Eiffel Turbine — Final Project Report

Department of Mechanical Engineering, University of California, Berkeley

ENGIN 26: Three-Dimensional Modeling for Design (Fall 2023)

Professor Kourosh Youssefi

Group 22: Aarush Panda, Arundhati Parikh, Daniel Lee, Laney Fong,
Paulina Rosales, Sahaj Sidhu, Tam Tran

December 08, 2023

Project Summary (Aarush)

In this project, a team of seven students explored the engineering principles underlying the effective harvesting of wind energy for electricity generation. The objective was to design, construct, and test a miniature wind turbine that would generate the maximum amount of power possible within the imposed constraints.

The first step was to design the turbine blades. In order to maximize power generation, curved blades were chosen as they would create a greater amount of lift. The blades were also limited to a maximum length of three inches to comply with the dimensional constraints of the project. The next step was to design the turbine's support tower. It was important to ensure that the tower was strong enough to support the weight of the turbine, but it was also necessary to keep the overall volume of the tower under 17 in^3. The motor housing was the final component of the turbine. The housing was designed to accommodate the specified motor generator, and a 3/16-inch hole was included for a bolt to be aligned with the motor's shaft.

Once all of the components of the turbine had been designed, finite-element analysis (FEA) testing was conducted in SOLIDWORKS to determine the stiffness and deflection of the tower. The results of the FEA testing indicated that the tower was sufficiently stiff to support the weight of the turbine and would not deflect significantly under load. The tower was constructed in two separate parts due to limitations of the 3D printer. A support plate was also provided for the tower assembly.

Physical testing was conducted on the turbine to measure its power output and rigidity. The results of the testing indicated that the turbine was capable of generating a maximum power output of 0.3908 watts. The turbine was also able to withstand a load of 1 kg with only a 0.94 millimeter deflection. The overall weight of the tower was 253.3g.

Overall, the results of the project were very satisfactory. A miniature wind turbine was successfully designed, constructed, and tested in that it was capable of generating a significant amount of power. The project also provided the participating students with a better understanding of the engineering principles underlying wind energy generation.

Table of Contents

Introduction (Paulina)

Since the Industrial Revolution, humans have started looking for and developing new energy sources to power the machinery being used. However, sources of energy such as coal have provoked immense destruction to the environment. Because of this, engineers have been looking for solutions to minimize the damage to our surroundings, resulting in the development of wind turbines as an improvement in the source of renewable energy.

Figure 1. Wind turbine

The use of wind turbines as a source of energy has been increasing throughout the years in the U.S. At the end of the 1800s, the first U.S. wind company was established and wind power was utilized by farm owners for irrigation purposes and provided electricity for homes and businesses. After that, wind power started to be part of the total energy contribution for the whole country. By 2022, wind turbines contributed as much as 10.2% of the country's utility-scale electricity generation. Along with this energy contribution, there were a lot of improvements in the development of the turbines, which contributed to the increment of the total energy that is being produced by each wind turbine.

A wind turbine has a dynamic that consists of using the blades as its main source to produce energy. These blades are moved by the wind, which causes them to spin a generator that is connected to it located in the housing and therefore, creates energy. The taller the wind turbine is, the wind speed increases, converting into more energy.

Figure 2. Inside of a wind turbine generator housing

Despite being a good source of energy, it also has challenges and many specifications when manufacturing these turbines that need to be taken into consideration to make it effective, affordable and minimize the error percentage.

For this course project, the team needed to design, build, and test a small-scale wind turbine by overcoming the challenges that this type of source of energy requires. Along with this, it was also taken in mind the goals of performance to achieve with the final design: a power of more than 2 Watts, stiffness of more than 8 N/mm, and a weight of less than 350 grams. To achieve this, the team researched to maximize the design potential by considering the following factors:

Blade Count

The number of blades in the turbine rotor would determine the performance of the wind turbine. Having an even number of blades would cause the turbine to be less effective than having an even number of blades, causing stability issues, and adding extra maintenance in the structure. To determine the total amount of blades, it is necessary to consider the weight that will contribute to the overall weight.

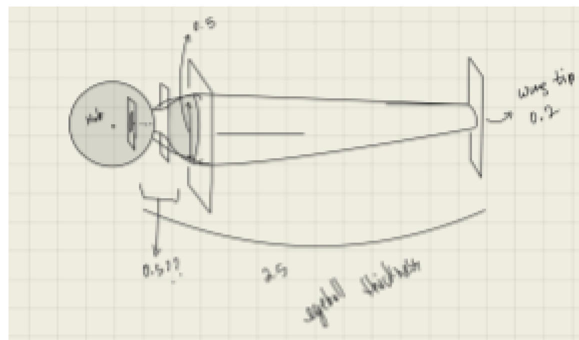


Figure 3. Initial draft of the blades by Sahaj

Blade Profile

Different blade profiles, such as curve and flat profiles, contribute in different ways to the blade design. Curve profiles allow more air to go along the curved ends and increase the rotational motion, but it can create friction of air against the blade if not designed well. Flat profiles are easier and cheaper to manufacture, but it has a low performance when generating electricity.

Angle of Attack

The purpose of this angle is to determine the flow of the wind that is hiding the blades of the wind turbine. It also determines the amount of lift at different wind speeds. The range for a good angle of attack is 10 to 15 grades. Surpassing this will decrease the performance and failing to reach this range will decrease the rotational motion of the turbine rotor blade.

Angle of Blade Twist

This specific angle helps the angle of attack to reduce stress. Along with that, it also helps the blade to reduce weight, which can reduce the cost of manufacturing and minimize the chances of damaging the tower because of the excessive weight.

For the tower design, it was taken into consideration by the team that it needed to be solid enough to resist the wind that was going to be faced by the wind turbine for testing and pass the stiffness in tension (>8 N/mm). To maintain a high stiffness, it was necessary to increase the area moment of inertia.

Besides the tower and the wind turbine blades, it was also asked to build the housing for the motor. For this, it was provided to the team the necessary measurements from the motor that was going to be utilized for the testing in order to design the housing. This housing was stated to be positioned at the top of the tower to maximize the production of energy.

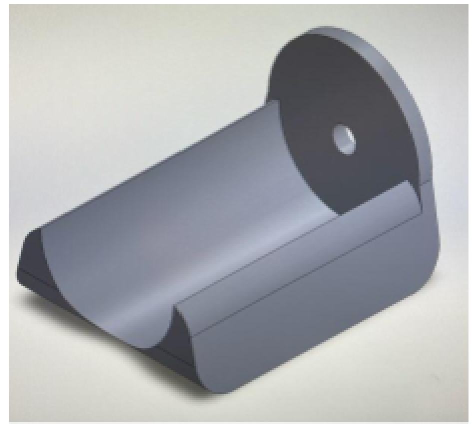


Figure 4. CAD design for the housing for the motor

Additional considerations for the overall design were that it needed to be divided into parts due to the limitations of the 3D printer that was going to be used, the base of the tower needed to be smaller than the plastic plate that was going to be placed (12 x 12 inches), and for the housing, it needed to have a 3/16 inches hole at the back for the motor to be inserted.

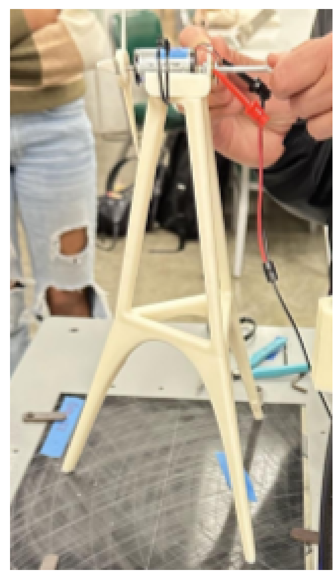


Figure 5. Attaching the motor to the wind turbine assembly before testing

The team gathered different design ideas for both the turbine rotor blades and the tower with the generator housing. It concluded that the general design would have 3 blades with a curved profile, an angle of attack of 15° degrees, and a twist of 21°. Besides that, other specifications needed to be followed. The tower was required to be 16 inches from the bottom of the tower to the center of the motor shaft with a volume of 17 cubic inches. For the turbine rotor blades, it was required to have a maximum of 3 inches for each blade.

Design

Blade (Arundhati):

In order to design the rotor, we took into account our combined research on various factors such as number of blades, blade length, angle of twist, angle of attack, and more. Based on our findings, we came up with the following design in order to optimize performance:

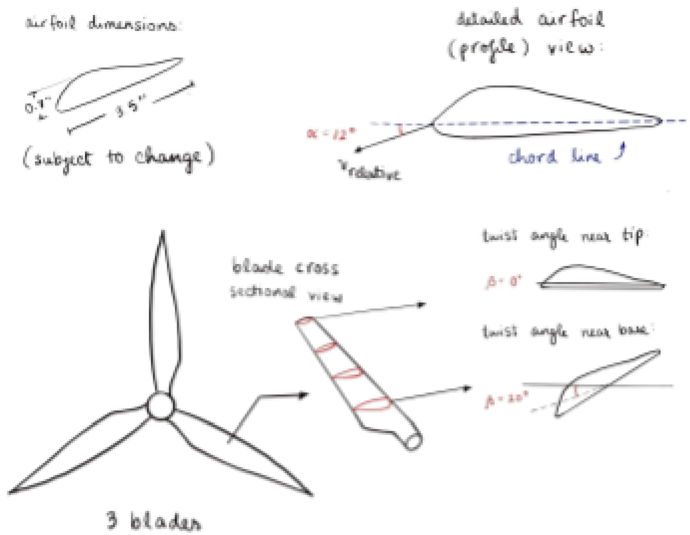


Figure 6. Initial blade design

To summarize, our final rotor design incorporated 3 blades, a blade length of 2.50” to meet the given design constraints, an angle of twist of 21°, and an angle of attack of 15° (slightly more than intended so that the loft feature could successfully render).

Although a turbine with 1-2 blades would theoretically have the least drag, the graph to the right (from a paper from the IOP Conference Series titled “[The Effect of the Number of Blades on the Efficiency of A Wind Turbine]”) shows that having fewer blades comes at the cost of reduced swept area, and therefore, less power generated overall. Additionally, we wanted to avoid having an even number of blades since this has been proven to reduce overall stability.

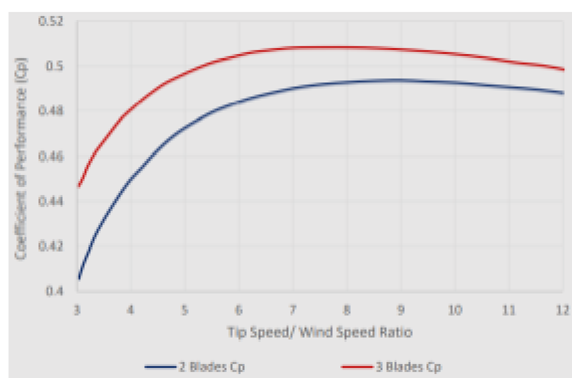


Figure 7. COP vs. Tip/Wind Speed Ratio for a 2-blade and 3-blade rotor

After the number of blades had been confirmed, our next priority was maximizing blade length — the longer the blades, the greater the rotor's total swept area, with the added benefit that longer yet slimmer blades encounter less drag than shorter yet wider blades. The final blade length (2.5") was the highest possible value that still ensured the rotor's diameter did not exceed 6". Once that had been finalized, the angle of twist and attack were next to be determined.

Figure 8. Screenshot from SolidWorks showing angle of attack

Ideally, our angle of twist (β) and angle of attack (α) should have equalled 20° and 12° respectively. However, in order for the geometry to comply with both the given constraints (maximum rotor diameter, the height of the hub, 3D-printing limitations) and our previously determined values for blade count and length, the best compromise was setting $\beta = 21°$ and $\alpha = 15°$.

Once the geometry of the rotor had been established, the last factor that remained was the shape of the blade, or the airfoil. In hindsight, this definitely should have been selected before the blade length and other geometry was set since it is arguably the most important characteristic with regards to the efficiency of a wind turbine. The following excerpt from the NM MESA paper "Aerodynamics of Wind Turbine Blades" summarizes why the airfoil shape has such a large impact on turbine performance: "[t]he airfoil shape of the blade helps to generate lift by taking advantage of the Bernoulli effect … Even minor changes in this blade shape can dramatically affect the power output produced by a wind turbine," since the airfoil is designed for the air above the blade to move faster than the air below (creating a pressure gradient that ultimately results in a lift force). Preliminary research on airfoil design showed that the camber (or curvature) of the airfoil was highly situation-dependent, so we ended up selecting a symmetric airfoil since we weren't sure whether positive or negative camber was better for our wind turbine.

Once all of the blade specifications were set, we created the following model in SolidWorks:

We used multiple reference planes as well as the loft feature in SolidWorks to create the blade, and the circular pattern feature to ensure that the blades were equidistant. After filleting the edges and embossing our group's information on top of the hub, the rotor was ready to be printed!

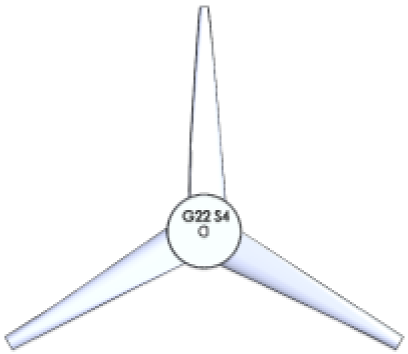


Figure 9. Final rotor design

Tower (Tam):

The final tower design took some inspiration from the Eiffel tower as a proven geometry (Fig. 10). The three-legged design was chosen for maintaining radial symmetry while also providing good stability for supporting loads and potential shearing forces. The tower itself had to be able to withstand shearing forces from 25 mph winds while also minimizing deflection at the top to maintain optimal airflow through the turbine blades. Due to the limitations of the 3D printer requiring a modular design, the bottom section was chosen to be slightly shorter and have more material to provide extra stability.

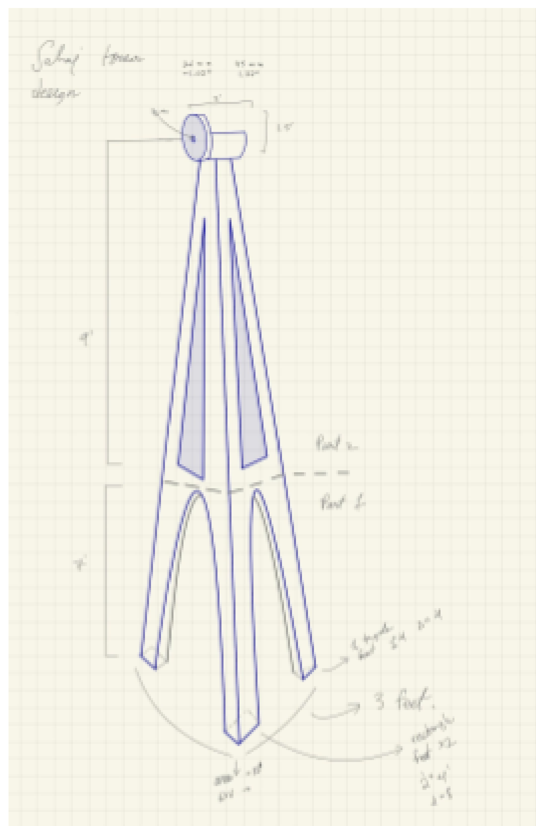


Figure 10: The initial tower design sketch.

The final tower CAD, which was done in Solidworks, very closely resembles the design sketch, with some slight modifications (Fig 11). The top-down cross section was an equilateral triangle to be radially symmetric, resulting in the feet being changed to fit this profile. The top structure was made more open for the sake of allocating more material to the support struts. The motor hub was placed in the cutout at the top, which was given a flat base to sit flush with the top structure. Fillets were also heavily utilized to improve the tower's profile against the wind and provide more effective support where needed. To improve the ease of printing and assembly, the bottom and top structures were each split into three modular sections. In addition, basic male-female coupling systems were added to each section to ensure proper alignment when assembling.

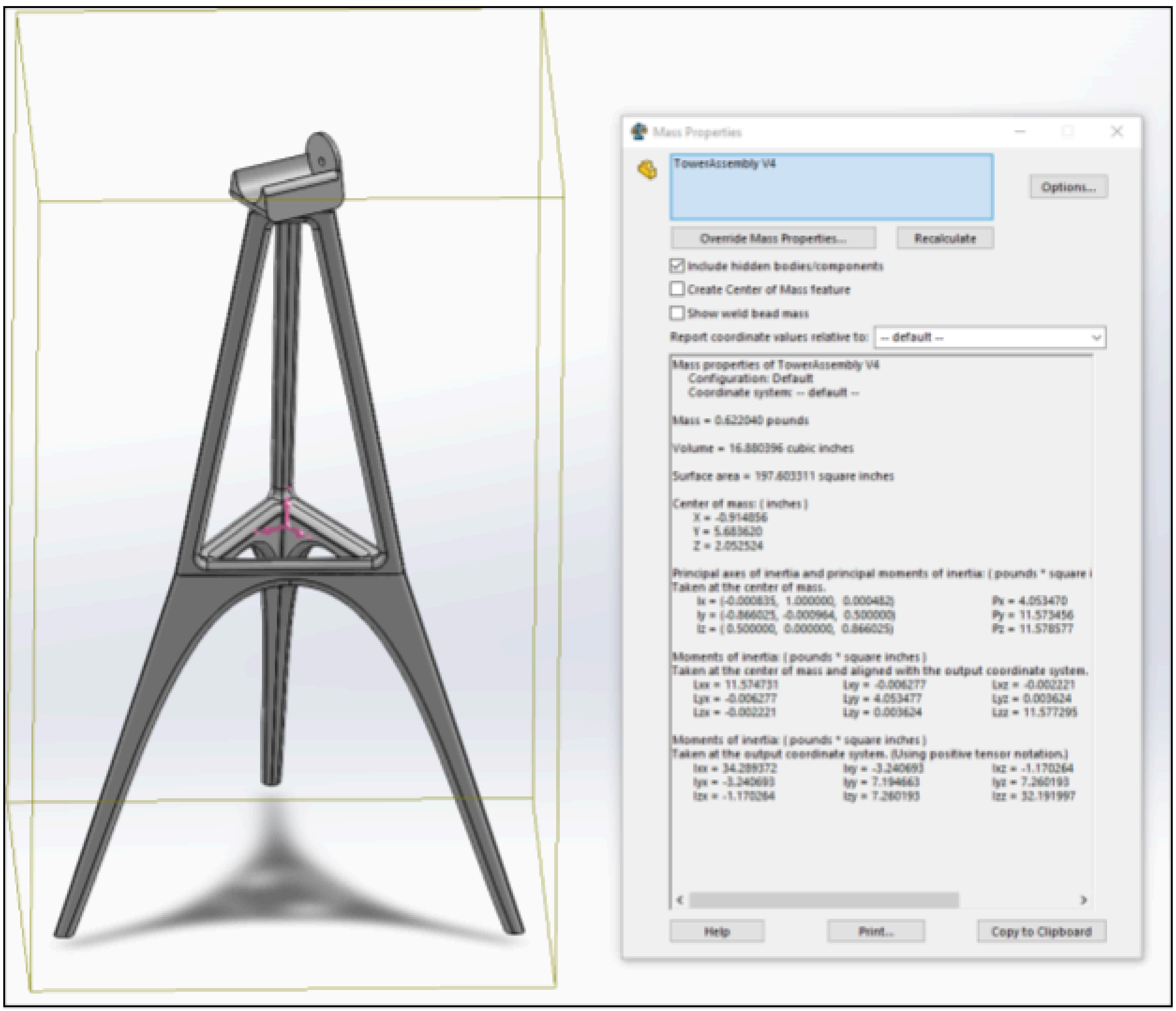


Figure 11: The final turbine tower CAD assembly.

Finite Element Analysis (FEA) was conducted using Solidworks Simulations, and no changes were needed when meshing the tower assembly. Analysis conditions were that the material was acrylic, with fixed geometry for the tower feet and a 9.81 N force applied at the inner face of the motor housing (Note: while the tower was made of ABS, Solidworks does not have a defined yield strength for it, hence why acrylic was used instead). Maximum displacement was measured to be 0.2145 mm at the top of the motor hub (Fig. 14). The tower support structure distributed stress relatively well, but a high amount of stress was experienced between the motor hub back plate and the cutout for holding the motor, which would likely become a point of failure if enough force was applied (Fig. 11). The factor of safety (FOS) was well within acceptable limits though, with the whole tower meeting the minimum FOS of 3 (Fig. 13).

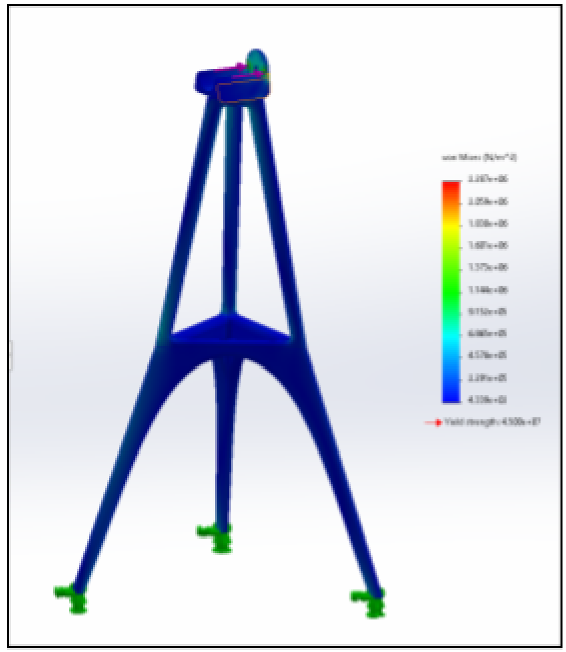


Figure 11: The FEA stress plot.

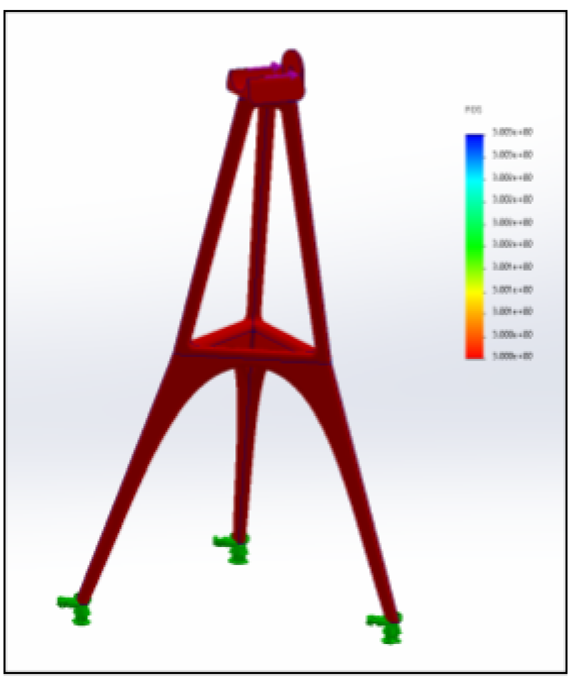


Figure 12: The FEA Factor of Safety plot.

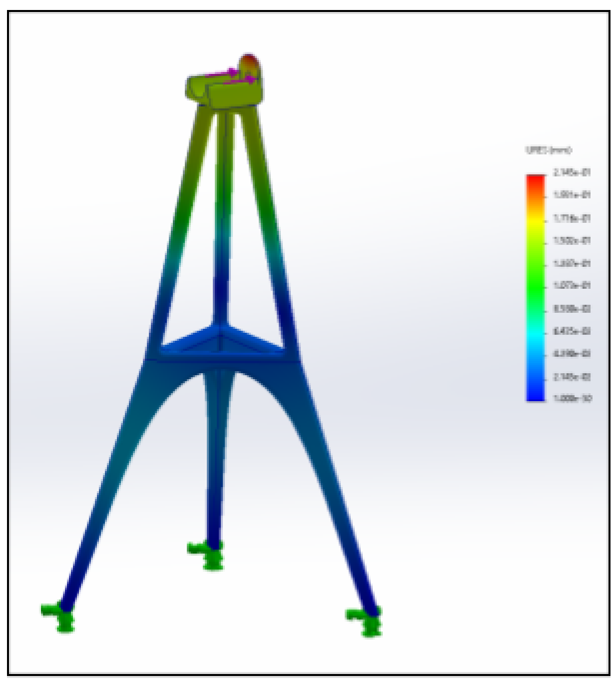


Figure 14: The FEA deflection plot.

Testing and Results (Sahaj, Aarush)

Our first experiment tested the amount of power the turbine outputs. First the turbine was secured into the test bench using ABS slab, which clamped down into the bench using an allen key (Fig. 15). Once secured, the distance between the tower and the fan was measured using a measuring tape. Then, an anemometer was placed in front of the fan in order to measure the speed of the wind, 25 miles/hr (Fig. 16). Wind produced by a wind blower and with the higher fan speed setting (Fig. 17).

After the initial reading from the anemometer, it was put to the side. Then we mounted our motor and the fan. One of the blades then was marked with a locator tape. This tape was used for the tachometer mounted adjacent to the fan which collected our turbine's rpm (Fig. 18).

The data collection for power, input and output was performed through a power meter (Fig. 19). The power meter was turned to an open circuit. Then we use two potentiometer knobs to control the ohms. One knob gave us control over 50 ohms with increments of 5 and then another knob provided more precise control on 10 ohms with increments of 1. We started from the lowest setting working our way up to see where the power output peaked. We recorded data until the peak power and then a few more points after to make sure the power dropped after. We used the power meter for the current, power, voltage and the RPM was collected from the tachometer.

The second experiment was the deflection test. This test simulated the amount of displacement the tower would undergo under heavy wind currents. This load was simulated using 100g weights. These weights were attached using a pulley system and the hook located at the back of the turbine. We secured our tower the same as before, then attached the pulley to the back of the tower. We then replaced the power piece with a plastic placeholder. We then aligned a digital indicator with the motor and pushed against the plastic placeholder. Finally, the indicator was zeroed and we started to add weight to the pulley. The weight was added in 100g increments and the data was recorded at every increment. We worked our way to 1kg, however, when 2kg was added to the pulley, the clamps on the test bench gave up so our test was stopped there.

Fig. 15.

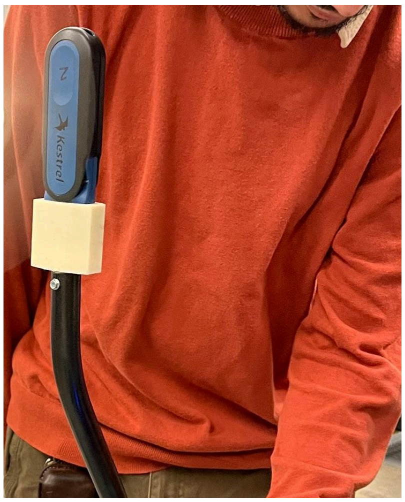


Fig. 16.

Fig. 17.

Fig. 18.

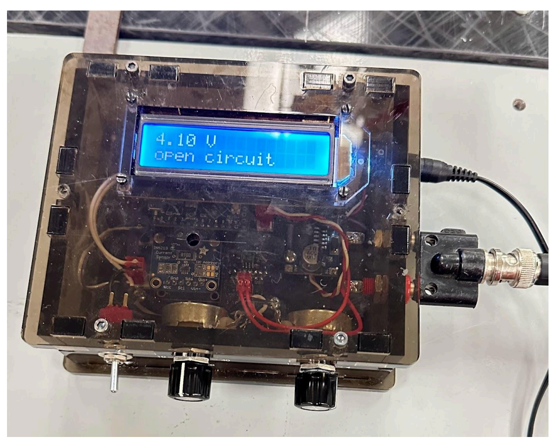


Fig. 19.

Stiffness Data

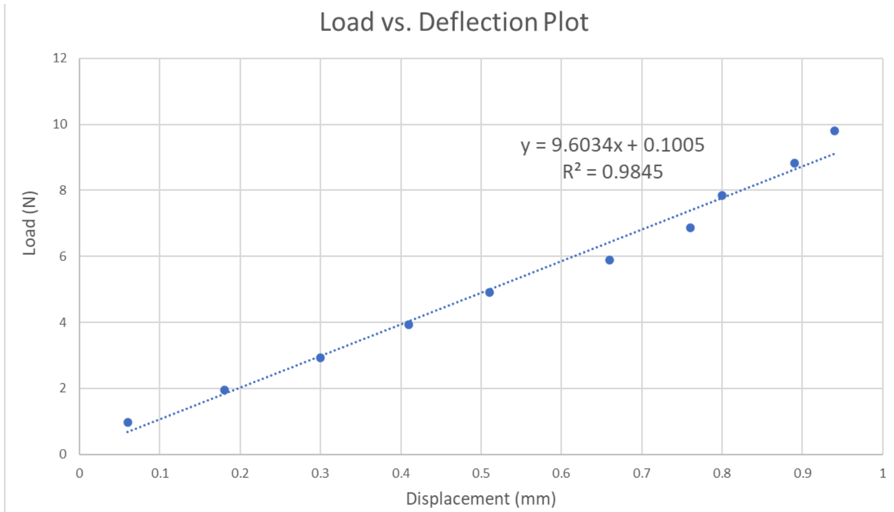
Data Points	Load (N)	Load (Kg)	Displacement (mm)
1	0.98	0.1	0.06
2	1.96	0.2	0.18
3	2.94	0.3	0.3
4	3.92	0.4	0.41
5	4.9	0.5	0.51
6	5.88	0.6	0.66
7	6.86	0.7	0.76
8	7.85	0.8	0.8
9	8.83	0.9	0.89
10	9.8	1	0.94
11	19.61	2	3.73

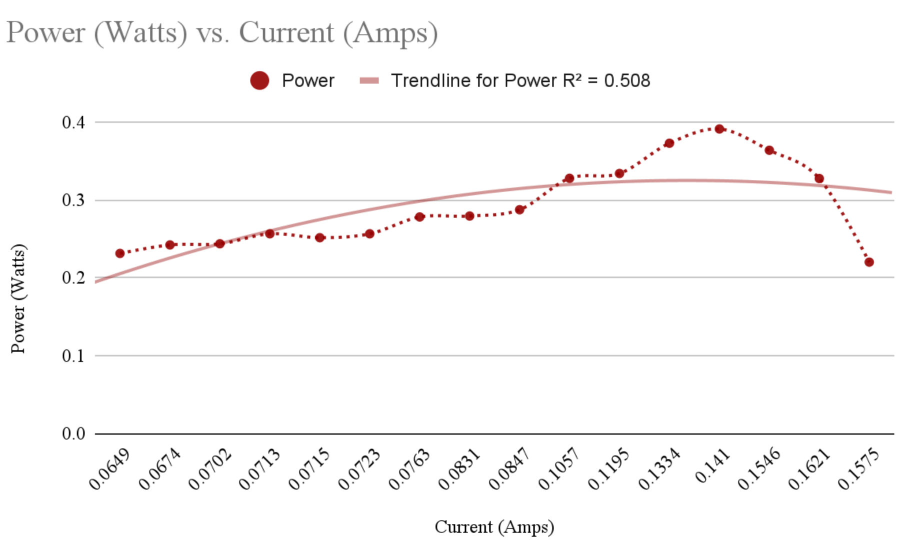
*Note: Upon applying 2 kg, the base that the tower was attached to shifted. As such, this data point may be inaccurate and has not been included in the load vs. displacement plot.

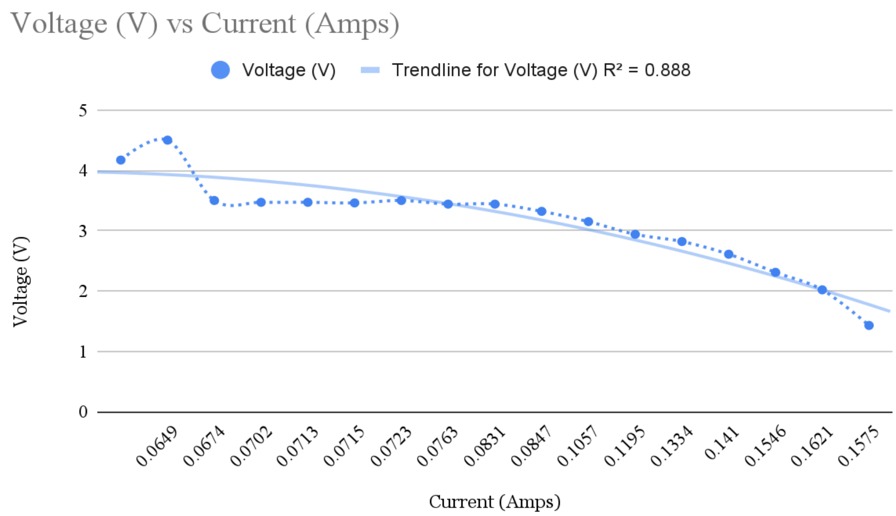
Power Data

Data Points	Voltage (V)	Current (Amps)	Power (V)	Blade Speed (rpm)
0	4.17			5853
1	4.5	0.0649	0.2311	5134
2	3.5	0.0674	0.242	5134
3	3.47	0.0702	0.2435	5125
4	3.47	0.0713	0.2563	5090
5	3.46	0.0715	0.2513	5070
6	3.5	0.0723	0.2563	5050
7	3.44	0.0763	0.2779	4990
8	3.44	0.0831	0.2791	4950
9	3.32	0.0847	0.2872	4869
10	3.15	0.1057	0.3275	4695
11	2.94	0.1195	0.3337	4371
12	2.82	0.1334	0.3725	4200
13	2.61	0.141	0.3908	4050
14	2.31	0.1546	0.3635	3646
15	2.02	0.1621	0.3272	3211

16	1.43	0.1575	0.21992	2339







To calculate the efficiency of our wind turbine, we used the formula for wind power to find the theoretical power of our turbine, and then compared the obtained values to the experimental power we found from our trials.

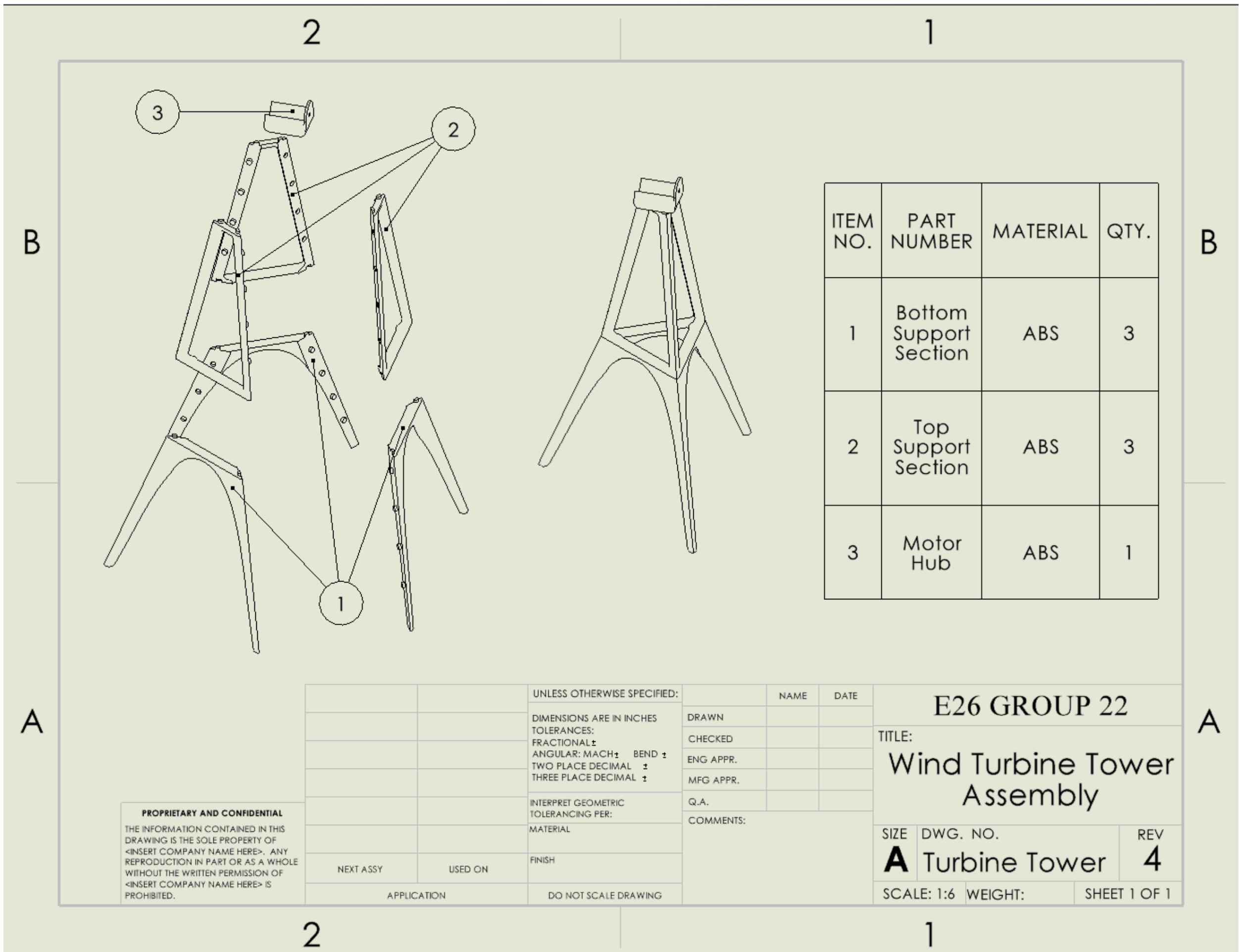
Wind Power Formula: $P_{wind} = \lambda * 0.5 * A * \rho * v^3$. In this formula, P_{wind} represents the theoretical wind power, λ represents the Betz coefficient (maximum possible wind efficiency of a turbine), A represents the swept area of all of the turbine blades combined, ρ represents the air density, and v is the wind speed. Λ is a constant value of 59.3%, or 0.593.

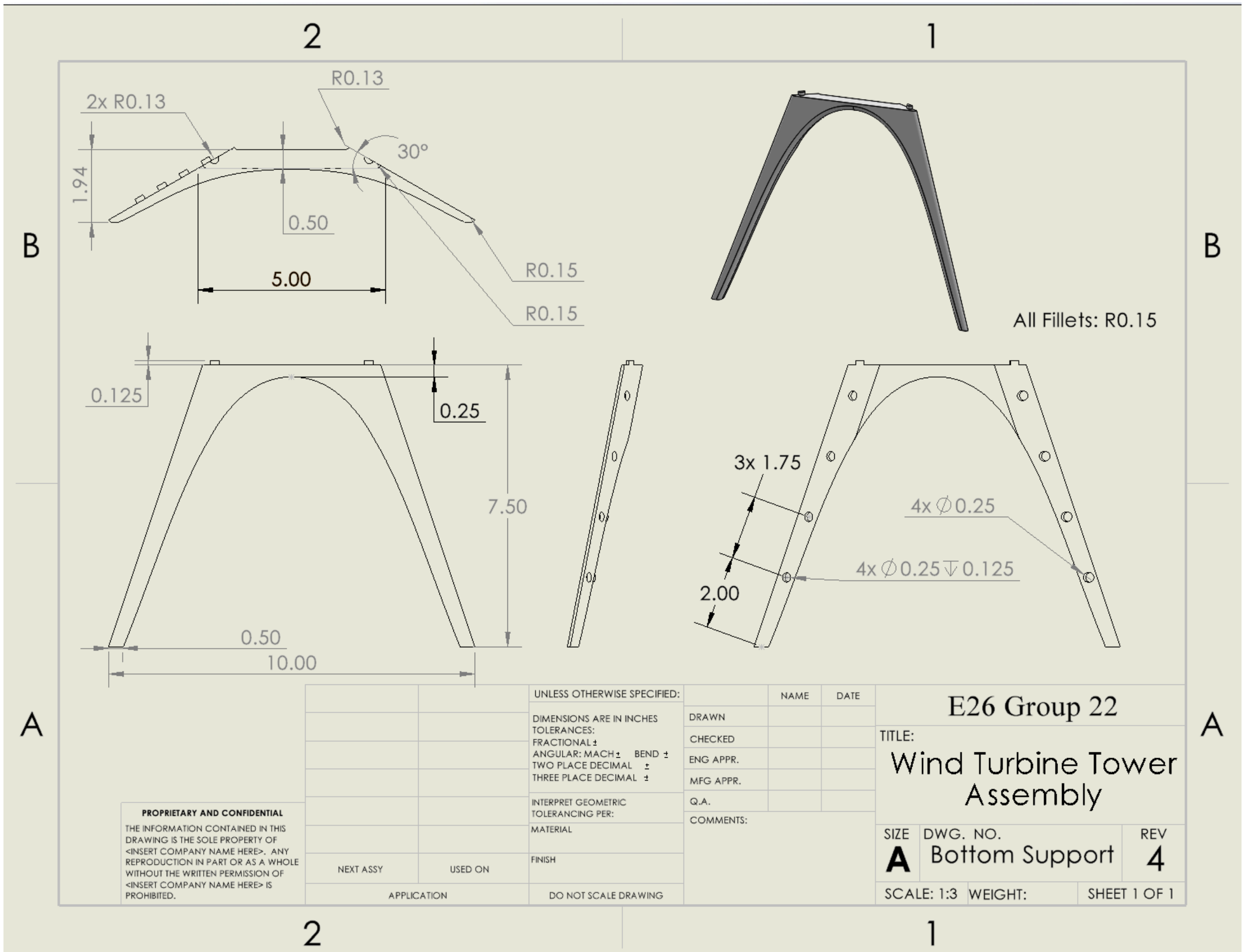
We must convert the wind speed from mph to m/s. We can do this by multiplying the wind speed by 0.44704, the conversion factor for miles per hour to meters per second. We get 25.7 * 0.44704 = 11.4972 m/s.

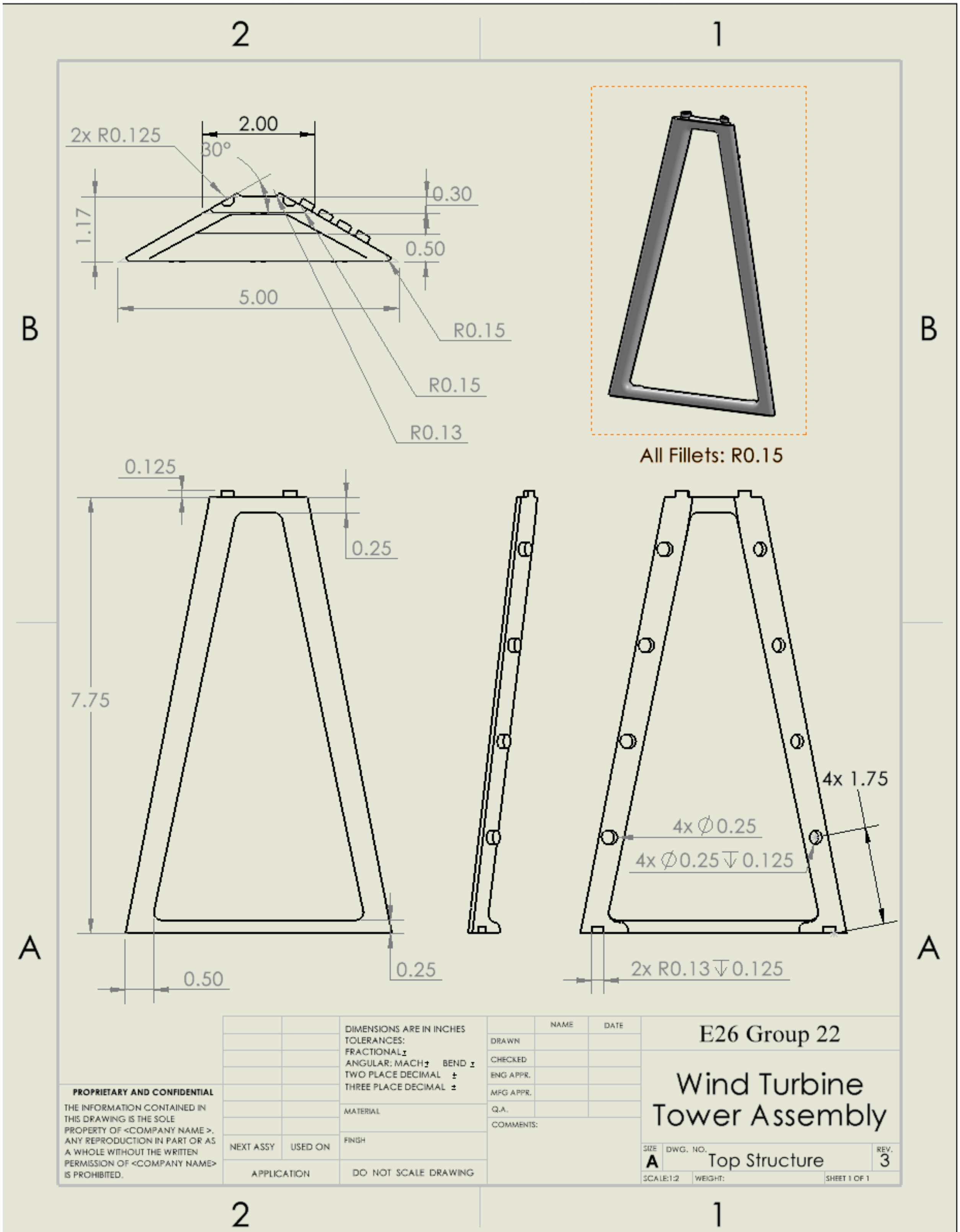
We must also convert the swept area of the wind turbine blades combined to m^2. Multiplying 3.2751 in^2 (1.0917*3 since each turbine blade has an area of approximately 1.0917 in^2) by 0.0254, the conversion factor for in^2 to m^2, gives us 0.0211 m^2, the total area of the wind turbine blades. With all our values being converted into equal units, we can substitute 0.0211m^2 for A, 1.293 kg/m^3 for ρ, and 11.4972 m/s for v. Our new equation becomes $0.593 * 0.5 * 0.0211\ m^2 * 1.293 * 11.4792^3$. Simplifying this, we get that P_{wind} is equal to 12.236 watts .

Finally, to calculate the efficiency, we must divide this obtained theoretical power value of 12.236 watts by our peak experimental power of 0.3908. This results in 0.3908 watts / 12.236 watts = 0.0319. Thus, we can conclude that our wind turbine's efficiency was 0.0319, or about 3.19%.

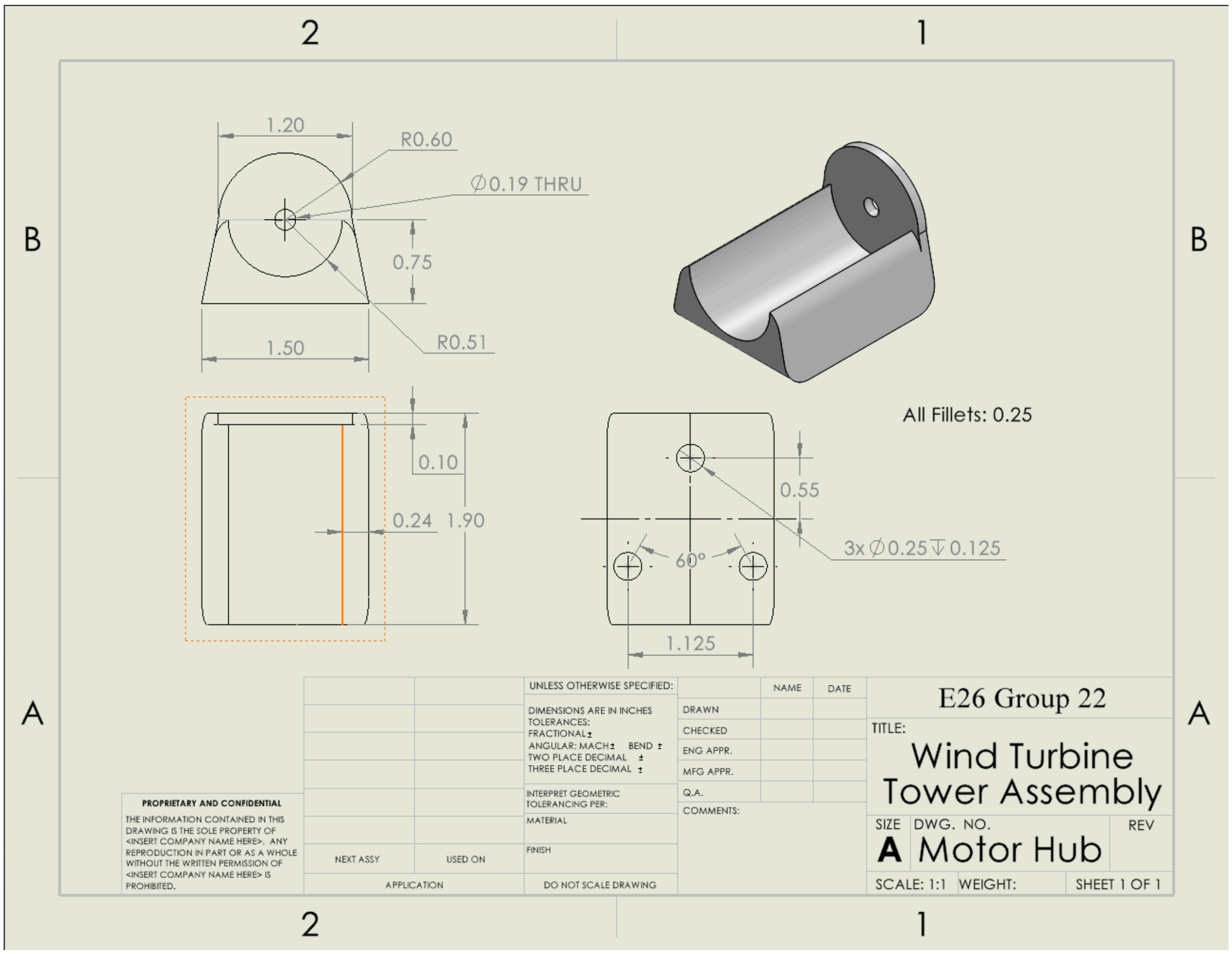
CAD Drawings




2x R0.13
R0.13
30°
1.94
0.50
5.00
R0.15
R0.15
All Fillets: R0.15
0.125
0.25
7.50
0.50
10.00
3x 1.75
4x ∅0.25
4x ∅0.25 ↧ 0.125
2.00
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
E26 Group 22
TITLE:
Wind Turbine Tower Assembly
SIZE A
DWG. NO. Bottom Support
REV 4
SCALE: 1:3
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.



2
1
B
A
2x R0.125
2.00
30°
0.30
1.17
0.50
5.00
R0.15
R0.15
R0.13
All Fillets: R0.15
0.125
0.25
7.75
0.25
0.50
4x 1.75
4x ∅0.25
4x ∅0.25 ↧ 0.125
2x R0.13 ↧ 0.125
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
MATERIAL
FINISH
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <COMPANY NAME>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <COMPANY NAME> IS PROHIBITED.
E26 Group 22
Wind Turbine Tower Assembly
SIZE A
DWG. NO. Top Structure
REV. 3
SCALE:1:2
WEIGHT:
SHEET 1 OF 1


1.20
R0.60
∅0.19 THRU
0.75
1.50
R0.51
0.10
0.24
1.90
0.55
3x ∅0.25 ↧ 0.125
60°
1.125
All Fillets: 0.25
E26 Group 22
TITLE:
Wind Turbine Tower Assembly
SIZE A
DWG. NO.
Motor Hub
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.

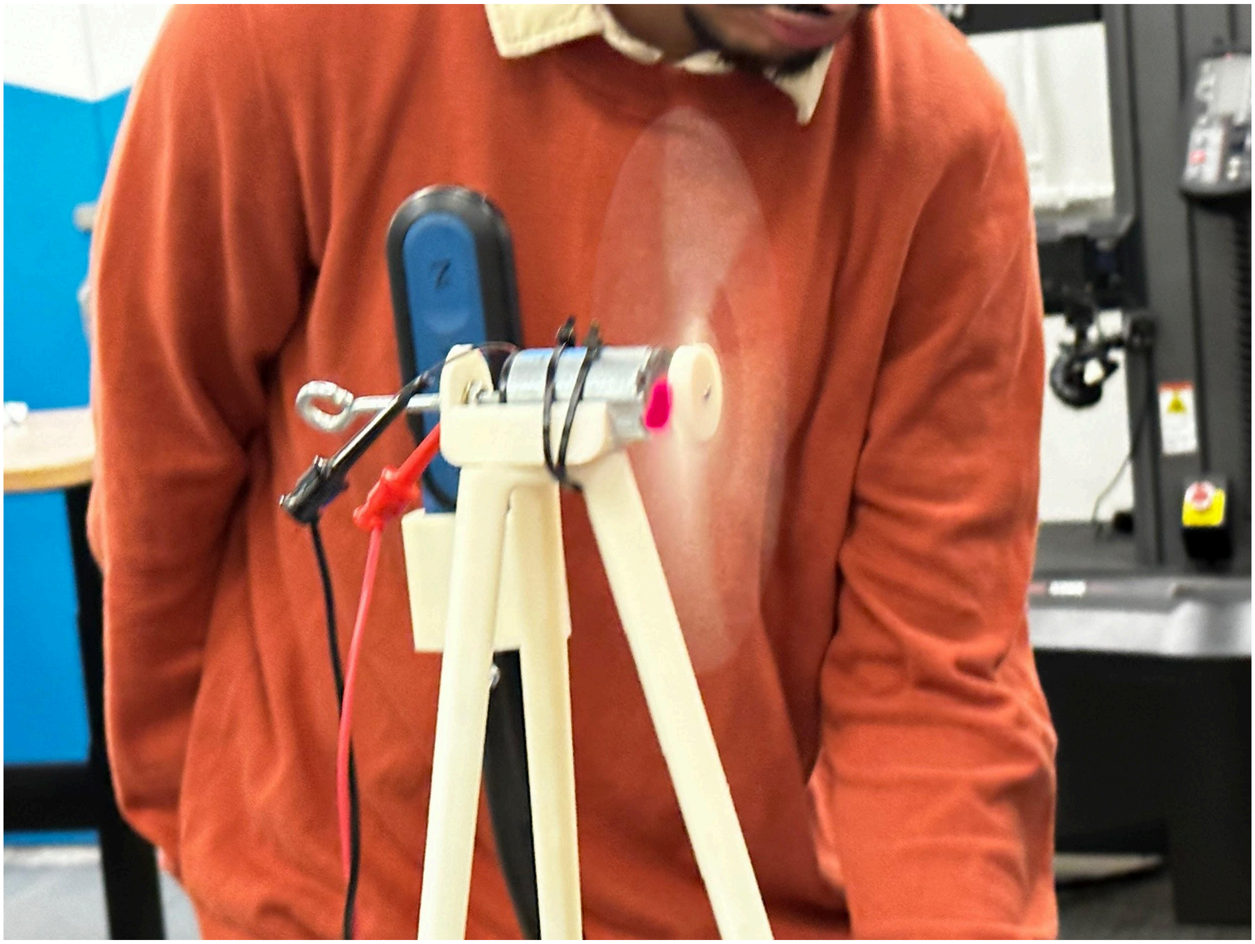
Conclusions (Laney)

In summary, the team's project involved the design, construction, and testing of a small-scale wind turbine, aiming to contribute to the ongoing efforts towards sustainable energy solutions. The design process considered critical factors such as blade count, profile, angle of attack, and blade twist while it also addressed challenges in tower design and motor housing. The testing phase, conducted by the team, provided valuable insights into the turbine's performance through load-displacement data, voltage, current, power, and blade speed measurements.

Throughout this project, the team gained pertinent revelations into the complexities of wind turbine design and manufacturing. The importance of balancing these various factors, such as blade dynamics and tower stability became apparent when reflecting on the complex relationship between engineering principles and practical considerations. The Finite Element Analysis (FEA) simulations provided a deeper understanding of the deflection and stiffness of the wind turbine tower. This contributed to the team's knowledge in structural analysis.

The outcome of this project was multifaceted as the wind turbine the team built was designed to meet specific performance goals. While we were able to achieve a stiffness value exceeding 8 N/mm and a weight below 350 grams, the efficiency calculation, comparing theoretical and experimental power values, shows that the turbine's efficiency was approximately 3.19%, which may leave something to be desired.

In conclusion, the project highlighted the significance of interdisciplinary collaboration, incorporating design principles, engineering analysis, and testing methodologies. The project created by the team contributes to the broader field of renewable energy by addressing the challenges associated with wind turbine technology. The experience not only enhanced the understanding of wind energy but also highlighted the need for continuous innovation and refinement in sustainable energy projects. As society continues to prioritize cleaner and greener alternatives, the insights gained from this project are valuable contributions to the ongoing efforts for a more sustainable future.



Recommendations for Future Work (Sahaj, Daniel)

Moving forwards, one major issue that needs to be reworked is the location of the motor housing. In this current iteration (see Fig. 20) , the blades lay on the same side as the third leg, however the blades need to lay on the opposite side of the third leg. In the future, the protruded third leg would decrease deflection against strong wind currents, making the tower design more stable.

Another issue that needs to be addressed is the fan hitting the tower (see Fig. 20) . In the real world, this would lead to catastrophic failure and damages. In order to avoid this, the blades would lay facing the opposite side of the third leg (same solution as before) . Since the tower is a triangular pyramid, the blades can sit alongside one of the flat faces on the tower, instead of the edge. Another fix would be to move the motor housing forwards so the blade has more clearance, this was our 'quick fix' (see Fig. 21).

Our blade also could have produced more power. As mentioned in the Blade Design subsection, our top priority was maximizing blade length when instead we should have devoted our time to implementing the most efficient airfoil shape. While choosing a symmetric airfoil was a safe option, a cambered airfoil would have been far more effective. In addition, we ended up changing our angle of attack slightly from what we had initially intended — if we stayed true to our original design, our turbine might have performed better.

One minor issue that we had run into while assembling our tower was the fitment of the parts. Aiming for a much more stable and rigid tower structure, we had decided on a modular system (similar to the interlocking system of lego bricks) to not only make the printing of the parts much easier but also to further reinforce structural integrity. Though the parts would fit together flawlessly in our renders, we did not account for any extra flashing or extra printed plastic that created irregular and imperfect measurements for the locking system. In the future, we would need to account for this by calculating a margin for error by the printer and decrease the diameter of the nubs that would lock in by around a millimeter or two.

Manufacturing is also a key component to look out for in the future. On a smaller scale, 3d printing does a great job printing structurally strong components. However if the scale is increased the manufacturing process would also change, the part would need to be broken down into smaller pieces. Each of the blades would be produced individually. The consistency and accuracy of each component becomes crucial. As this project states, uneven blades can lead to wobbles and vibrations which causes performance losses and shortens the lifespan on the windmill. This is where manufacturing becomes crucial, the best way to go about this would be molding with materials like fiberglass and carbon fiber. (source)

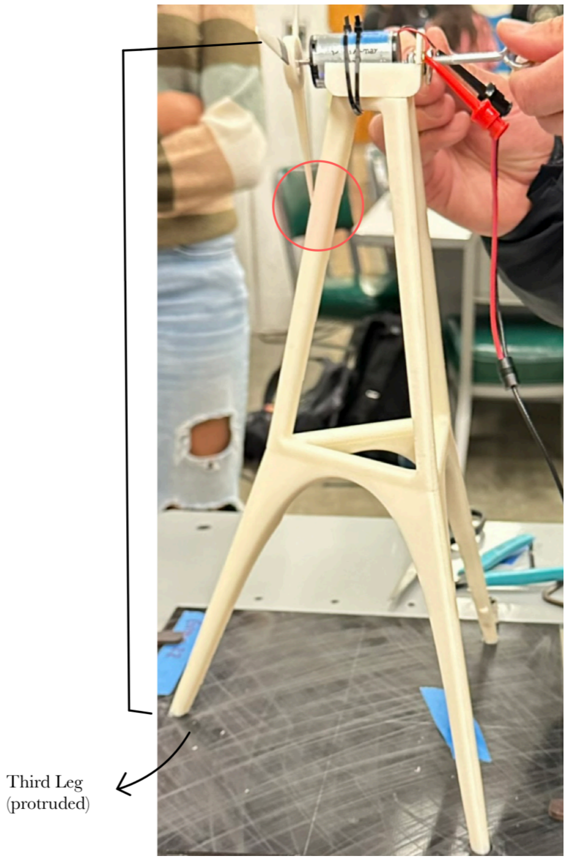


Fig 20. The protruded leg aligns with the blade. The red circle around the blade and the leg shows the clearance issues mentioned above

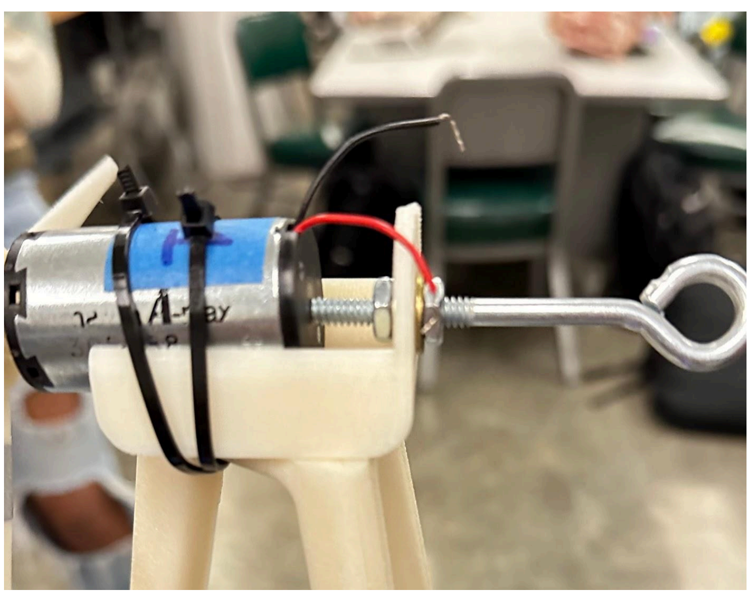


Fig. 21. Makeshift solution to the clearance issues. The metal hook pushes the motor forwards providing enough clearance for the face to work.

References

"4 Wind Turbine Rotor Design Issues." *Assessment of Research Needs for Wind Turbine Rotor Materials Technology*, National Research Council et al, National Academy Press, Washington D.C., 1991, pp. 67–80, https://nap.nationalacademies.org/read/1824/chapter/6.

Adeyeye1, Kehinde Adeseye, et al. "The Effect of the Number of Blades on the Efficiency of A Wind Turbine." *IOP Conference Series: Earth and Environmental Science*, IOP Publishing, 1 June 2021, iopscience.iop.org/article/10.1088/1755-1315/801/1/012020.

"Advantages and Challenges of Wind Energy." *Energy.Gov*, www.energy.gov/eere/wind/advantages-and-challenges-wind-energy. Accessed 8 Dec. 2023.

Aerodynamics of Wind Turbine Blades - NM Mesa, www.nmmesa.org/wp-content/uploads/2019/10/Aerodynamics-of-Wind-Turbine-Blades.pdf. Accessed 9 Dec. 2023.

AG, Infineon Technologies. "Wind." *Infineon Technologies*, www.infineon.com/cms/en/applications/renewables/wind/. Accessed 8 Dec. 2023.

"Bends, Twists, and Flat Edges Change the Game for Wind Energy." *Energy.Gov*, 23 Aug. 2023, www.energy.gov/eere/wind/articles/bends-twists-and-flat-edges-change-game-wind-energy#:~:text=As%20wind%20forces%20the%20blade,without%20added%20weight%20or%20expense.

"How Do Wind Turbines Work?" *Energy.Gov*, www.energy.gov/eere/wind/how-do-wind-turbines-work. Accessed 8 Dec. 2023.

"How Does a Wind Turbine Work?" *Energy.Gov*, www.energy.gov/how-does-wind-turbine-work#:~:text=Wind%20turbines%20operate%20on%20a,a%20generator%20to%20create%20electricity. Accessed 8 Dec. 2023.

"Optimized Blade Design for Homemade Windmills - Appropedia: The Sustainability Wiki." Appropedia.org, 2009, www.appropedia.org/Optimized_Blade_Design_for_Homemade_Windmills.

"O Que é Uma Turbina Eólica E Como Funciona." Iberdrola, www.iberdrola.com/sustainability/wind-turbines-blades#:~:text=What%20materials%20are%20used%3F.

Spivak, Randi. "Coal." *Center for Biological Diversity*, www.biologicaldiversity.org/programs/public_lands/energy/dirty_energy_development/coal/index.html#:~:text=Coal%20mining%20comes%20with%20a,the%20deterioration%20of%20drinking%20water. Accessed 8 Dec. 2023.

Schubel, Peter J., and Richard J. Crossley. “Wind Turbine Blade Design.” *MDPI*, Molecular Diversity Preservation International, 6 Sept. 2012, www.mdpi.com/1996-1073/5/9/3425.

Tangler, J., et al. “Seri Advanced Wind Turbine Blades.” *National Renewable Energy Laboratory*, U.S. Department of Energy, Feb. 1992, www.nrel.gov/docs/legosti/old/4492.pdf.

“Top 10 Things You Didn’t Know about Wind Power.” *Energy.Gov*, 24 Aug. 2023, www.energy.gov/eere/wind/articles/top-10-things-you-didnt-know-about-wind-power.

“U.S. Energy Information Administration - EIA - Independent Statistics and Analysis.” *Electricity Generation from Wind - U.S. Energy Information Administration (EIA)*, 20 Apr. 2023, www.eia.gov/energyexplained/wind/electricity-generation-from-wind.php#:~:text=Wind%20electricity%20generation%20has%20increased%20significantly&text=Total%20annual%20U.S.%20electricity%20generation,U.S.%20utility%2Dscale%20electricity%20generation.