 3-blade design, the asymmetries could be addressed properly while also finding optimal efficiency considering that more blades create more drag. (Blade design considerations of small wind turbines)

For the angle of twist, our group found much more variance in our conclusions, but ultimately decided that we wanted to go from a 25° towards the root of the rotor/blade connection to a 5° angle at the tip of the blade. By having the angle of twist change gradually as it gets farther away from the fan hub, the airflow will be much smoother across the blade (Design of Airfoils for Wind Turbine Blades), and allow for us to prioritize the stability of our design.

Similarly for the angle of attack, we had a diverse set of observations as a group, but ultimately decided that a lower angle of attack approximately at 6° would be the best for a design, as it compromised the lower energy outputs of smaller angles and the potential to stall at greater attack angles (Optimized linearization of chord and twist angle profiles for fixed-pitch fixed-speed wind turbine blades). This would also guarantee a more stable experience for our turbine as this angle would make the rotations more smooth and efficient as opposed to other angles.

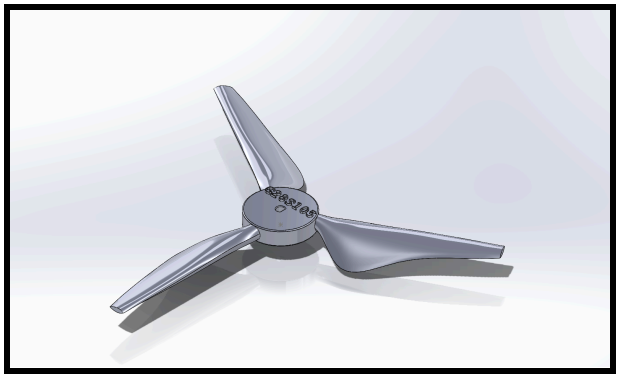


Figure 2. Shows final 3-blade design concept implementing general design requirements and the provided fan hub.

The next step of our wind turbine design was to create an appropriate tower design for our blade and motor. For this part of the design process, we had the most contention with what we wanted to do. In the early stages of this process, we wanted to have a triangular design for our base given that we had an understanding of triangles most effectively distributing the load. However, we eventually scrapped the idea in favor of a more circular base for our tower while maintaining triangular elements throughout the rest of the tower. To get to this circular base, we decided on having 4 main legs that ran through the entirety of the tower and then have 4 sub-legs that ran between each of the main legs. By doing this, we were able to ensure that the load could be more effectively distributed at the base of our tower. Throughout the rest of the tower, we decided to add supports to make sure each of the legs were receiving the same amounts of stress throughout the tests. In having a large number of contact points at the base of the tower, we were able to

maximize our stability and ensure that our tower stayed rigid when tested with the stiffness test, especially with our main legs being relatively thick.

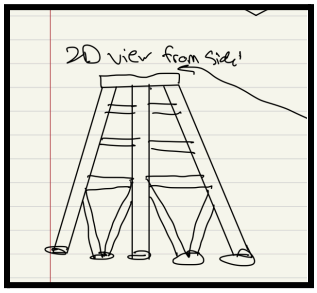
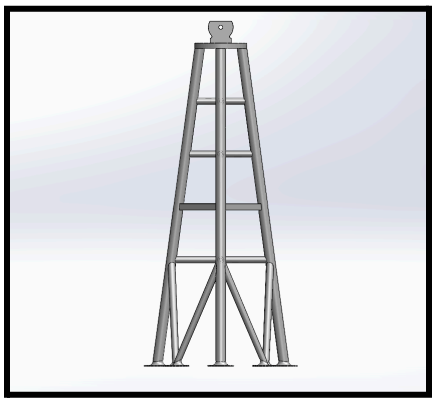


Figure 3. Illustrates a tower design sketch with thicker central legs and smaller support legs. Also shows general placement of support brackets throughout the tower.

Design

Tower:

The primary purpose of the tower is to be quite strong and not deflect much. Thus, it needs to have a strong base and lots of contact points with the ground while maintaining the volume requirement. We had a few constraints, such as the maximum height of the tower due to the motor, the base size, symmetry, and volume. We also needed a motor base at the top and we were told it would be good to have zip tie holes so we also incorporated those. To determine the actual structure of the tower, we knew we wanted to have a multi-leg base. We decided to have 4 since it is quite nice geometrically and we wanted to add crosses so it is easy to add crosses for 4 legs compared to 3. We also wanted more contact points so we made 2 smaller legs stick out from each leg and connected pairs of 2 so as to create more structural stability. To distribute mass even better and have more contact area we extended each leg and filleted to create a circular base. Since our print was to be printed in 2 parts, we needed to find a good place to cut it. Because of this, we made the lowest cross a different shape so it could

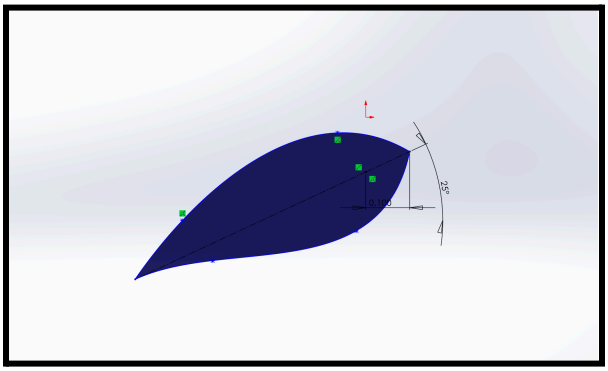


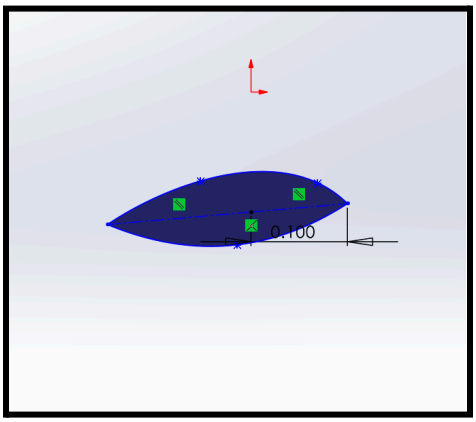
be cut but still have a good region to glue. We decided on 3 crosses since more would increase volume and 3 seemed reasonable and produced decent results in SolidWorks simulation. Since this gave a good base, we adjusted the top platform to have a motor base as the professor described and created ziptie holes for easy mounting. The length and diameter of each cross was optimized to maximize volume while staying under 17 in^3, having the motor reach 16 in, and minimizing to a maximum of 2 parts.

Rotor:

Initially, our group all decided on having a 3-bladed rotor, inspired by the conventional wind turbines we would see in real life. However, after conducting more official research, we found that a 3-bladed rotor was indeed the most optimal for a wind turbine. This is because having less blades means less drag, meaning that having the least amount of blades possible would result in the most efficiency. Despite this idea, our group opted for a 3-bladed design instead of a 2-bladed one as only having two would result in unwanted stability issues (BBC Science Focus).

We then implemented a 25 degree angle of attack at the root of the blade because we realized that the root of the blade would be moving slower than the tip. During our research we found that a 10-15 degree angle of attack was optimal as it was a perfect balance between lift and drag (Aerodynamics of Wind Turbine Blades). However, a uniform blade angle would mean that different parts of the blade would be able to be as efficient as they could be. For this reason we added a 25 degree angle at the root that gradually twists to a 5 degree angle at the tip. This twist allows each part of the blade to operate closer to an efficient lift-to-drag balance while reducing excess drag at the tip.



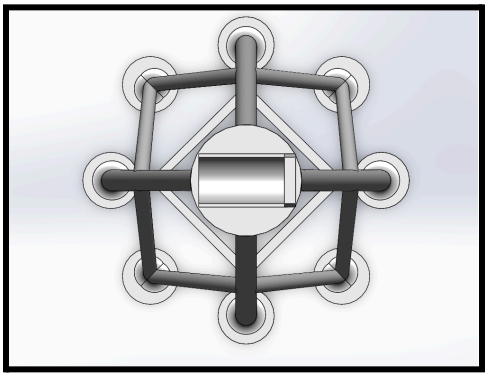


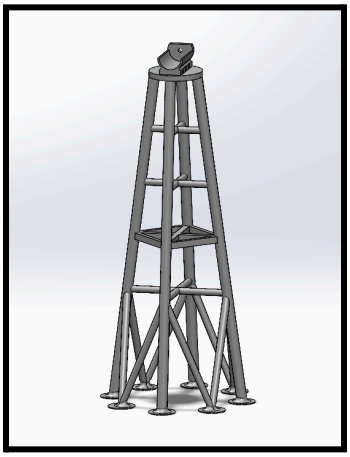
Root

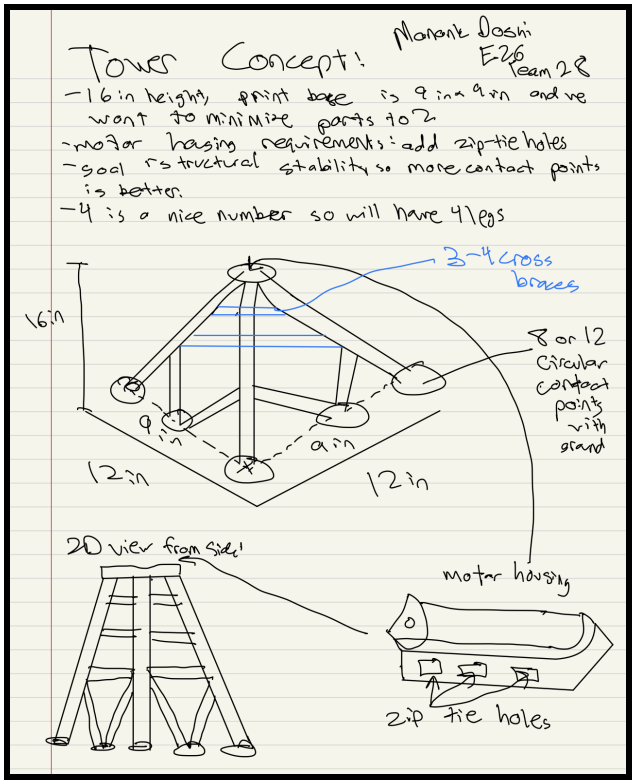
Tip

(Size not to scale)

A) Relevant sketches, drawings, pictures







B) Design Process Using SolidWorks

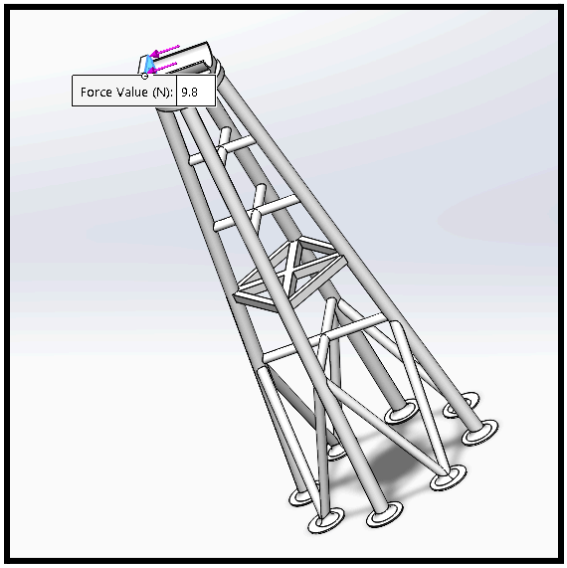
The major tool using the design process is SolidWorks. SolidWorks is a 3-D computer-aided design (CAD) software which allows us to easily model and refine our tower and blade. SolidWorks is an application-based software where we can make detailed sketches of every shape, circles, squares, splines, and whatever we want. Using these sketches, we can create a 3D model using extrusion features such as sweep, extrude, and loft. This makes it easy to design and visualize the tower and blade and see how they look and perform. Due to the features that exist in SolidWorks, it is easy to adjust the tower and make it good for structural integrity, like the

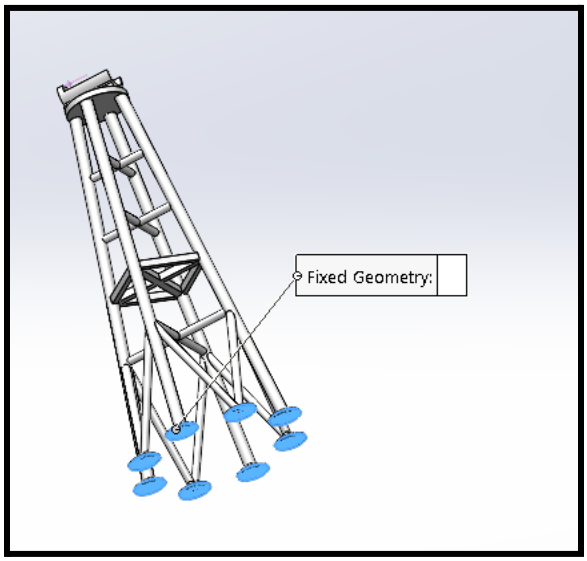
deflection test we performed. SolidWorks also has built-in simulation and analysis tools, which are very good at preliminary analysis. For example, we used SolidWorks to perform FEAs on our tower to see how it performs in the deflection test. For the blade, we primarily used the loft function, which allowed us to connect multiple cross-sectional profiles, which is how we created our blade. For the tower, we primarily used extrude base and extrude cut. Extrude base was useful since it could extend sketches, while the extrude cut was used to create partial shapes like the motor housing. For the trusses, it made sense to use the sweep feature which allows us to create a profile and then have a path that the profile follows. SolidWorks is overall a great CAD software that provides lots of functions and easy simulation tools for engineers like us to design, simulate, and print items like the tower and blade. All CAD files made using SolidWorks can be found here.

C) Deflection FEA and analysis

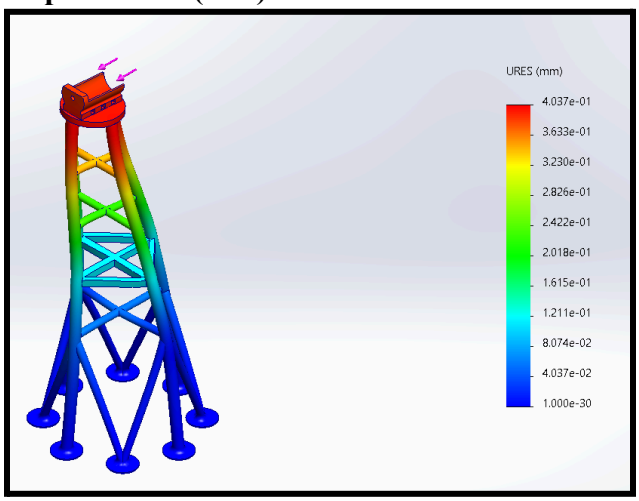
The FEA simulation was set up using the SolidWorks simulation feature as this was the way we were taught in class. We set the material to ABS as that is what the professor mentioned in class would be the default material since the shop printed it. Since we wanted to have 8 contact points that would be glued to the base, all 8 of these surfaces were set as fixed. These 8 surfaces are the flat circular plates at the very bottom of the tower. The load was going to happen at the back of the motor casing that is connected to the eye bolt. Accordingly, we set the load there at 9.8 N since we were looking to find the deflection at 1 kg, and since $g = 9.8\ m/s^2$, the total force is 9.8 N. For some reason, yield strength was not defined in the Onshape library of ABS. After referring to the Onshape material library (which had a yield strength of ABS defined), we created

a custom material that had a yield strength of 6498 psi. Images of the setup in SolidWorks and the results are below. One thing to note is that Solidworks assumes a full infill. However, we were told that the infill would be 70-80%, although based on what was printed, it appears that it might have only been 50% since our estimated mass from solidworks was 284 grams and the actual mass was 140.7g. Assuming that infill was 50% and there is a linear relationship between displacement and mass, our results were quite accurate since the simulation estimated 0.404 mm. Multiplying by 2 to account for infill, we get 0.808 mm while our actual displacement at 9.8 N was 0.77 mm. Therefore, we performed quite similarly compared to our simulation. Looking at the simulation results, the displacement is what we expected. Since the load is at the top, the top would likely stretch first and decrease as you get closer to the fixed points. This is what the displacement simulation showed, the highest deflection at the top and no deflection at the bottom. The stress plot shows that the highest stress is at the joints where the crosses meet the big legs. We believe this makes sense since there is a compressive stress since the back leg wants to move forward and the joint is the reason this does not happen so it experiences the most stress. The highest stress is the top cross since it is closest to the force, so it experiences more stress.

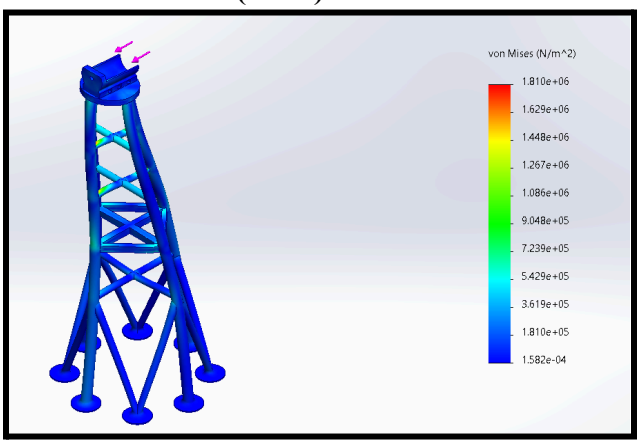




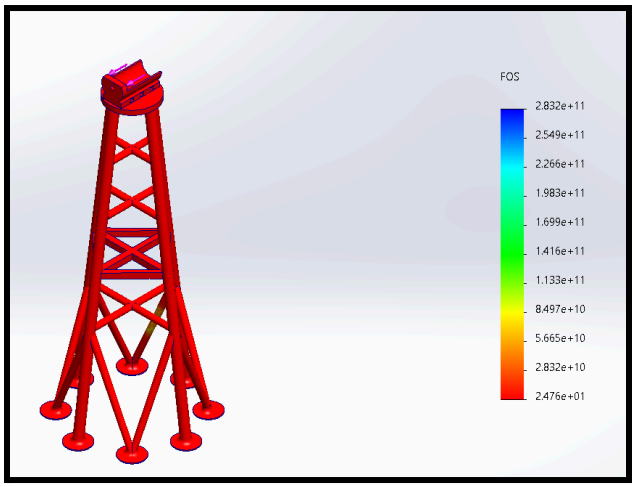
Displacement (mm):



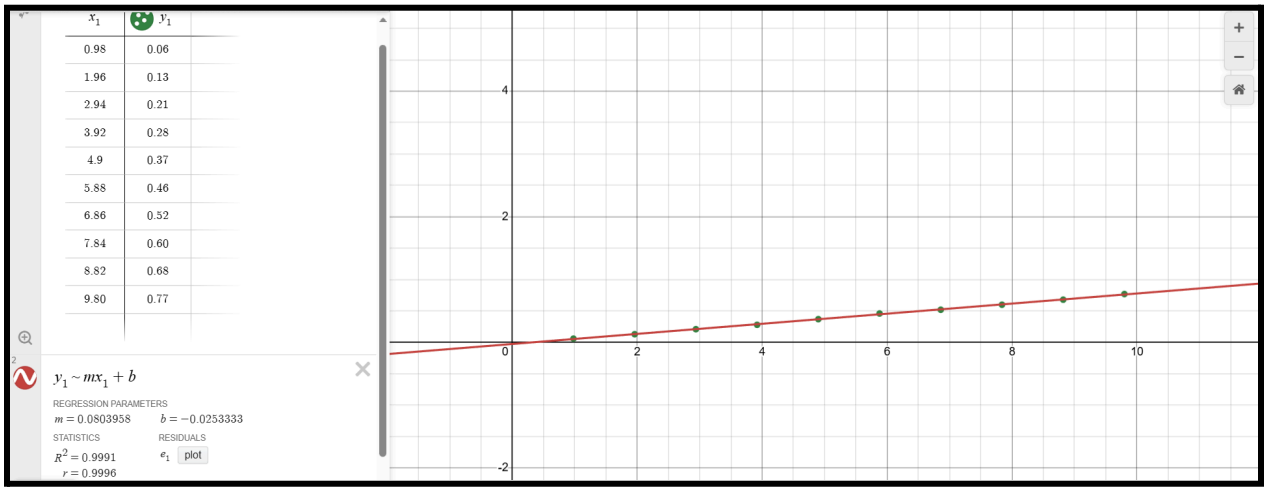
Von Mises Stress (N/m^2):



Factor of Safety (no units):

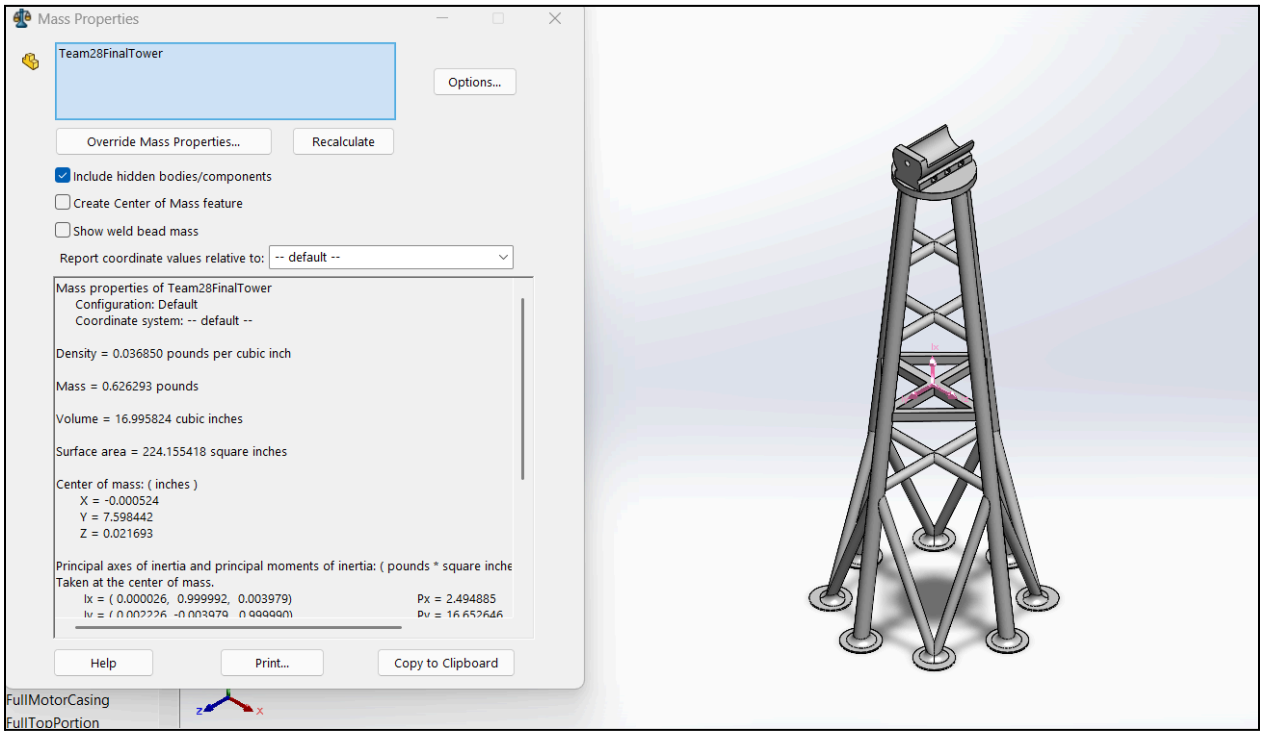


D) Plot of the load vs. deflection (displacement) and comparison to FEA analysis



The R^2 is 0.9991, which is quite high, so our data was very good. This is not too surprising as the dial indicator was very precise and the loads were exact. We excluded the 2 kg mass as that was mostly just for fun, and we wanted to primarily measure up to 1 kg. Our measured data for displacement is about twice the value of the FEA analysis. This logically makes sense since our measured mass was about half the mass on SolidWorks, likely due to infill. More comparison was also done in the previous section.

E) Volume Properties



Testing and Results

Our testing goal was to test the wind turbine's maximum power output as well as its energy efficiency and tower displacement stiffness. This tells us about our towers overall strength and structural rigidity

A) Equipment Used:

Power Meter



- It was used to control and read the Power output (nW), Current output (mA), Voltage output (V), and Resistance (Ohms) of the wind turbine.

Anemometer



- Used to measure the wind velocity (mph) from the blower

Tachometer



- Used to measure rational speed of blade (rpm)

Dial Indicator



- Used to measure deflection (mm) of tower

Our Procedure for Stiffness Test (Deflection)

1: To start our deflection testing, we weighted the tower without its motor and blade. Then, we placed our tower and base on the testing platform attached via latches fastened with allen keys.

2: Then we had to screw an i-bolt into the motor housing in order to attach a hook and string that would pull on the tower. After attaching the hook, we put it over a pulley system that was rigged up to attach weights to the bottom of it.

3: Then, we placed the dial indicator and then zeroed the value out to begin our testing.

4: We then started adding weights to the string in increments of 100g for 10 trials, recording the data each time. After everytime we attached a weight we would wait a couple of seconds to ensure our data stabilized making sure our data was as accurate as can be. Once a total of 1000g were added we finished with the trials. Although our team didn't stop here we pushed our tower a bit farther adding another 1000g on top making a total of 2000g of resistance acting against our tower.

5: Using all of this data we gathered, we then plotted it all onto our sheets and then transferred the data to google sheets. To start, we created a load vs. deflection and a load vs. displacement graph to clearly show our data and determine the overall stiffness of the tower.

Our Procedure for Power Generation Test

1: First, we secured the tower to the testing table through latches fastened with allen keys. In addition, we had to make sure the motor was fastened correctly into the motor housing using zip ties that wrapped around the whole housing.

2: Then, we positioned a wind blower in front of our turbine and used an anemometer to measure the required wind velocity for our testing (~25 mph).

3: For the voltage, we first had to find a relative maximum energy output given that the trend of the energy output was parabolic. From there we went in increments of ~6-3 ohms for the resistance of the power meter. Reading the power meter, we noted down the observations in our data table for the 16 data points we chose.

4: At each interval, we also made sure to turn on the tachometer and align it with the tape on the blade so that we could get an accurate reading of the RPMs. With these readings, we were able to note them down in our data table alongside the other results of the test.

5: With the data collected in our tables, we were able to plot out the voltage against the current and the power against the current in their respective graphs. From these plots we were able to approximate a curve of the relationships which allowed us to determine the maximum potential output of our turbine.

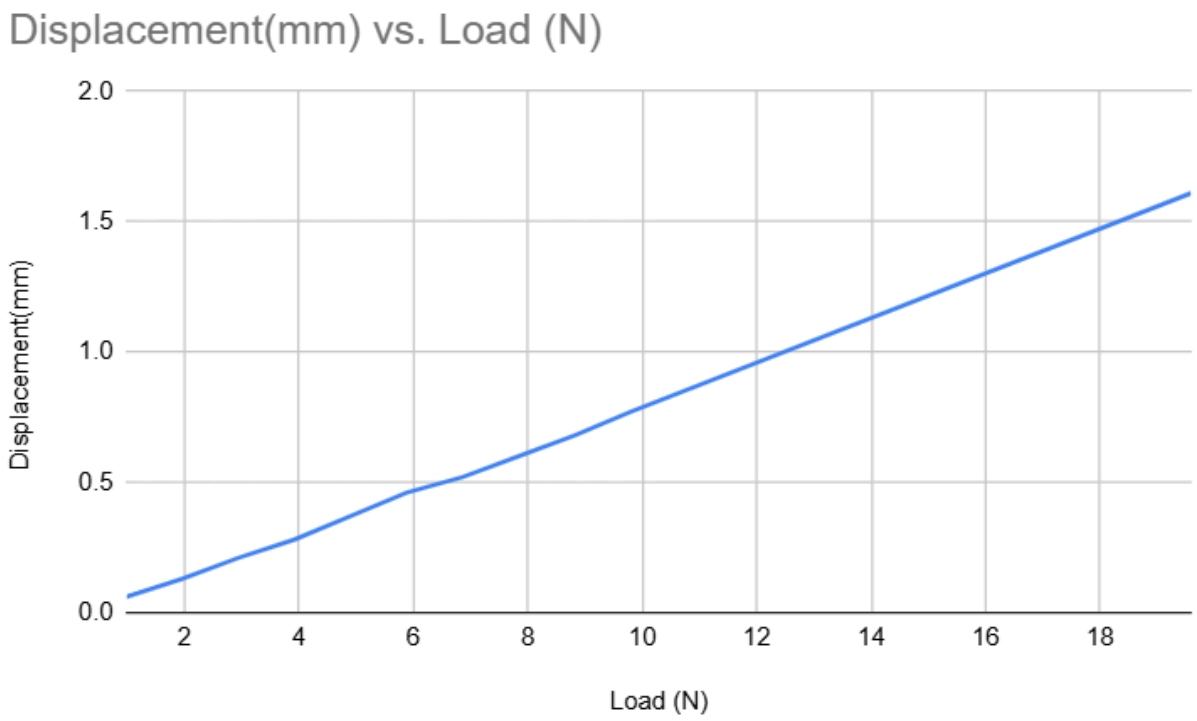
C) Power Measurements

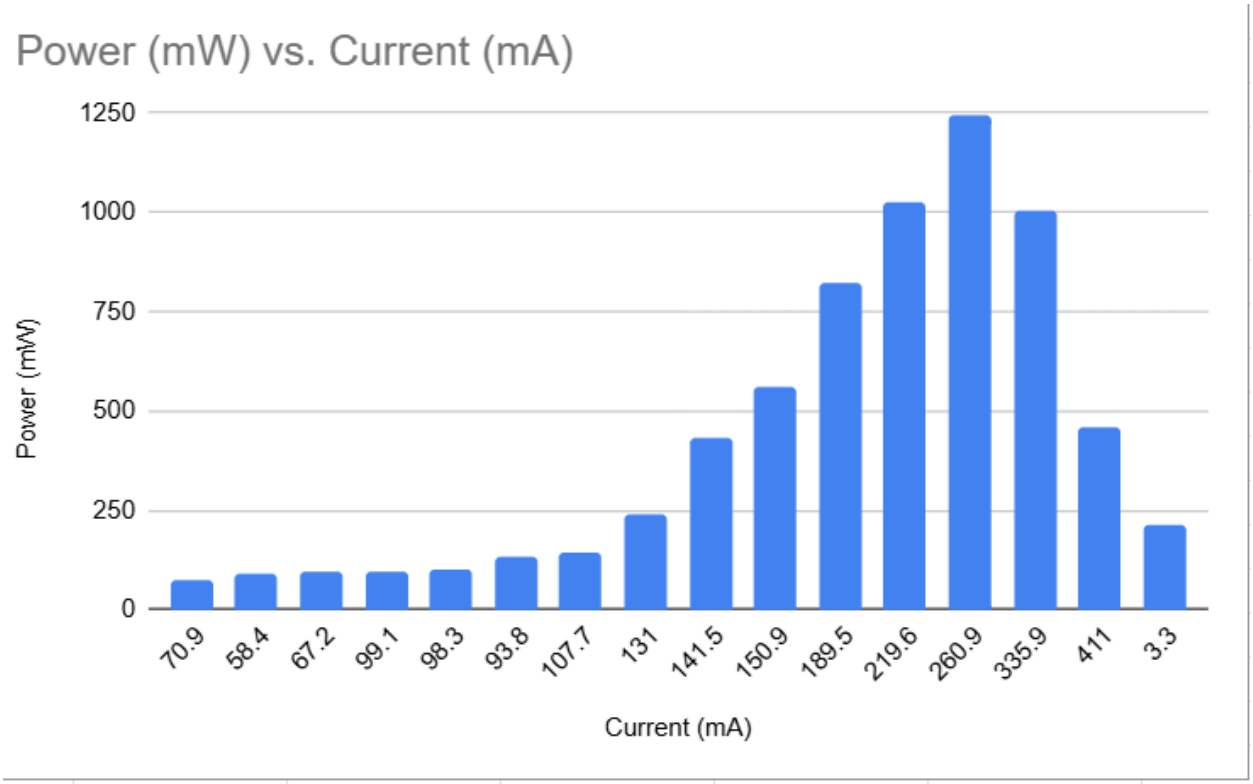
Row	Voltage (V)	Current (mA)	Power (mW)	RPM	Notes (Ohms)
0	2.03	37.8	76.7	2585	53.8
1	2.08	43.0	89.5	2682	49.6
2	2.11	46.2	97.4	2741	42.0
3	2.06	46.3	95.3	2718	37.0
4	2.12	47.4	100.5	2816	34.6
5	2.21	61.1	135.0	2934	31.0
6	2.29	63.8	146.0	3047	28.0
7	2.47	97.2	240.0	3191	23.7
8	2.62	164.1	430.0	3386	21.5
9	2.74	204.8	561.0	3542	18.3
10	2.86	288.1	824.0	3728	15.2
11	2.92	351.0	1025.0	3887	12.4
12	3.02	411.3	1242.0	4046	9.3
13	2.94	341.1	1003.0	3861	6.0
14	2.39	192.1	459.0	3468	3.1
15	1.83	116.4	213.0	2529	0.4

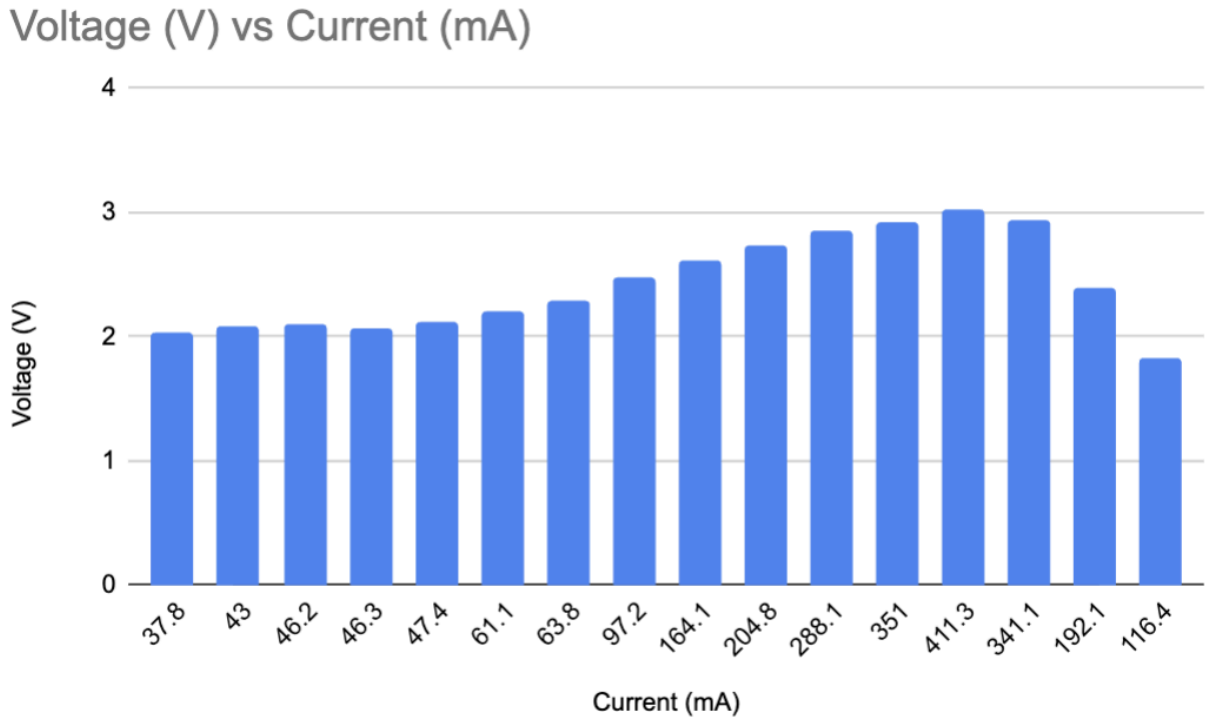
D) Deflection Measurements

Row	Load (kg)	Load (N)	Deflection (mm)	Notes
1	0.10	**0.98**	**0.06**	—
2	0.20	**1.96**	**0.13**	—
3	0.30	**2.94**	**0.21**	—
4	0.40	**3.92**	**0.28**	—
5	0.50	**4.90**	**0.37**	—
6	0.60	**5.88**	**0.46**	—
7	0.70	**6.86**	**0.52**	—
8	0.80	**7.84**	**0.60**	—
9	0.90	**8.82**	**0.68**	—
10	1.00	**9.80**	**0.77**	—
11	**2.00**	**19.6**	**1.61**	*(extra trial)*

E) Plots and Efficiency Calculations




Power (mW) vs. Current (mA)
1250
1000
750
500
250
0
Power (mW)
70.9
58.4
67.2
99.1
98.3
93.8
107.7
131
141.5
150.9
189.5
219.6
260.9
335.9
411
3.3
Current (mA)


Voltage (V) vs Current (mA)
4
3
2
1
0
Voltage (V)
37.8
43
46.2
46.3
47.4
61.1
63.8
97.2
164.1
204.8
288.1
351
411.3
341.1
192.1
116.4
Current (mA)

Stiffness = 12.4 N/mm

Efficiency Calculations

Efficiency = $\frac{Experimental\ Power}{Theoretical\ Power}$

Theoretical power = ½(p)(A)(V^3)

P = Density of air = apx 1.2kg/m^3

A= Swept Area = πr^2= 0.0176m^2

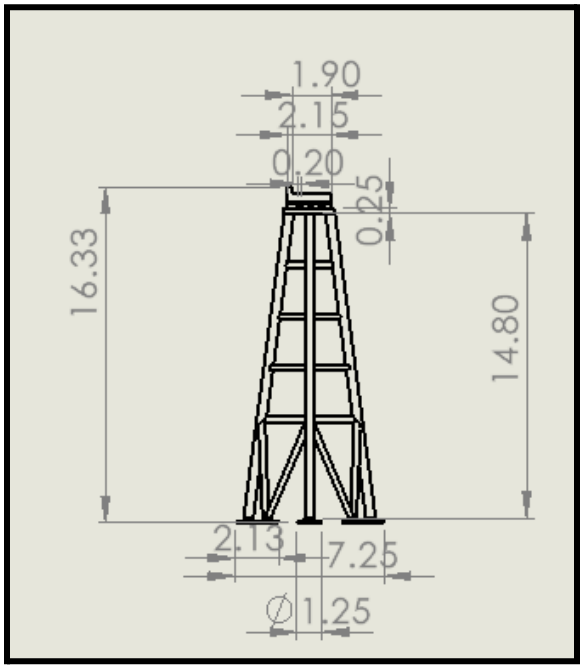
V = Wind velocity = 24.6mph= 10.996 m/s

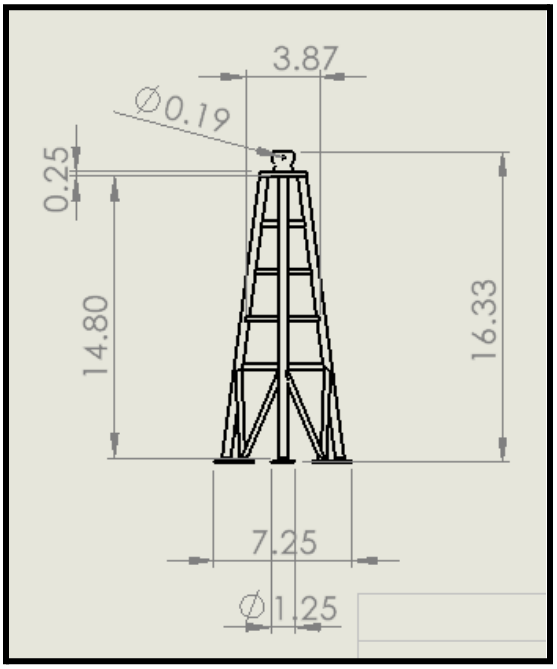
Theoretical power = $\frac{1}{2}$ (1. 2)(0.0176m^2)(10.996 m/s)=14.37W

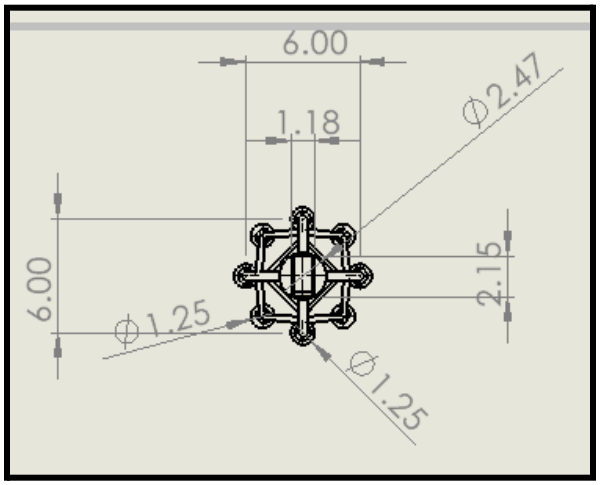
Efficiency = $\frac{1.242W}{14.37W}$= 0.0864 = **8.64%** Meaning our tower performed quite well

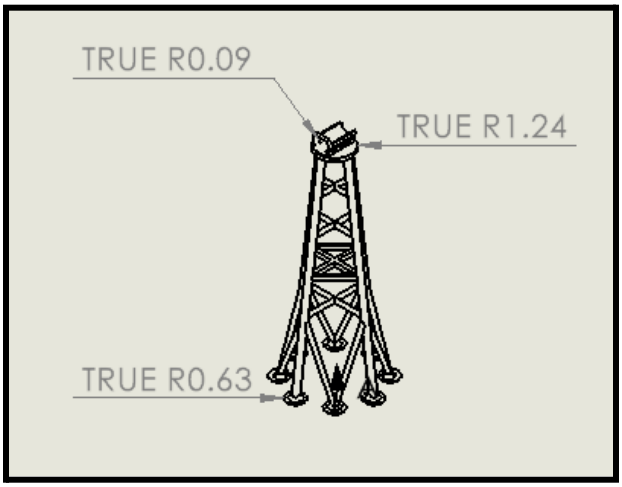
CAD Drawings

A) 2D Engineering Drawings of Tower with Dimensions

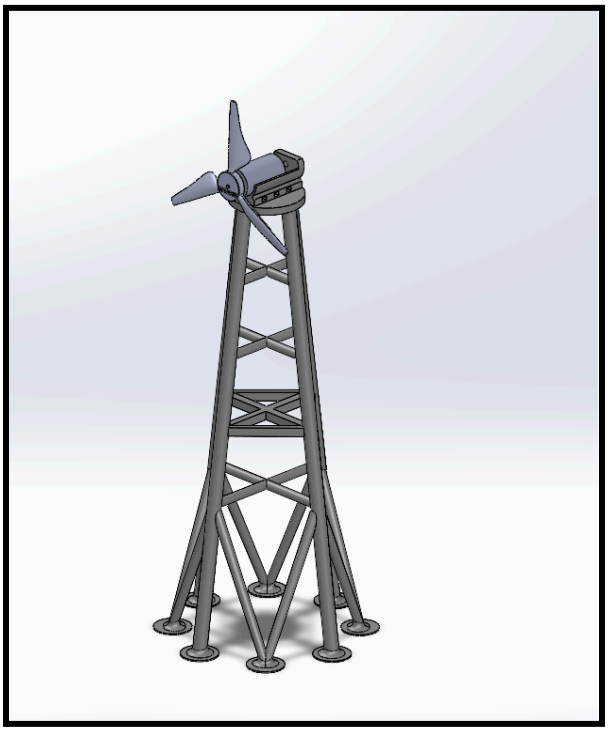


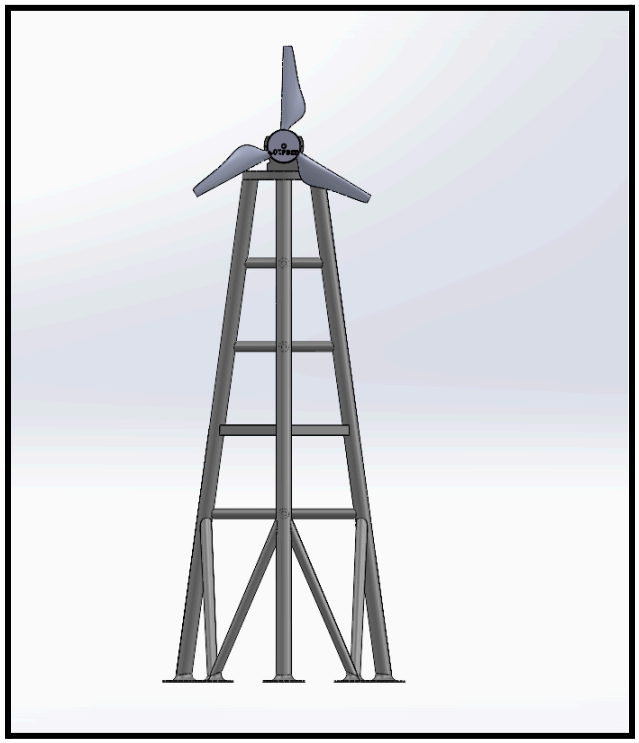




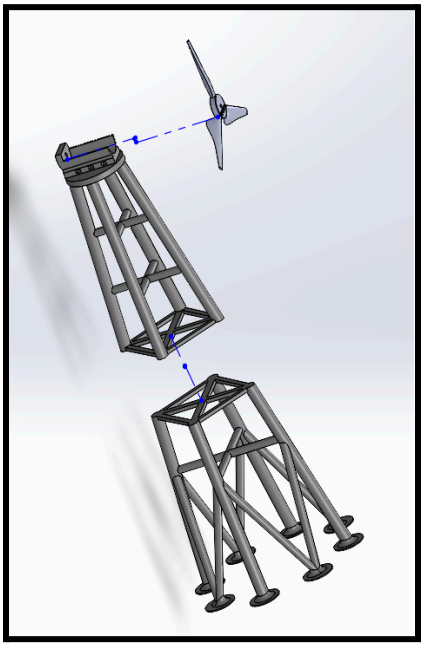


B) 3D Assembly View of Tower

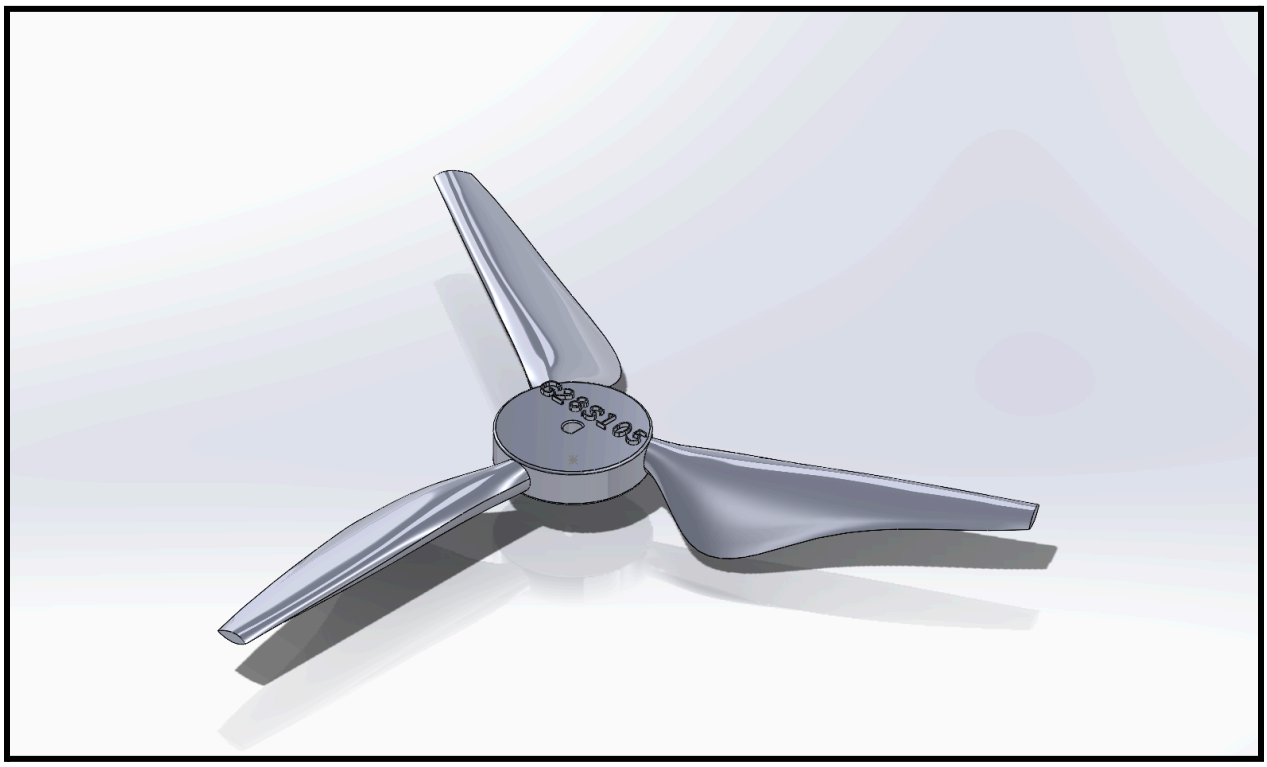




C) Exploded View



D) Rotor 3D View



Conclusions

The objective of this project, to design, build and test a small scale wind turbine capable of producing power while maintaining strong structural support and maximizing energy output, was successful. The final turbine design fits the volume and height requirements, and demonstrated strong results on all tests. The turbine produced a maximum power output of 1.242 W, validating the efficiency of our blade design. Additionally, the tower showed excellent structural integrity, demonstrating a measured stiffness of approximately 12.4 N/mm and up to a load of 9.8N. One flaw in our design was an observed blade wobble at low RPMs during testing, later self-corrected during an increase in rotation speed. This issue was due to a slight movement in the motor housing connection. This issue can be resolved in the future by designing the hole a little bigger to adjust for the small 3D printing mistakes. The results of this project were overall positive and showed us the power of design, building and testing, skills all engineers must have in industry careers. For future projects, I would focus on the blade design, more specifically fine tuning the geometry to maximize efficiency at higher speeds. Although our blade achieved great results, I believe we could have pushed the limit on the amount of power we could have generated. In conclusion, this project delivered a strong, fully functional and robust wind turbine. This prototype provided a solid foundational design, allowing for future development.

Recommendations For Future Work

Overall the project went smoothly but there are for sure some areas where we can improve a significant amount on. If we were to redo the project we may want to build a more complex design refining our tower as well as utilizing the 3d printer a lot more making more prototypes prior to choosing a final design. Next time we would redesign the motor housing as we had a difficult time ensuring the motor was in the correct position to ensure the blades would hit the tower.

As well as redesigning the blade where it attaches to the motor itself because when trying to test the tower we ran into the issue of having to jam the blade into the motor shaft. By redesigning this part we save ourselves from major headaches as well as the blade will wobble way less being more secure in the motor. We would also add more of a twist distribution to the blades for improved lift making the blades more efficient. Also, modifying the angle of attack and experimenting with a different blade count. To find which would work the best in our circumstances and requirements.

Furthermore we could ensure our base tower could be a bit lighter saving weight whilst maintaining a high level of stability. We could accomplish this by slimming down some of our beams and potentially removing some of the cross members that don't provide as much support as its cost in weight. By doing all this I'd picture this project potentially going from a 8.64% efficiency to maybe 12 plus percent making this a very efficient small scale wind turbine.

References

Aerodynamics of wind turbine blades. (n.d.). https://www.nmmesa.org/wp-content/uploads/2019/10/Aerodynamics-of-Wind-Turbine-Blades.pdf

Alternative energy Tutorials. (2024, March 16). Wind turbine blade design: Flat, bent or curved? https://www.alternative-energy-tutorials.com/wind-energy/wind-turbine-blade-design.html

"Blade Design Considerations of Small Wind Turbines: From Classical to Emerging Bio-Inspired Profiles/Shapes."(23 Nov 2022.) https://pubs.aip.org/aip/jrse/article/14/4/042701/2848659/Blade-design-considerations-of-small-wind-turbines

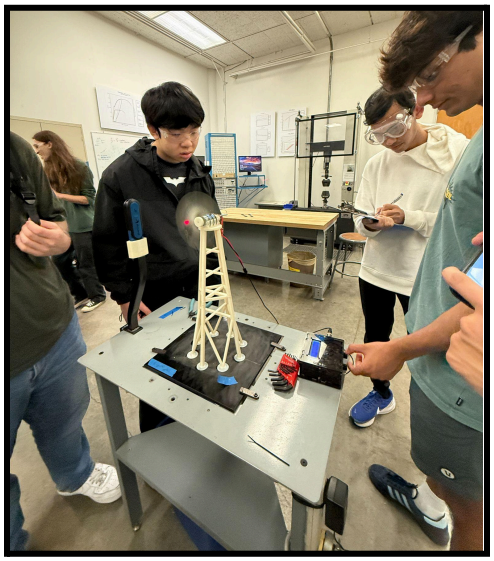
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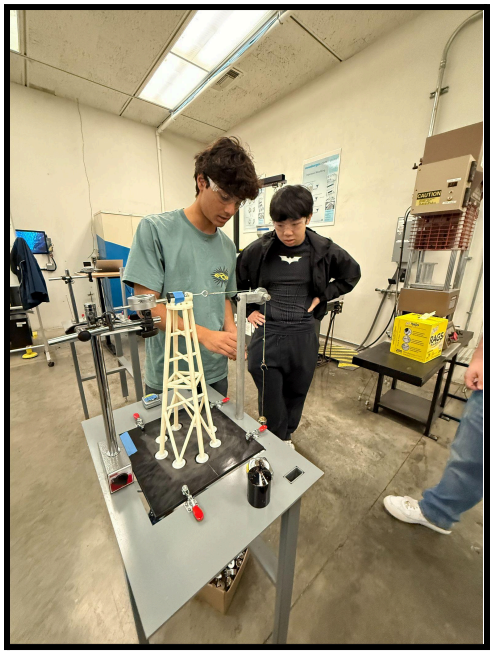
Why Do Wind Turbines Have Three Blades? https://www.sciencefocus.com/science/why-do-wind-turbines-have-three-blades

Appendix

Appendix A



Engineering 26 Group 28 Testing Day 12/9/2025 Blade Efficiency

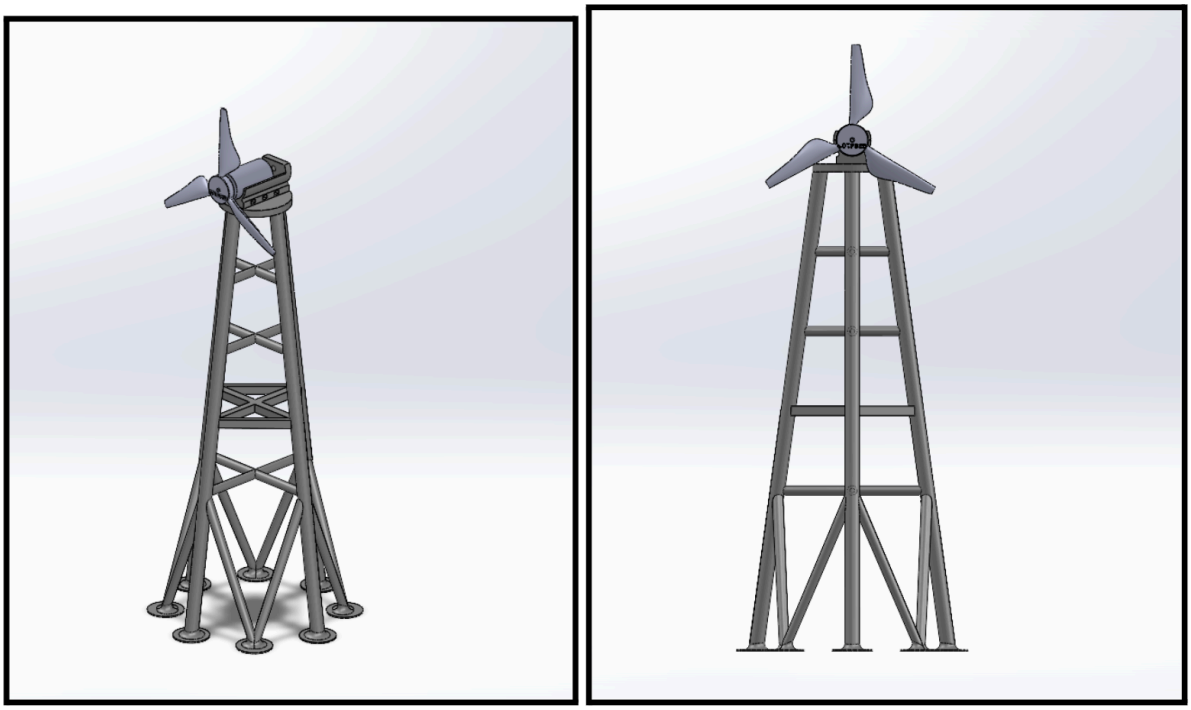


Engineering 26 Group 28 Testing Day 12/9/2025 Durability Test

Appendix B

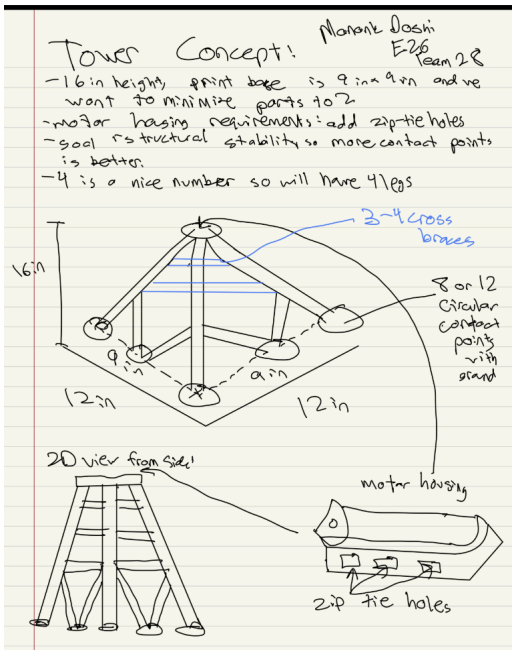
Row	Voltage (V)	Current (mA)	Power (mW)	RPM	Notes (Ohms)
0	2.03	37.8	76.7	2585	53.8
1	2.08	43	89.5	2682	49.6
2	2.11	46.2	97.4	2741	42
3	2.06	46.3	95.3	2718	37
4	2.12	47.4	100.5	2816	34.6
5	2.21	61.1	135	2934	31
6	2.29	63.8	146	3047	28
7	2.47	97.2	240	3191	23.7
8	2.62	164.1	430	3386	21.5
9	2.74	204.8	561	3542	18.3
10	2.86	288.1	824	3728	15.2
11	2.92	351	1025	3887	12.4
12	3.02	411.3	1242	4046	9.3
13	2.94	341.1	1003	3861	6
14	2.39	192.1	459	3468	3.1
15	1.83	116.4	213	2529	0.4

Raw Data Set, 15 different Testing points, took measurements in: Voltage, Current, Power, Rotations per Minute and Notes.



Computer Aid Design (Soldworks) 3d Model of Tower

Appendix C



Original tower design concept, hand drawn by Manank Doshi in early stages of development

Appendix D

https://www.nmmesa.org/wp-content/uploads/2019/10/Aerodynamics-of-Wind-Turbine-Blades.pdf

Very helpful information on wind turbines and blade geometry

Appendix E

Link to solidworks files:

https://drive.google.com/drive/folders/1zxu8yJST4LR-JlLj5kMYIQybbadp0MMY?usp=sharing