ENGIN 26 Group 8 Wind Turbine Power Generation Project

University of California, Mechanical Engineering Dept. E26

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Figure 1: Final 3D printed tower after gluing.

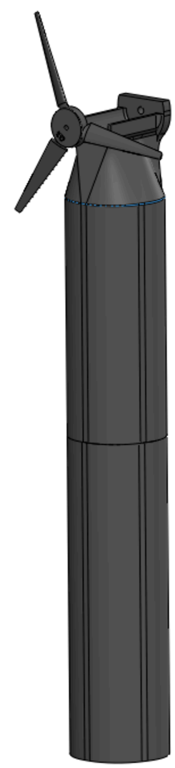

Figure 2: Colored 3D Model of Assembly

Project Summary

The objective of this project is to design, 3D print, and test a wind turbine that is capable of converting wind energy into electrical power while exploring various engineering principles involved. The three main components of the turbine are rotor blades, the support tower, and motor housing. After completing the design and manufacturing phases, the turbine was tested to evaluate its stiffness and power output. Evaluation of the turbine measured the power generation in watts and stiffness in N/mm of deflection.

We prioritized creating a tower that has low weight and volume, but is structurally sound. The final tower design weighed 192g, achieved a stiffness of 8.61 N/mm, while staying within the volume constraint of 17 inches^3 and allowing the motor to sit 16 inches above the surface. After initial brainstorming, we came to a decision to go with a filleted pentagon that resembles a cylinder for our support tower because of its stability and stiffness under FEA analysis.

In terms of power generation, we assessed the turbine's ability to convert wind power to electricity. Here, our design focused on balancing material and performance. By researching existing blade profiles used in industrial wind turbines as well as attributes such as angle of attack, angle of twist, and number of blades, we designed and iterated multiple blade prototypes to reach our final design, which during testing generated a peak of 0.48 watts of power.

Through the project, we designed, prototyped, iterated, and tested a functional, small-scale wind turbine while working with weight, volume, and material constraints. In the long term, future improvements include exploring different blade profiles, trying to further optimize the tower structure, and using other types of 3D printing materials. We were also able to acquire a strong understanding of the engineering design process through the multiple design iterations of the tower structure and blades. Starting off with defining and researching the problem, to actually assembling the project during gluing, and finally evaluating it during testing gave us a better understanding of what an engineering project entails and how a team can work together to accomplish some great results.

Figure 3: *Group Photo with Glued Tower*

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Introduction

Wind Turbine Fundamentals and History

Wind turbines are a modern evolution of a power source used for millennia. The use of wind energy has its origins in ancient civilization, and has been utilized in different ways throughout history, from sailboats in ancient Egypt and wind powered water pumps in China, to woven-reed windmills in Persia (U.S. Energy Information Administration, n.d.). However, unlike previous uses of wind power that use it for direct mechanical power, such as moving a vehicle or turning a grain wheel, modern wind turbines instead turn motors that generate electrical power.

Wind turbines are a modern evolution of humanity's long-standing practice of harnessing wind energy, now refined with advanced design and manufacturing techniques. Their operation begins with the wind blowing over the turbine blades, which are shaped like airplane wings. This shape causes a pressure difference: one side of the blade experiences high pressure, and the other side experiences low pressure. This difference generates lift, similar to how an airplane wing works (U.S. Department of Energy, n.d.).

The blades are angled (or tilted) so that the lift force causes them to spin. This rotational motion is then used to generate electricity. In some turbines, the spinning rotor drives a direct-drive generator, which converts rotational energy into electrical energy without additional components. In others, the motion is transferred to a gearbox, which increases the rotational speed before it reaches the generator. This generator then produces electricity through electromagnetic induction. (How Do Wind Turbines Work?, n.d.).

The simple construction and small footprint of wind turbines allows it to be a potent zero-emission power source. Wind is one of the cheapest ways of generating power, with a low estimate of $26/MWh compared to $65/MWh for coal (Joshi & Gokhale-Welch, 2022), a historically cheap but extremely polluting source of electricity. As such, wind carries great potential for competing to be not just a much cleaner form of electricity but also one that is cheaper than legacy fossil-fuel generation.

Objective

Given the importance of wind turbines to the energy transition, our project looks at what design specifically would be the most effective and materially efficient at a small scale utilizing 3D printing with PLA plastic, a cheap process of Fused Deposition Modeling (FDM) manufacturing. One of the primary challenges in testing large-scale wind turbines is the need for specialized facilities capable of accommodating increasingly larger components. The Wind Technology Testing Center (WTTC) in Boston, Massachusetts, can test blades up to 90 meters in length (U.S. Department of Energy, n.d.). Testing at the 3D printed scale allows for low-cost testing and validation of a variety of blade and tower designs before costly implementation at industrial scales.

In our project, the turbine consists of two parts: the blades and the tower. We designed both to maximize the parameters given. For the blade, the objective was to optimize for power generation of 2+ watts when subjected to forward - facing winds of 25 mph. Because of this, the blade design needed to satisfy the following objectives:

1. Easily mountable to the generator shaft
2. Stability and structural integrity under load
3. Efficient optimization of design parameters to optimize power production (Angle of Attack, Angle of Twist, etc)
4. Fabrication feasibility and consideration for 3D printing capabilities and footprint

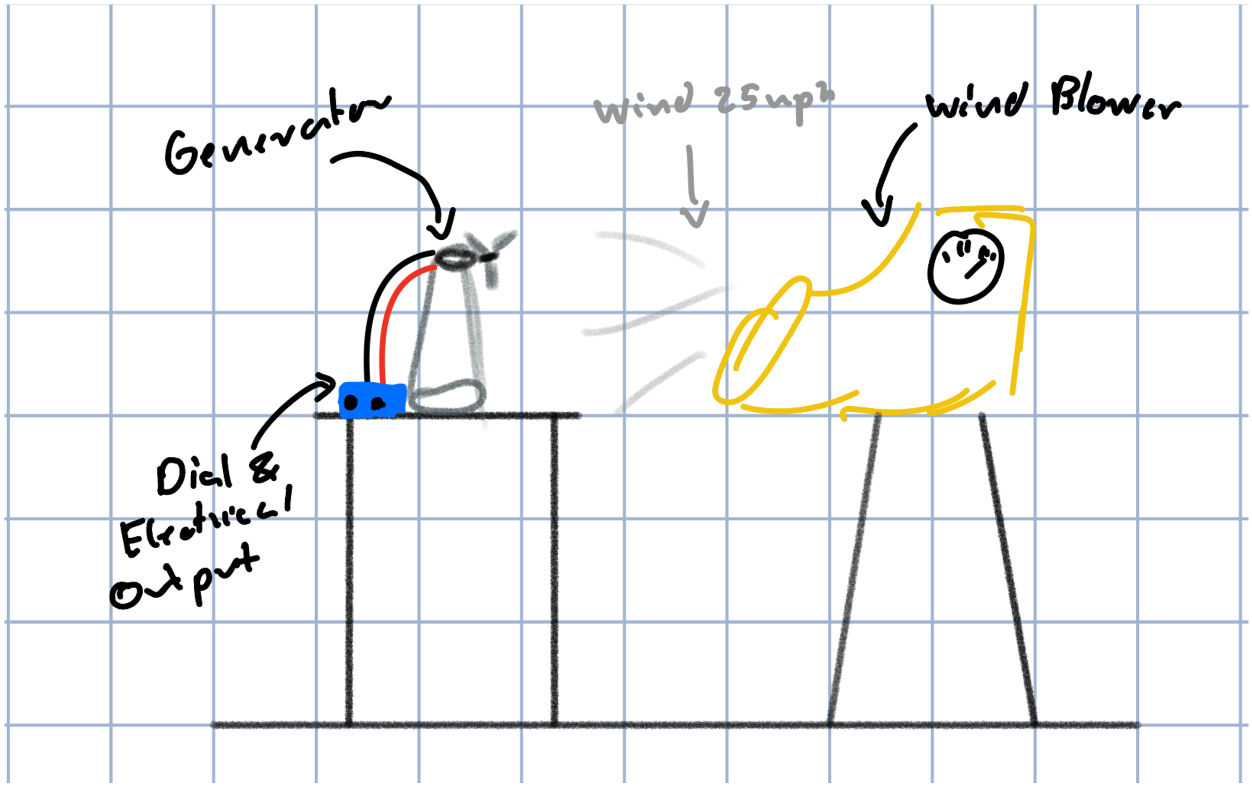

Figure 4: *Sketch of Blade Testing Setup*

For the tower, we sought to optimize stiffness given loads of up to 10N while minimizing the amount of construction material and mass. This load would be applied to an eyebolt attached at the top of the tower with weights of ascending increments. In order to satisfy these needs, our design objectives for the tower were to:

1. Meet all given geometric constraints (< 17 in^3 volume, 16” motor shaft height, 3/16” eye bolt mounting hole)
2. Ensure sufficient stiffness through Finite Element Analysis (FEA)
3. Minimize mass of tower while satisfying all other objectives
4. Fabrication feasibility and consideration for 3D printing capabilities and footprint

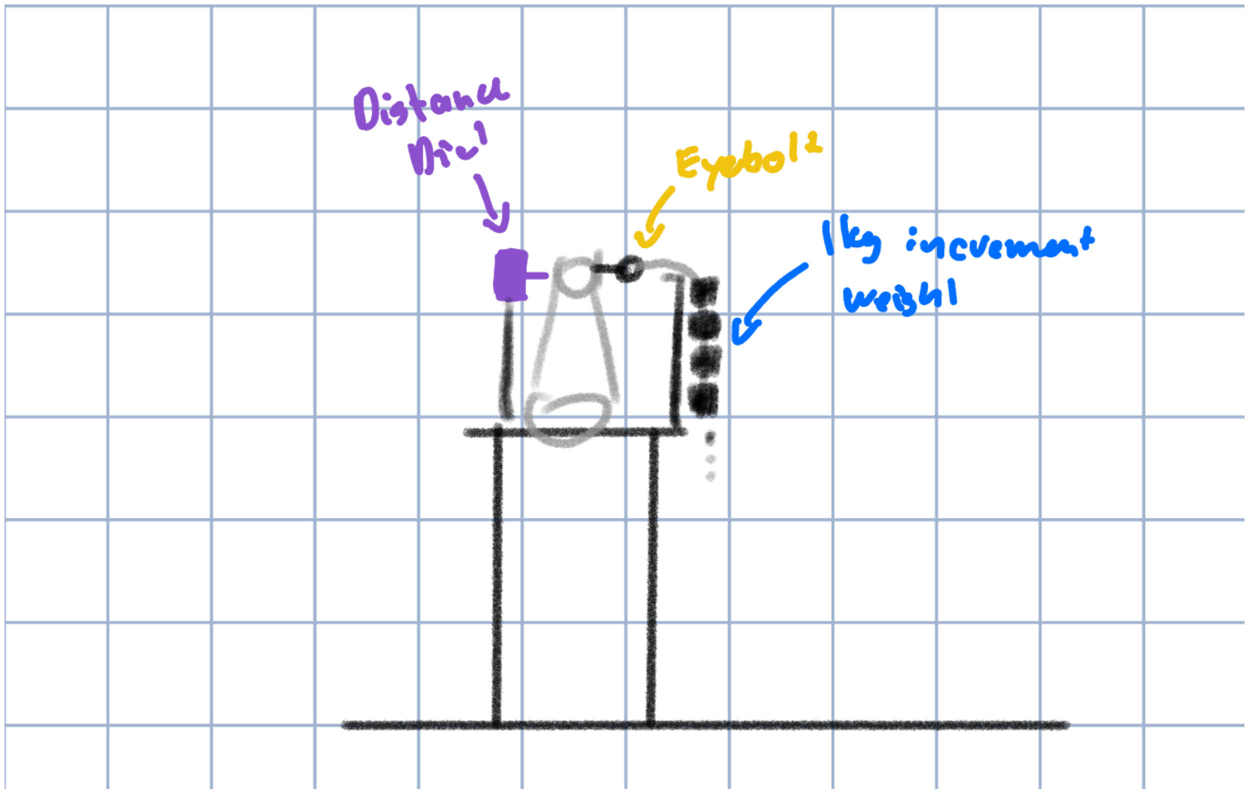

Figure 5: *Sketch of Tower Stiffness Testing Setup*

By working together as a team to satisfy all objectives for both the blade and tower, we also strive to further our understanding of wind turbines, CAD, and FDM processes with 3D printing. Completing this project covered the entire engineering design process and tested our group collaboration and communication.

Theory

Power Generation and Efficiency

The maximum power (W) provided by the wind follows the Power Equation :

$$Theoretical\ Max\ Power\ = C_p\ *\ \frac{1}{2}\rho A v^3$$

C_p = Coefficient of Performance Under Betz Law (0.593)[1]

ρ = Density of Air $(1.225\ kg/m^3)$

A = Cross-sectional Area of the Wind $(0.0183\ m^3)$

v = Wind Velocity $(11.18\ m/s)$

In our case, wind velocity and air density are constant. The only directly proportional single variable that affects the amount of power the turbine can harness is the swept area A. As such, we worked to maximize this value within our parameters, selecting a blade radius of 3 in (0.0762 m), which is the maximum radius allowed. This increases the swept area, and thus increases the power generated. Given Betz Law, the maximum power that can be captured is roughly 59.35%. The actual proportion of the max power our wind turbine can extract is dependent on other factors and not directly based on any one attribute of the turbine (Pennsylvania State University, n.d.). Understanding how effective our design was can be examined by examining the overall efficiency.

$$Efficiency\ =\ ((Testing\ Output)\ /\ (Theoretical\ Power))\ *\ 100$$

The theoretical maximum power from the equation is 9.25W. Given our watts produced by 0.48 W, this yields an efficiency of 5.29%. This is likely due to mechanical losses in friction and generator inefficiency, electrical loss in the testing setup, and aerodynamic loss due to the blade design.

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[1] Wikipedia contributors. (n.d.). Betz's law. Wikipedia. Retrieved December 12, 2024, from https://en.wikipedia.org/wiki/Betz%27s_law

Stiffness

The first equation regarding stiffness that can be applied to our tower is Hooke's Law. The tower, when imagined as a spring, follows a linear relationship between the force applied and the displacement. Elastic materials such as the PLA used in our tower deform proportionally to the force applied. The slope k is the stiffness in N / mm, which we can find through running multiple trials at various forces and taking the slope.

$$k = \frac{F}{\Delta x}$$

This second equation treats the tower as a simple beam using the Beam Bending Stiffness equation. The equation is derived using the material's inherent properties, shape of the object, and length.

$$k = \frac{3EI}{L^e}$$

k = Stiffness (N/mm)

E = Young's Modulus (Pa)

I = Area Moment of Inertia (m^4)

L = Length of Beam (m)

Researching online, most common PLA filaments have a Young's Modulus of 3500 mPA[2]. The length of the beam is 16 inches, which is equal to 406.4 mm. The mass properties tool on Solidworks specified the Area Moment of Inertia is 5061.14 kg / mm^2. Together in the equation, this yields a stiffness of 7.91 N/mm. However, this value is also dependent on a variety of external factors due print settings and differences between manufacturers.

[2] MakeItFrom. (n.d.). Polylactic acid (PLA) - Polylactide. MakeItFrom. Retrieved December 12, 2024, from https://www.makeitfrom.com/material-properties/Polylactic-Acid-PLA-Polylactide

Design

Blade Design

Profile

The profile of the blade is based on an airfoil. In general, airfoils are certain profiles similar to a tapered ellipse with advantageous aerodynamic properties. Although they are usually developed with aerospace considerations in mind, for example for the wing of an aircraft, their characteristics such as high lift or low drag are still applicable to our use case. Airfoils generally are designed within a series or group, with airfoils in that series prioritizing certain features such as stability at high speeds or low drag (Cantwell, B.). During our search for an appropriate airfoil, we compared the NACA, S, DU, and FX series below.

Table 1

Airfoil Series Comparison

Name	Examples	Notes	Companies
NACA	4 Digit (4412, 2412) 5 Digit	Developed by National Advisory Committee for - Aeronautics, widely used in small-medium turbines - Simple to manufacture and offers decent aerodynamic performance	GE WinVesters Nordex
S-Series	S809 S825	- Developed by National Renewable Energy Lab, widely used in high performance large turbines - Designed for high lift and moderate drag	Vestas Siemens Suzlon

DU	DU91-W2-250 DU93-W-210	- Developed by Delft University of Technology, widely used in modern large scale turbines - Engineered to handle thick boundary levels at in board sections	
FX Series	FX 63 137	- Commonly used for small scale wind turbines - Achieves high lift at low Reynolds Numbers	

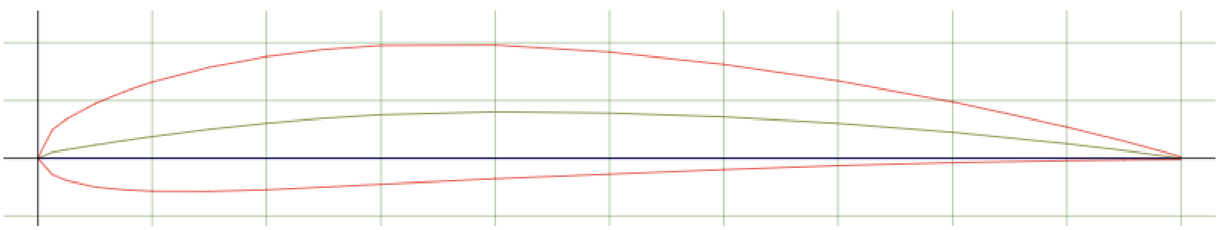

Figure 6: *Profile of NACA 4412*[3]

After comparing different airfoils from each series, we ultimately chose the NACA 4412 series. This airfoil was selected due to its simple construction and extensive documentation. Specifically, it allowed us to easily import the profile from Airfoiltools.com into SolidWorks using a set of coordinates.

The NACA 4412 series was particularly well-suited for a small 3D-printed turbine because of its proven aerodynamic characteristics, which provide efficient lift and control. Its moderate camber and thickness make it an excellent choice for the balance of performance and manufacturability, ensuring that it would perform well in a turbine application while being feasible to produce using 3D printing technology (Heffley, 2007).

[3] From [NACA 4412 (naca4412-il)]

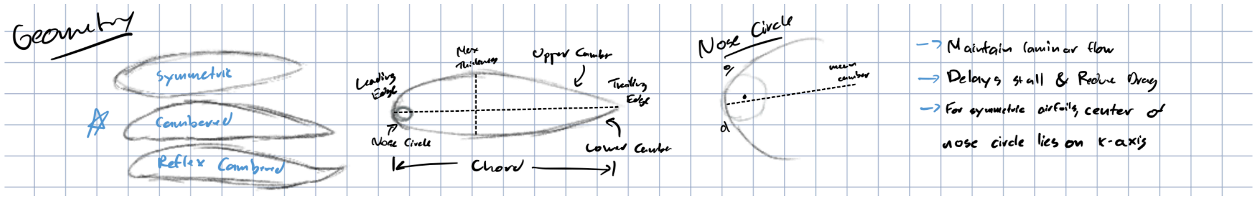

Figure 7: *Airfoil Geometry Attributes*

In addition to the series type, airfoils additionally have different attributes that contribute to its performance. This includes the overall shape, from symmetric, cambered, and reflex cambered (referring to the shape about the x-axis), chord length (the length from the nose to the trailing edge), and the camber (the angle and curve for both the upper and lower edge). We decided to mainly focus on cambered airfoils, as they generate the most amount of lift. The upper surface of a cambered airfoil is more curved, causing the air pressure above the airfoil to decrease. Meanwhile, the relatively flatter lower surface maintains higher air pressure, creating a pressure difference that generates lift. (*Wind Turbine Blade Design, Flat, Bent or Curved*, n.d.). This lift is crucial for applications like wind turbine blades, where efficient power generation is needed. Cambered airfoils also optimize the lift-to-drag ratio, balancing the forces to maximize performance and efficiency (Cadence Design Systems, 2022).

Angle of Attack

In addition to the profile, we looked at the angle of attack (α). The angle of attack is specifically the angle between the chord and the direction of the airflow. The angle of attack was chosen to extract the most energy from the wind, or maximizing the lift:drag (Cl/CD) ratio. However, lift itself should also be maximized, so the optimal angle should be between the point of maximum Cl/CD and the point of maximum lift (Thumthae & Chitsomboon, 2008). This ensures that the airfoil produces the most lift while still maintaining manageable drag, contributing to better energy capture and overall aerodynamic performance.

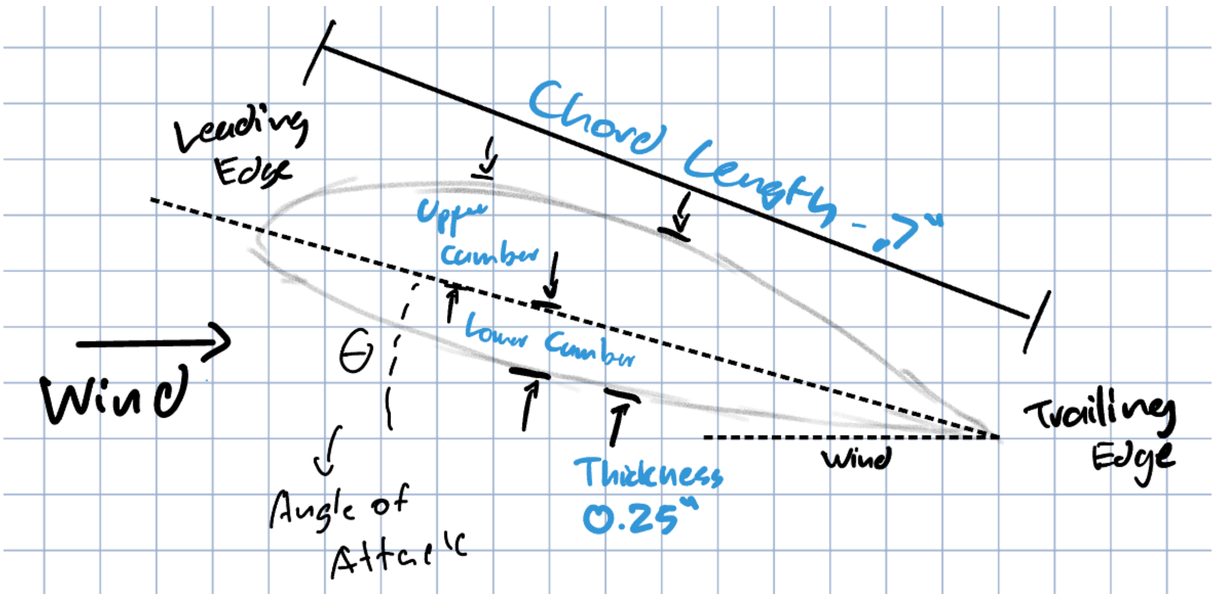

Figure 8: *Angle of Attack Diagram*

Why does Angle of Attack influence lift? Wind flowing over the airfoil generates lift because of the pressure difference between the top and bottom surfaces. Small angle of attack directs air towards the bottom airfoil to create upwards lift. As α increases, the pressure difference gets bigger and bigger until it reaches a state of flow turbulence which leads to stall that reduces power generation. Based on Figure 8, existing research from the Journal of Renewable Energy identified αs that maximize the lift coefficient as well as the ratio to drag.

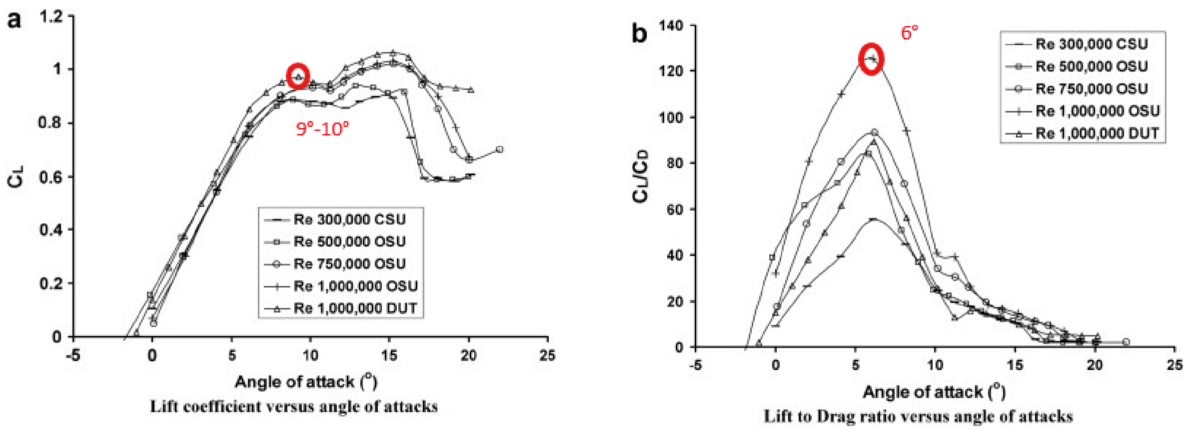

Figure 9: *Graph comparing Angle of Attack to Lift and Lift to Drag Ratio*[4]

Based on this data, we identified an angle of 8° as it would be between that where the coefficient of lift (Cl) peaks and the Cl/Cd peak (Thumthae & Chitsomboon, 2009).

Angle of Twist

The angle of twist refers to how much the airfoil twists along its axis. It is measured as the gradual change in the twist or pitch angle of the airfoil along the length of the blade, from the root (closest to the hub) to the tip. This is done because the velocity of the wind is different across the length of the blade, increasing towards the tip. As such, with an angle of twist we can keep an optimal angle of attack along the entire length of the blade. In a wind turbine where the angle of attack is constant across the length of the blade, the tips would experience an α that is too large, causing excessive drag, reduced lift, and possible flow separation. Meanwhile, the root may have a suboptimal α for its slower speed, resulting in less lift and inefficient energy capture. Thus, an angle of twist is needed to gradually account for this across the length of the blade.

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[4] Thumthae, C., & Chitsomboon, T. (2009). Optimal angle of attack for untwisted blade wind turbine. *Renewable Energy, 34*(5), 1279-1284. https://doi.org/10.1016/j.renene.2008.09.017

For optimal results, the angle of twist decreases from the root of the blade to the tip. In research done by the University of South Africa, a design with a maximum pitch angle of 12° was optimal (Yass, Rasheed, & Muhiesen, 2022). With this in mind, we selected the following angles of twist:

Table 2

Designed Angles of Twist Along Turbine Blade

Length (%)	Angle of Twist (°)
0% (Root)	13°
25%	10°
50%	6°
75%	2°
100% (Tip)	0°

Number of Blades

We chose a three-bladed design. In theory having more blades would be the most energy efficient design, as little wind in the swept area passes through without conversion to energy by the blades. However, it is found that having an excessive amount of blades is not an optimal design. As the number of blades increases, the distance between them decreases. This increases the possibility of the wind flow from one blade disrupting the other blades. This increases drag and power loss, negating the benefits from an increased coverage area. (Alternative Energy Tutorials, n.d.)

That said, having too few blades introduces new concerns. A single blade would be a materially efficient design, with the least amount of material needed to create the blade. Yet, its asymmetrical design comes with serious stability concerns. A counterweight must be used on the opposite end of the single blade to maintain stability as the turbine spins, increasing stress on the motor connection point without additional power generation improvements.

A double bladed design is suboptimal as well. As with any even number of blades, it suffers from instability as corresponding blades are oriented 180 degrees from each other. When the blades are oriented perfectly vertically, the blade pointing upwards receives the full wind force whereas the lower blade has less wind force by being aligned with the support tower. This causes the two blades to receive different amounts of wind force, causing increased and uneven stress on the turbine blades.

As such, three blades meet a balance between stability and power generation. As an odd-numbered and radially symmetrical design, it has inherent stability. With an increased number of blades, it provides adequate coverage of the swept area.

Stability

A unique design choice we made was using a so-called “flatback” design. After 3D printing our initial design we noticed a considerable deficit in blade integrity causing it to flex easily under stress. This increases drag, as force is lost to the bending of the blade itself rather than being transformed into rotational motion.

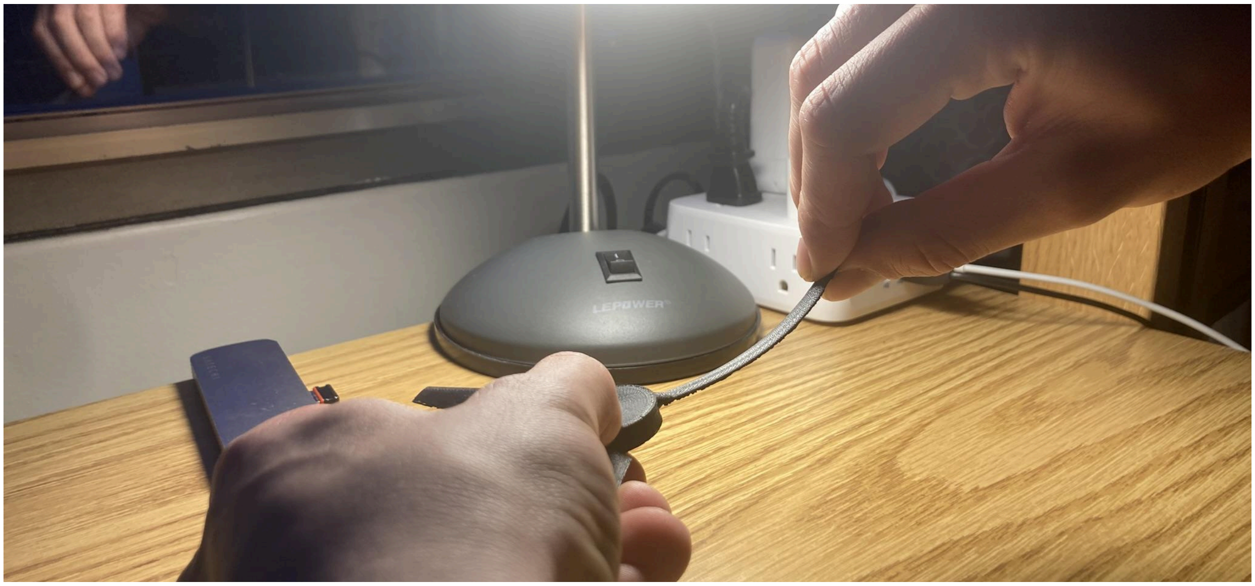

Figure 10: *Flex of Initial Printed Blade*

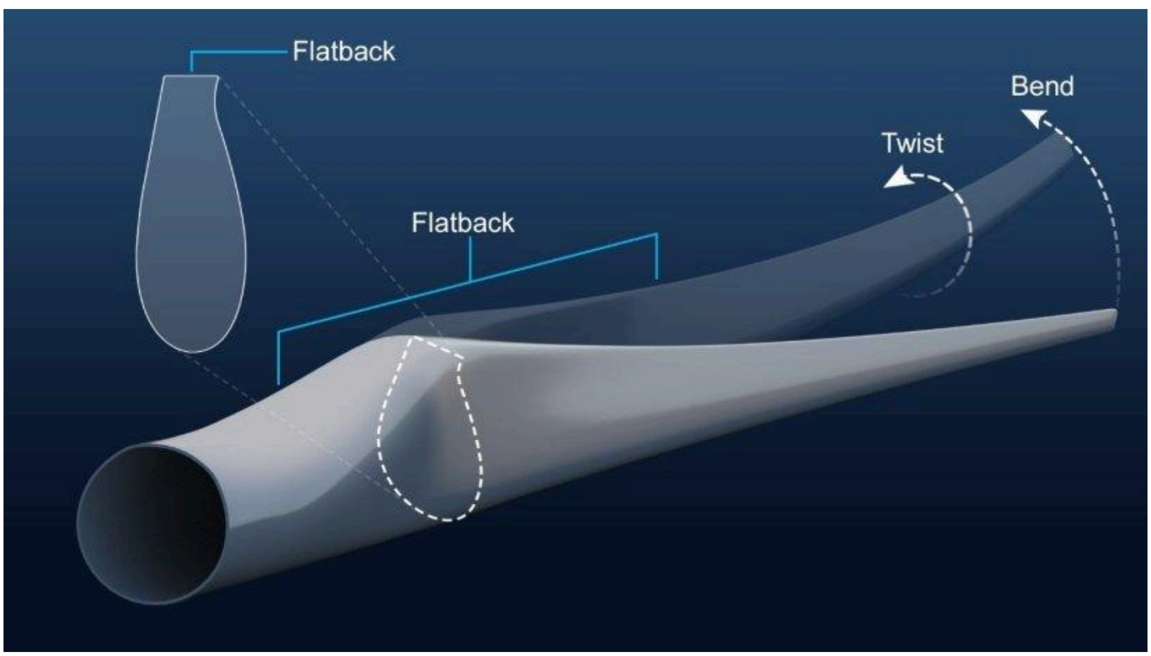

Figure 11: Graphic of a Flatback Wind Turbine Blade Design[5]

[5] Wind Energy Technologies Office. (2023, August 23). *Bends, Twists, and Flat Edges Change the Game for Wind Energy*. Department of Energy. Retrieved December 12, 2024, from https://www.energy.gov/eere/wind/articles/bends-twists-and-flat-edges-change-game-wind-energy

The United States Government Wind Energy Technologies Office highlights the value of using a flat back design to support the higher speeds experienced at the tip with more structurally sound bases to effectively convert the energy to the generator. This design increases efficiency enough that many modern wind turbine blades from global manufacturers like General Electric, Siemens Gamesa, and Nordex use flatback airfoils despite their increased complexity.

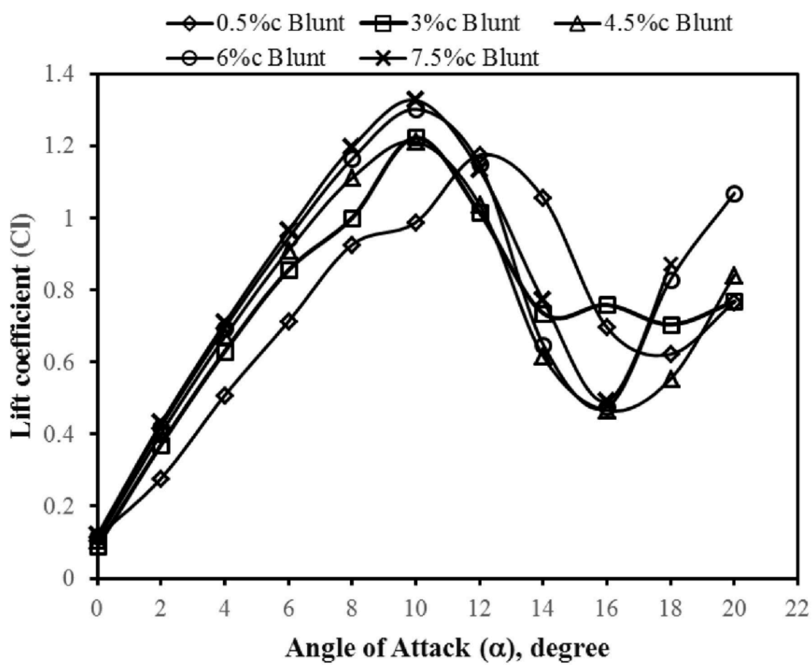

Figure 12: *Graph of Cl vs. Angle of Attack (α) For Differing Levels of Bluntness*[6]

This study (Jaffar et al., 2022) presents data pictured above showing that increasing the flatback maximizes the lift coefficient while minimizing drag. The airfoil with the highest lift coefficient, 1.2, at 8°, the angle of attack we chose, is the one with a bluntness of 7.5%. This is

[6] Jaffar, H., Al-Sadawi, L., Khudhair, A., & Biedermann, T. (2022, December 16). *Aerodynamics improvement of DU97-W-300 wind turbine flat-back airfoil using slot-induced air jet*. ScienceDirect. https://www.sciencedirect.com/science/article/pii/S2666202722001306

compared to the baseline of 0.5% with a CI of only 0.7. We concluded that this demonstrates the benefit of a flatback design, which not only increased the CI value, but also made our blade structurally stiffer.

Tower Design

Our process for designing the tower started with an open ended round of brainstorming. With less strict variable parameters to consider compared to designing the blade, our team chose to start with a large pool of designs and narrowing down a single choice that optimized for our design objectives of maximizing stiffness and and minimizing displacement.

Preliminary Design Sketches

At the brainstorming stage, we saw that there were two main types of towers: tubular designs and beam designs. Tubular designs usually used a single geometric shape and had this profile going up from the base to the top. Meanwhile, beam designs utilized beams that intersect together and form a lattice going up to the top. A third wildcard design of a grid similar to 3D printer infill was also considered.

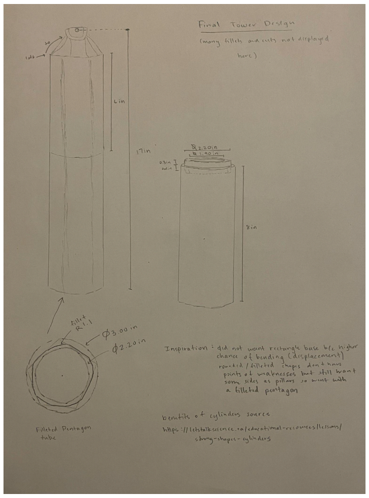

Figure 13: Tubular Tower

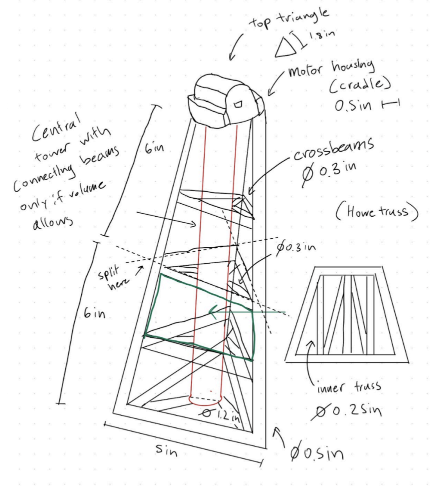

Figure 14: Beam Tower

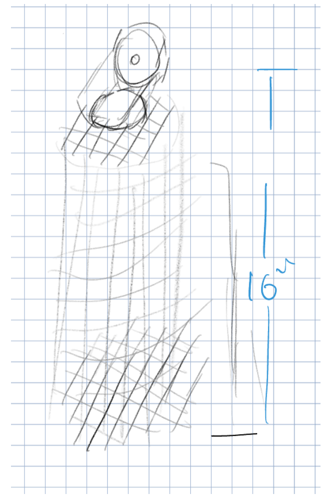

Figure 15: Grid Tower

Tools Used in Design

The towers were designed in Solidworks, a 3D modeling software where various 2D sketches are represented into 3D through features. Starting with 2D sketches, we extruded these profiles up to below the motor casing, where a loft command allowed for a gradual incline upwards. Cut-extrudes allowed us to remove geometry and create space for the motor and eye bolt holes. Mass properties were used to ensure the volume was within the limit allowed.

These part files were then uploaded as STL files, where “each file is made up of a series of linked triangles that describe the surface geometry of a 3D model or object” (Adobe, n.d.). These STL files were uploaded to Cura, a slicer that prepares the models for 3D printing. The towers were printed using Mk3S printers in Jacobs Hall, which have a print volume of (9.84 in × 8.3 in × 8.3 in) and 0.4mm nozzle size. In order to balance the tradeoff between the resolution of the print with the amount of time it would take, the settings of the print were set to:

- 0.15mm Layer Height (Sufficient resolution for capturing fine details of the design)
- 0.8mm Wall Thickness (Sufficient strength/rigidity without excessive material usage)
- 215 C temperature (Optimal for PLA with good layer adhesion and consistent extrusion)
- 70% infill density (Balance between strength and material usage)

These 3D printing settings were chosen to balance print quality, structural integrity, and time efficiency, making them ideal for the project. Given an extended project timeline, it would be worthwhile to print at a finer resolution and with various types of PLA filament.

Tower Selection

After brainstorming and CAD, we 3D printed 3 separate towers. The first one (Figure 15), at 175g, displayed a greater tendency to bend when we applied force, while the later two (Figure 16 & 17) were much more rigid. Based on our FEA testing and the difference in mass, we decided to go with the rounded tower since it best fitted our objectives.

Figure 16: Lightsaber Tower

Figure 17: Rounded Tower

Figure 18: Grid Tower

The general decision to go with a more rounded tower over a beam one came down to stiffness. Beam towers work well for metal due to the material's high strength, ability to handle stress concentrations, and precision manufacturing techniques that allow for reinforcement, making them effective in load-bearing applications. However, for 3D-printed structures, especially with materials like plastics, beam designs are less effective because they struggle with stress distribution, weaker layer bonds at sharp angles, and material limitations. 3D printing typically performs better with rounded or organic shapes, as these designs distribute stress more evenly, reducing the risk of failure and making better use of the material's properties (ScienceDirect, n.d.).

Specifically, a rounded or cylindrical design distributes stress more evenly along the entire structure. In a beam design, stresses tend to concentrate at the points where the load is applied, which can lead to bending or failure in those localized areas. As a 3D printer goes from layer to layer, it extrudes filament to that specific area. When the structure is rounded, there is a lower likelihood of failure along layer lines or a single weak point that may form in a more angular beam design. This ensures that the printed material performs optimally under loading conditions.

A cylinder like structure was ideal as there are no points of weakness and breaking, allowing the stress to be spread more uniformly, compared to triangles and hexagons. Thus to ensure we had structural stability and roundness, we opted for a pentagon shape (to avoid bending) with large radii fillets to mimic a cylindrical tube but with added structural support.

The connection point between towers was also a major concern because of our 3D printers' approximately 8 inch limitation of length. We created a round extrusion from the base where the top piece could be slipped on and glued with a tight fit. A cylindrical extrusion was again chosen for not having points of weakness when the tower is glued and pulled to one side.

Simulation

Our process for Finite Element Analysis (FEA) used to determine the deflection (stiffness) of the tower used a fixture of the bottom of the tower attaching to the glue plate where the force is applied at the rear face of the eye bolt attachment hole. In order to balance the accuracy of the simulation to the run time of the simulation, we used a minimum element size of 0.304in and a maximum element size of 0.338in. The material of the tower is set to ABS, which has an elastic modulus of 290,000 psi. The two pieces of the tower are mated together to form the tower assembly which the simulation is run on.

For each trial, increments of 1N were applied to the tower. This simulated the testing environment where masses of 1kg are added to the contraption. We recorded the maximum deflection of the tower during each trial. We ran simulations on our two major design choices - the rounded tower and the grid tower - to come to a decision on which to use as the final design. The first set of screenshots are for the grid design.

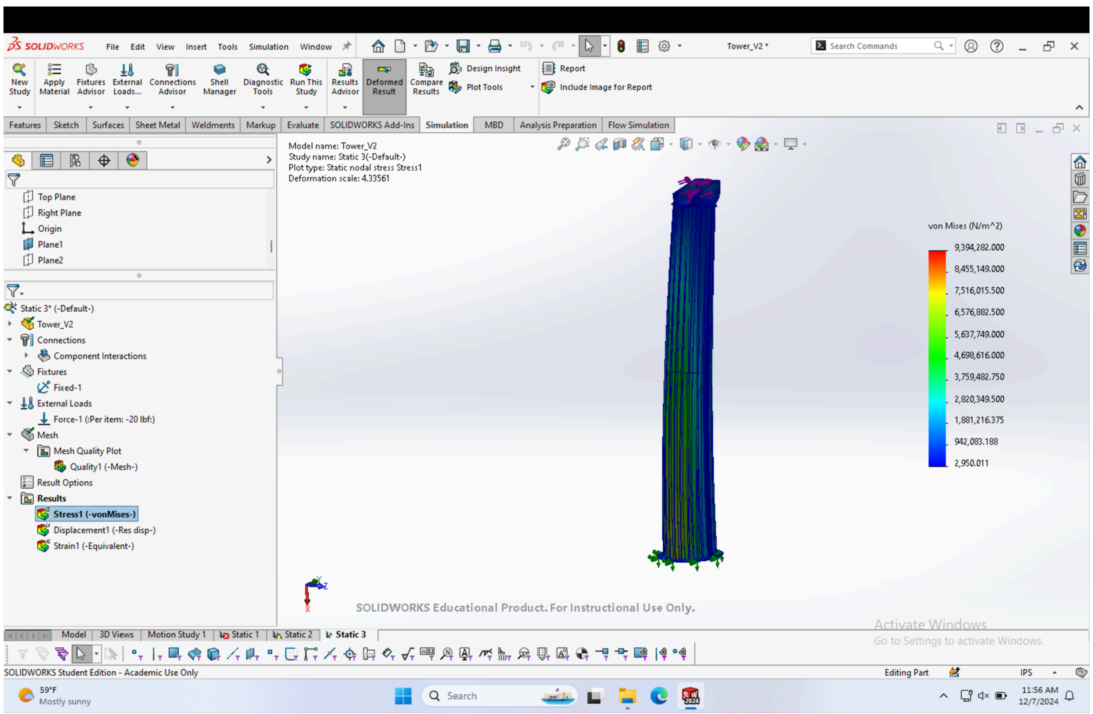

Figure 19: Stress FEA Plot of Grid Tower

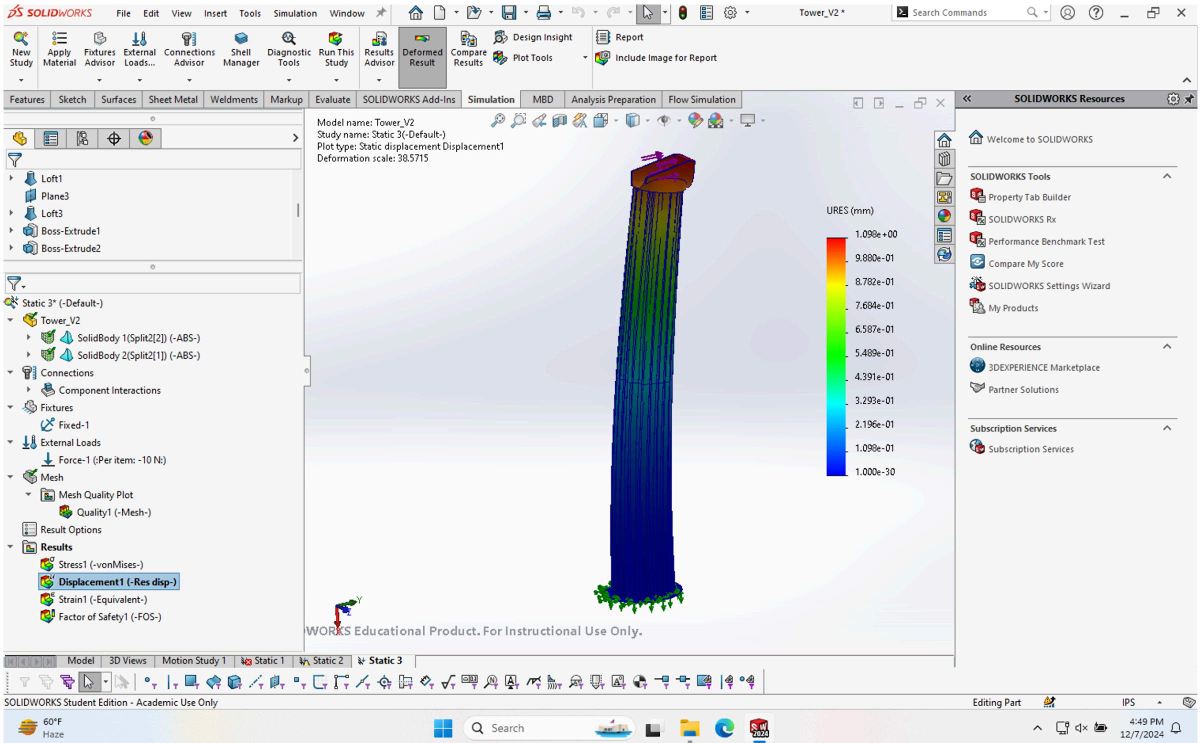

Figure 20: Displacement FEA Plot of Grid Tower

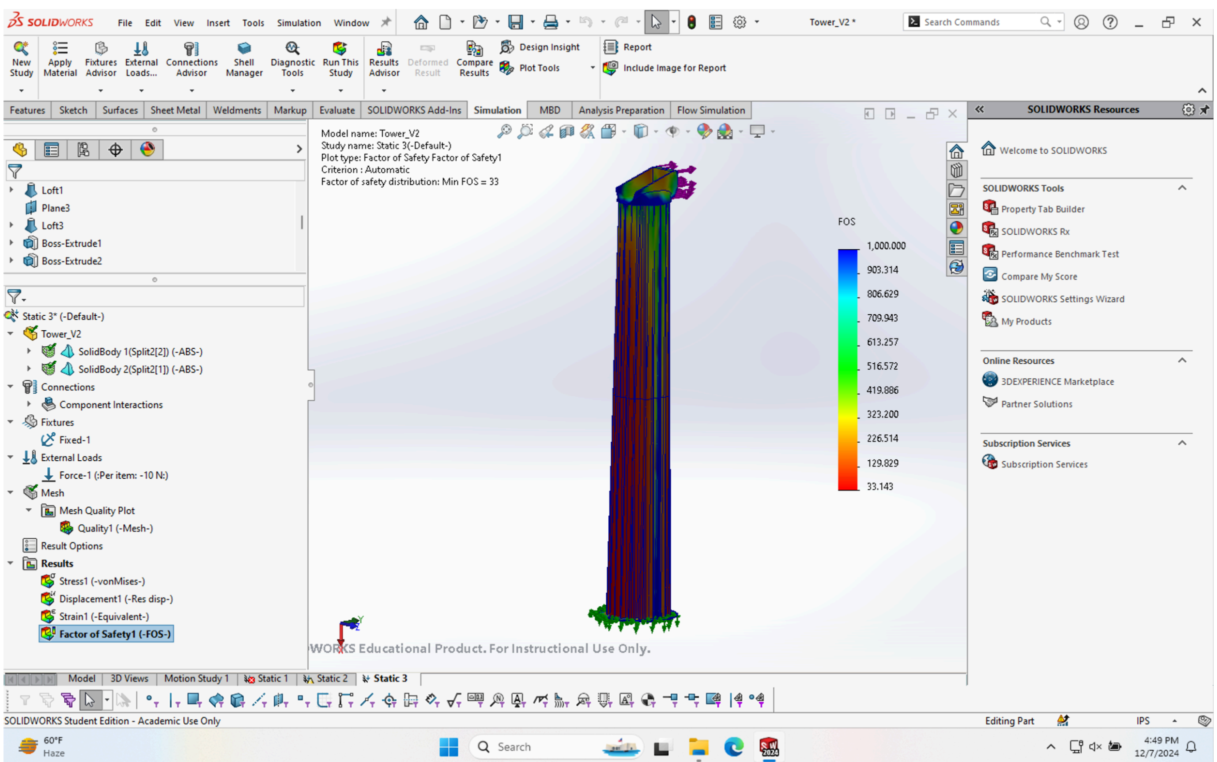

Figure 21: Factor of Safety FEA Plot of Grid Tower

The following stress, displacement, and FOS plots are for the rounded pentagon tower design.

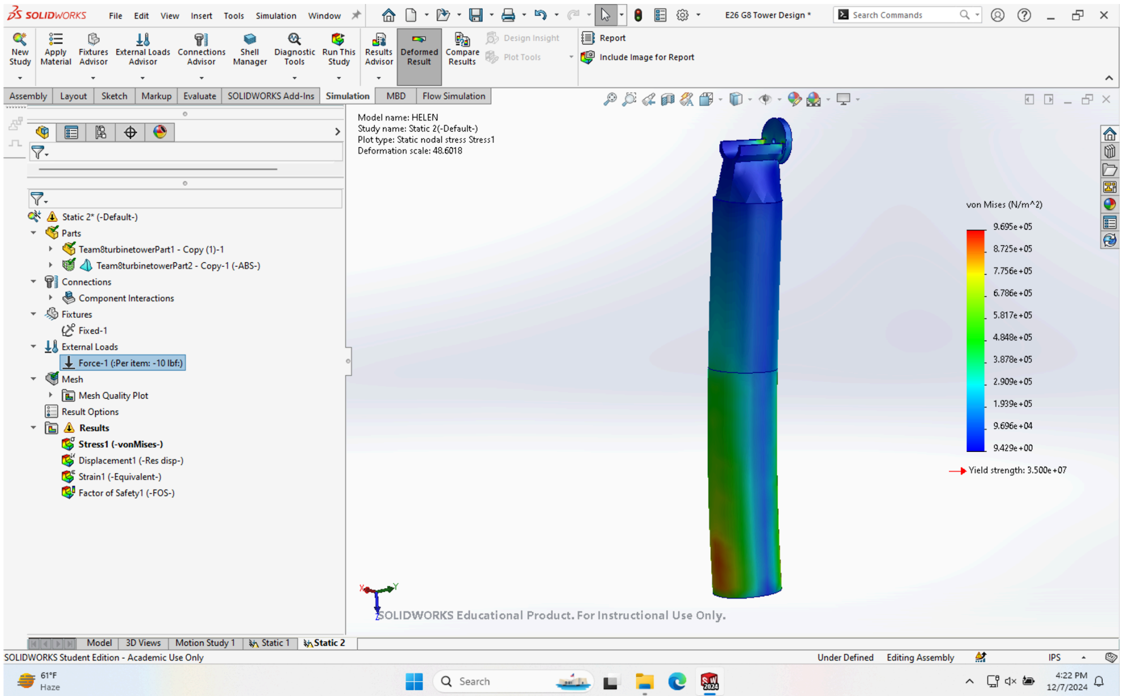

Figure 22: Stress FEA of Rounded Tower

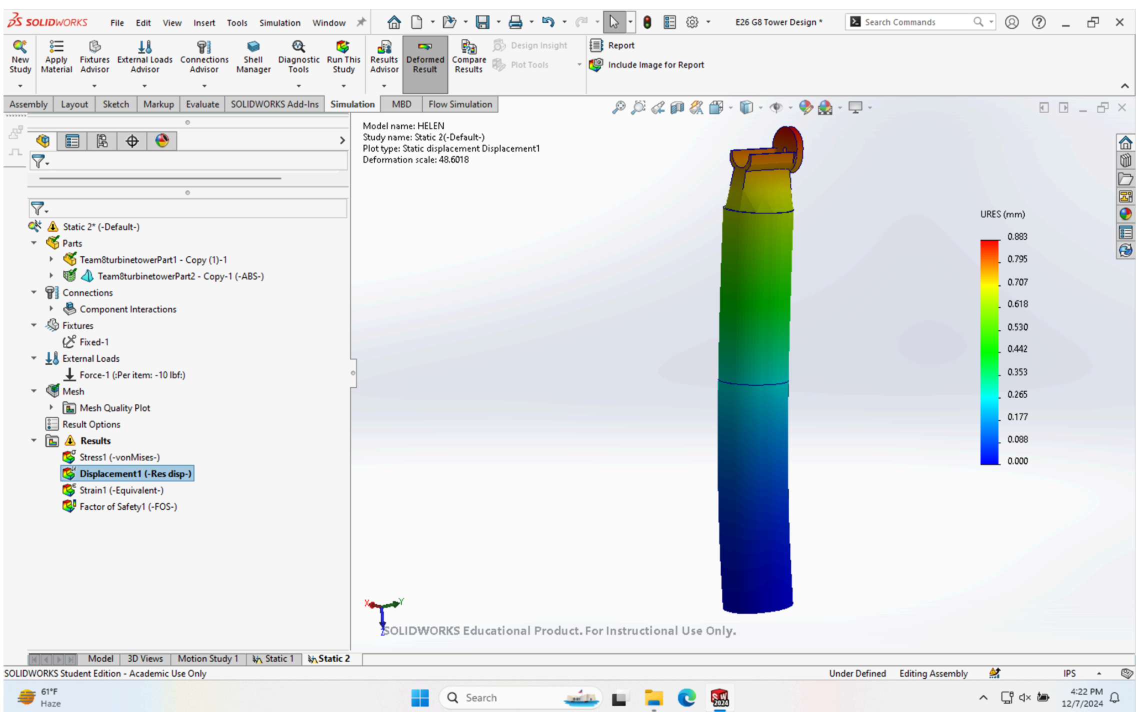

Figure 23: Displacement FEA of Rounded Tower

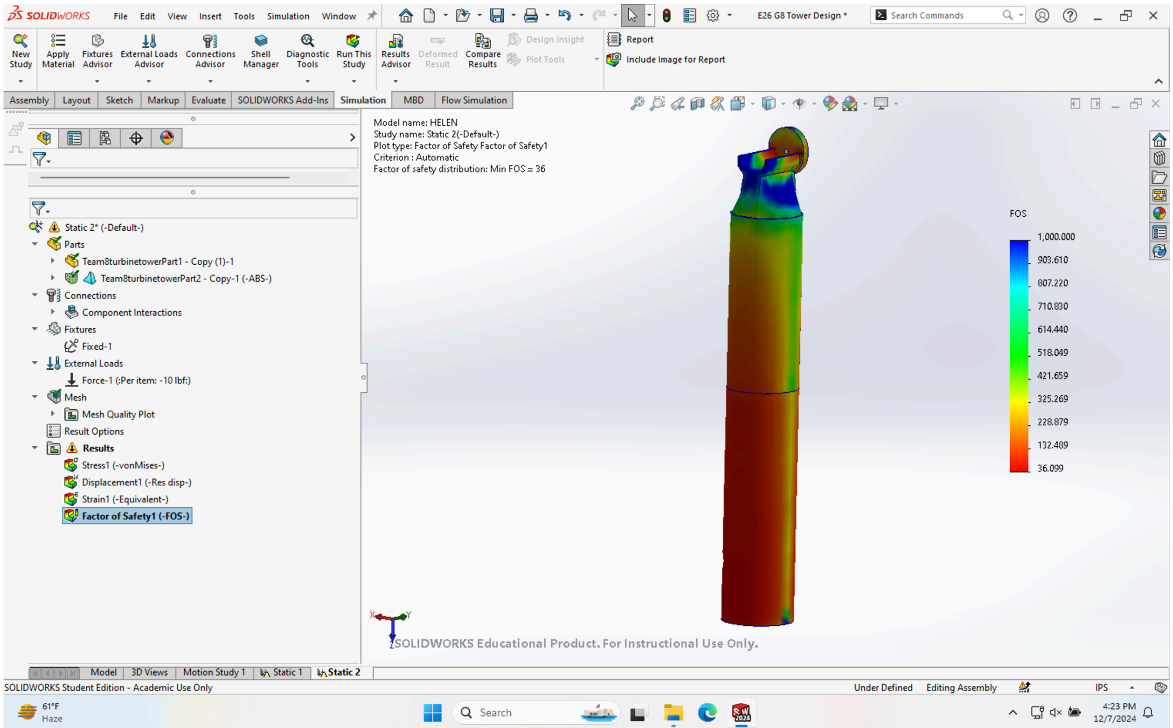

Figure 24: Factor of Safety FEA of Rounded Tower

The FEA results above were for a load of 10N, representing the maximum expected force on the tower, are shown above. The stress plot reveals the highest stress concentrations at the front and rear of the tower. As anticipated, the displacement is greatest at the top of the tower, with a smooth gradient downward, indicating an even distribution of force. A minimum factor of safety of 36 for the rounded pentagon and 33 for the lofted grid confirms that the components are significantly above their tensile strength limits.

Graphing out the relationship Load (N) and Deflection (mm) indicates the stiffness of each respective tower. Through 15 rounds of FEA, each with a 1N increase in load, the displacement was recorded and graphed to load to determine the stiffness of the tower. Using linear regression, equation of the line of best fit for the lofted grid tower was:

$$Load\ (N) = 9.12(N/mm) * Displacement\ (mm)$$

Based on the value of the slope, the stiffness of the tower is 9.12 N/mm.

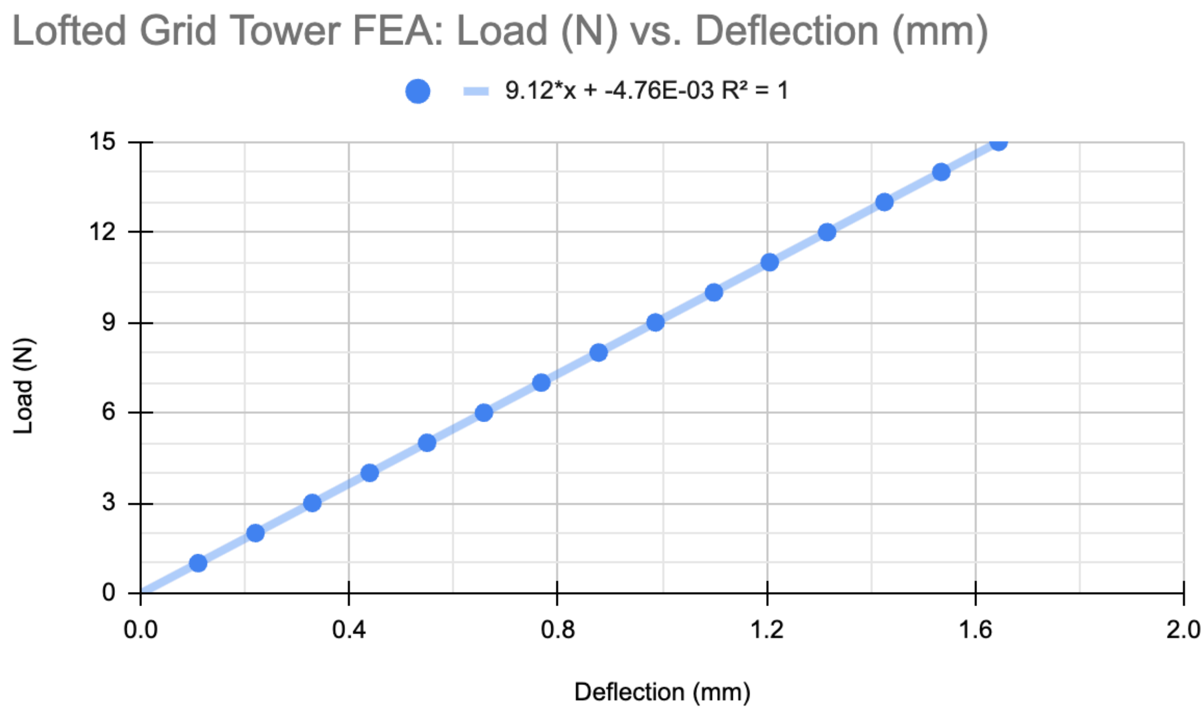

Figure 25: Load-Displacement Graph of Grid tower

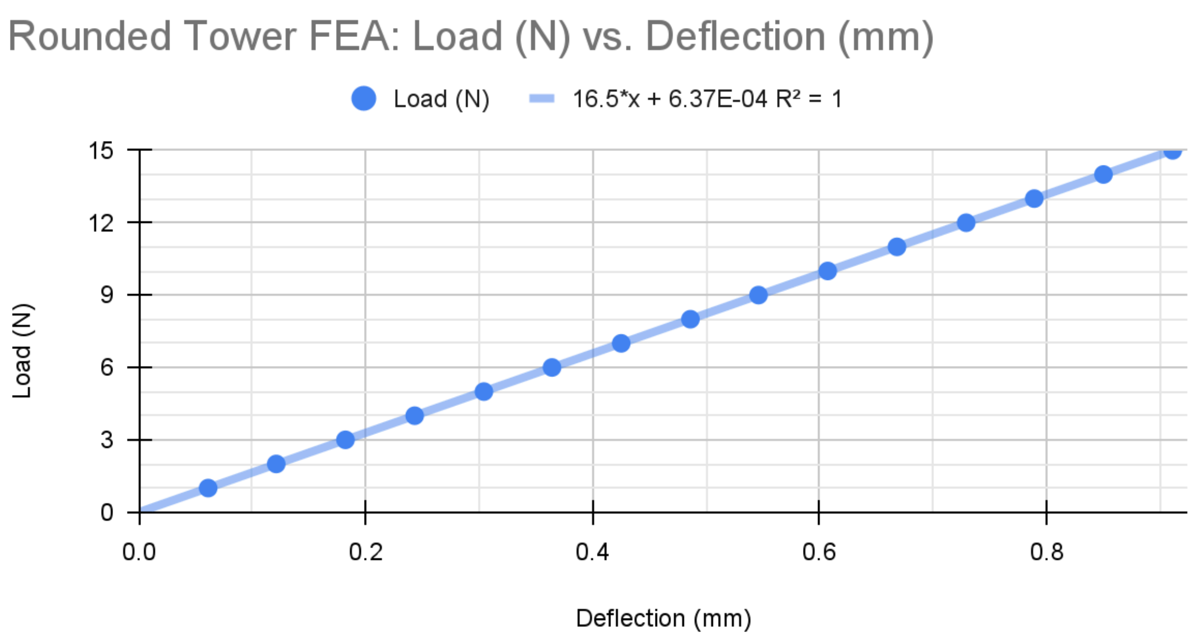

Figure 26: Load-Displacement Graph of Rounded Tower

Based on the line of best fit of the rounded tower, the equation is:

$$Load\ (N) = 16.5\ (N/mm)\ *\ Displacement\ (mm)$$

The slope indicates that the tower has a stiffness of 16.5 N/mm. Compared to the grid tower, the rounded tower stiffness is 1.8 times greater. Given this comparison, we decided to go with the rounded tower design. Because the specific properties of the material is dependent on the specific brand of filament, we decided to go with Solidworks ABS for the material properties because it was the most similar material type to PLA plastic. The specific brand of filament at Jacobs Hall - Jessie Premium PLA 1.75mm - did not indicate its material properties.

Volume

The following screenshot is of the mass properties of the rounded tower. The final volume of the tower was 16.91 cubic inches. The mass of the tower was measured using a scale before testing to be 192g. During the day of testing, we needed to drill out two additional holes to pass a zip tie through in order to secure the motor. Because of this, the tower weighed in at 182 g during the day of testing. Initial iterations of a near solid tower was greatly above the volume limit. Because of this, we hollowed out the inside of the tower until the volume was under 17 inches cubed.

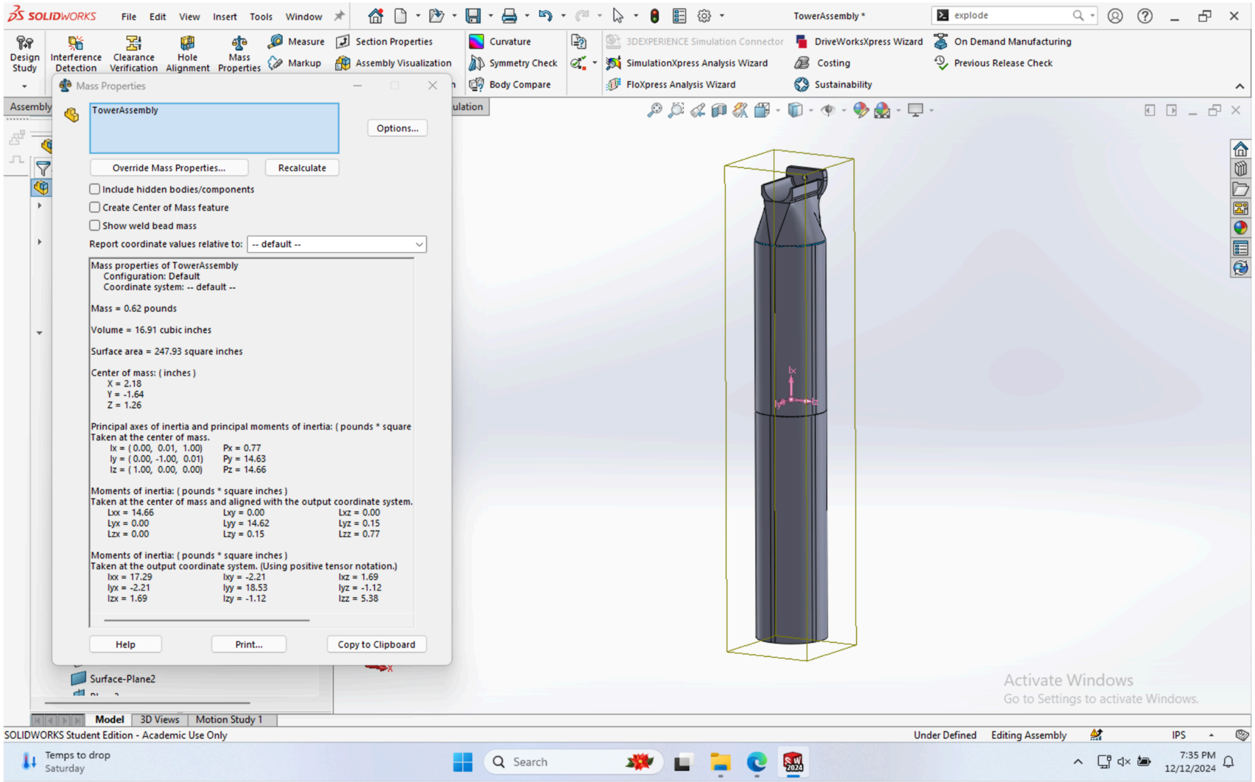

Figure 27: Final Volume of Rounded Tower

Costs

Based on the specific brand of PLA used by the Prusa printers in Jacobs Hall, the average cost of PLA filament comes out to around 2.5 cents per gram. With our total assembly of the tower and the blades coming out to around 200 grams, the total cost of our final iteration is around $5. There are a variety of 3D printing filaments at various price points with different levels of stiffness and durability. This includes ABS (~4 cents/g), PETG (~5 cents/g), and Nylon (~8 cents/g). Based on this comparison, PLA offers the most cost efficient choice given its strength (AnkerMake, 2024).

Testing and Results

Testing Process and Apparatus

We conducted two separate tests as part of our testing process. First was the power generation test, where we measured electrical data (power, resistance, current, voltage) as well as the rpm of the turbine blade using a Maxom A-max motor. A blower (seen on the top right of Figure 28) was provided, and placed in front of the turbine testing area. The distance between the blower and the turbine face was determined by placing an anemometer (seen on the right side of Figure 27) in front of the turbine tower and altering the distance of the blower until a 25 mph wind speed was reached as was in line with the design specifications. Once that was complete we placed our motor into the motor housing and secured it down with zip ties. We then connected the electrical wires of the motor to the multimeter using the provided safe-hook mechanism. This multimeter (seen on the bottom left of Figure 28) gave us the ability to alter resistance while monitoring the consequential changes in voltage, amperage, and wattage. We then slid our blades on the motor shaft and tested the blower to ensure the blades would spin. We ensured the blades were facing the optimal direction by testing the wattage outputs of both orientations at 3 points (near no resistance, median resistance, near full resistance), which clearly showed a variance of maximum power from ~.2 watts to ~.5 watts showing the correct placement of the blades. We also added reflective tape to one of the blades to measure rpm of the turbine with a tachometer (seen in the top left of Figure 28) placed alongside the blower. Once the testing rig was assembled we began testing the tower's power efficiency.

To begin testing we set the multimeter to the maximum value of ohms for resistance (55 ohms) and turned on the blower. We noted the wattage output and continued monitoring this as we began decreasing the amount of ohms applied to the circuit at a slow rate, pausing frequently to allow the circuit to settle. We eventually found our maximum wattage to be .48 watts at 10.4 ohms of resistance as the power output decreased sharply at any lower value of ohms. Seeing this value to be our maximum we returned the multimeter to the maximum number of ohms and noted the baseline output wattage of our turbine. We then took the difference between the baseline and the maximum and divided it by ten to indicate we should take 12 data points at roughly .03 watt differences to show the complete curve of power generation of our turbine. Subsequently we incrementally decreased the ohms to increase the wattage by roughly .03 each time and notated the values of the circuit and the rotational speed of the turbine in our log. Once the 10 points leading up to the maximum power output and the 2 taken after the efficiency spike were recorded we turned off the fan and reset the testing space.

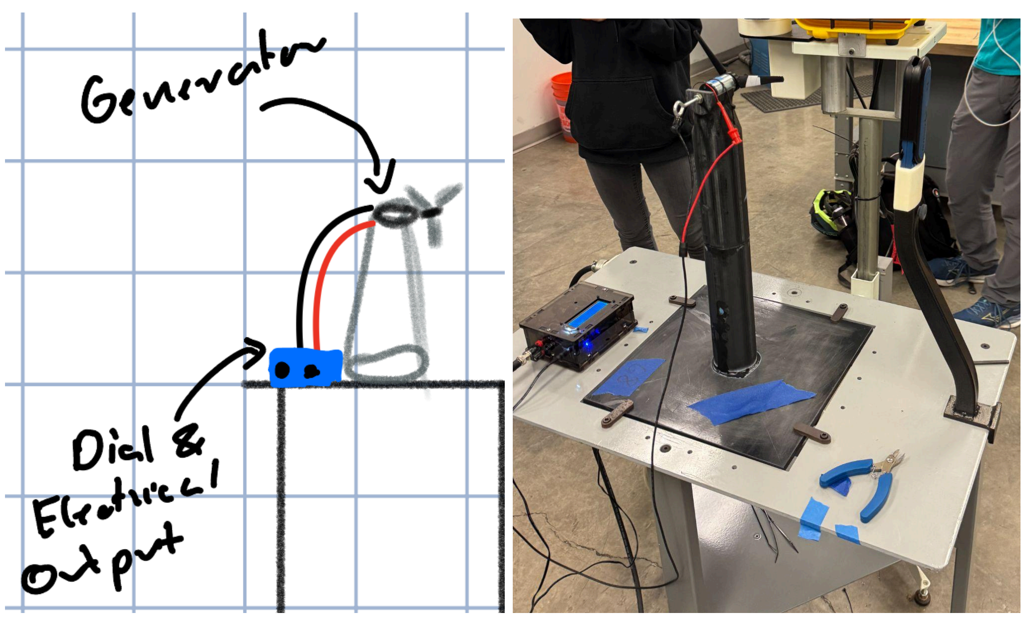

Figure 28: *Drawing and Picture of Electrical Testing Equipment*

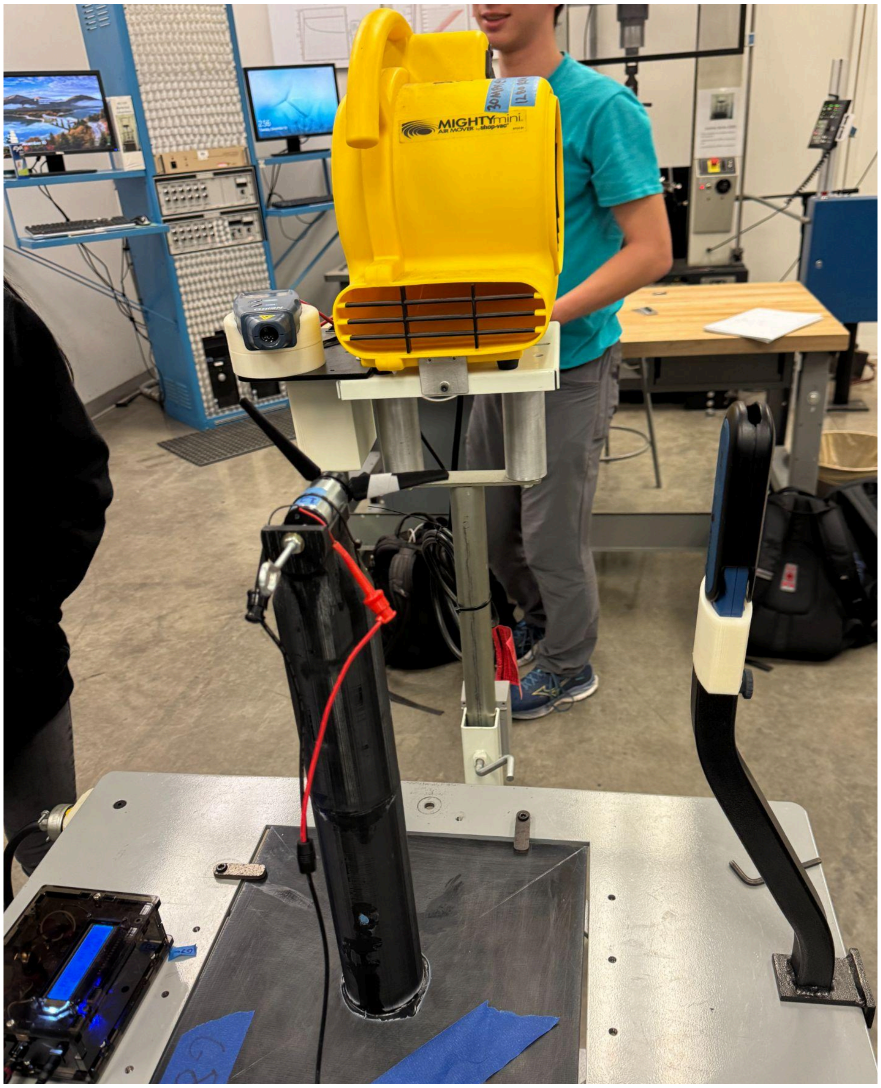

Figure 29: *Picture of All Equipment Used for Power Testing*

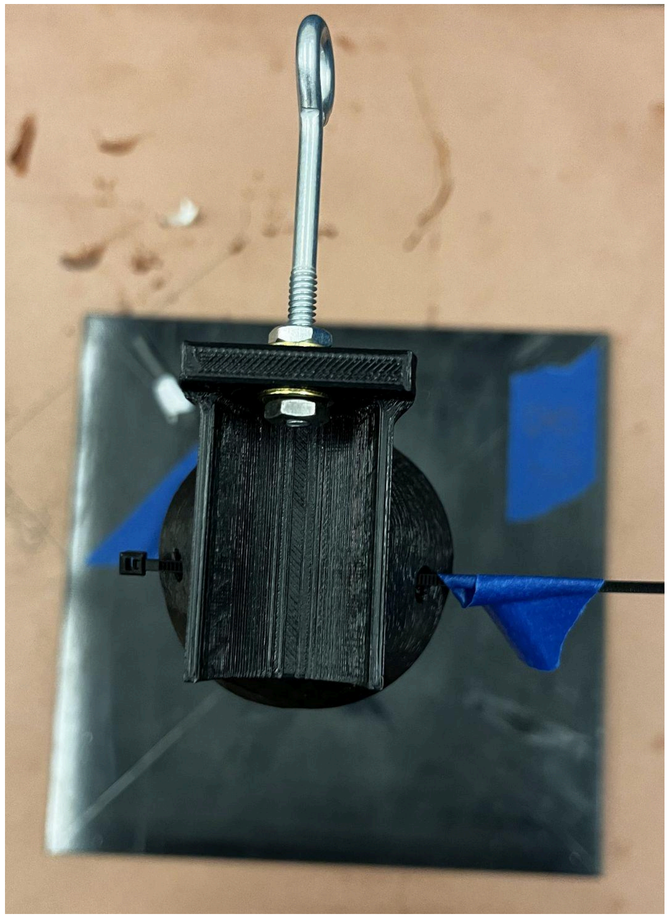

Figure 30: *Picture of Eye Bolt in Motor Housing*

Next, we tested the strength and stiffness of the tower. In order to test this, we used 0.1 kg masses, a displacement detector, and a pulley system. The overall procedure was depicted by Figure 4 in the introduction. The masses were attached to a pulley system, with the other end of the string attached to the eye bolt (Figure 29). This caused a horizontal load to be applied on the tower.

Figure 31: *Picture of Displacement Sensor During Displacement Testing*

Placing a magnetic displacement sensor on the opposite side, the technician added 0.1 kg masses in increasing increments until 1 kg was reached. We collected the displacement data (in mm) for every 0.1 kg added. This allowed us to plot this data below, and obtain the stiffness of our tower.

Table 3

Testing Results for Load v. Displacement

Load (N)[a]	Deflection (mm)	Mass (kg)
0.98	0.04	0.1
1.96	0.13	0.2
2.94	0.24	0.3
3.92	0.35	0.4
4.9	0.44	0.5
5.88	0.62	0.6
6.86	0.71	0.7
7.84	0.8	0.8
8.82	0.94	0.9
9.8	1.04	1

[a] *Load is calculated by the equation* $N = mass * g$ *where* $g = 9.8\, m/s$

Table 4

Testing Results for Power v. Current [b]

Current (mA)	Power (mW)
60.8	194
72.5	232
83.3	259
93.7	290
109	320.1
118.9	350.1
136.2	390.2
160.7	430.2
183.6	460.4
212.4	480.6
220.3	420.3

[b] *This data set included what appeared to be a significant outlier after the peak power generated, so we decided to not include it.*

Table 5

Testing Results for Voltage v. Current [c]

Current (mA)	Voltage (V)
60.8	3.19
72.5	3.15
83.3	3.05
93.7	3.04
109	2.96
118.9	2.84
136.2	2.64
160.7	2.47
183.6	2.27
212.4	2.2
220.3	2.09

[c] *This data set included what appeared to be a significant outlier after the peak power generated, so we decided to not include it.*

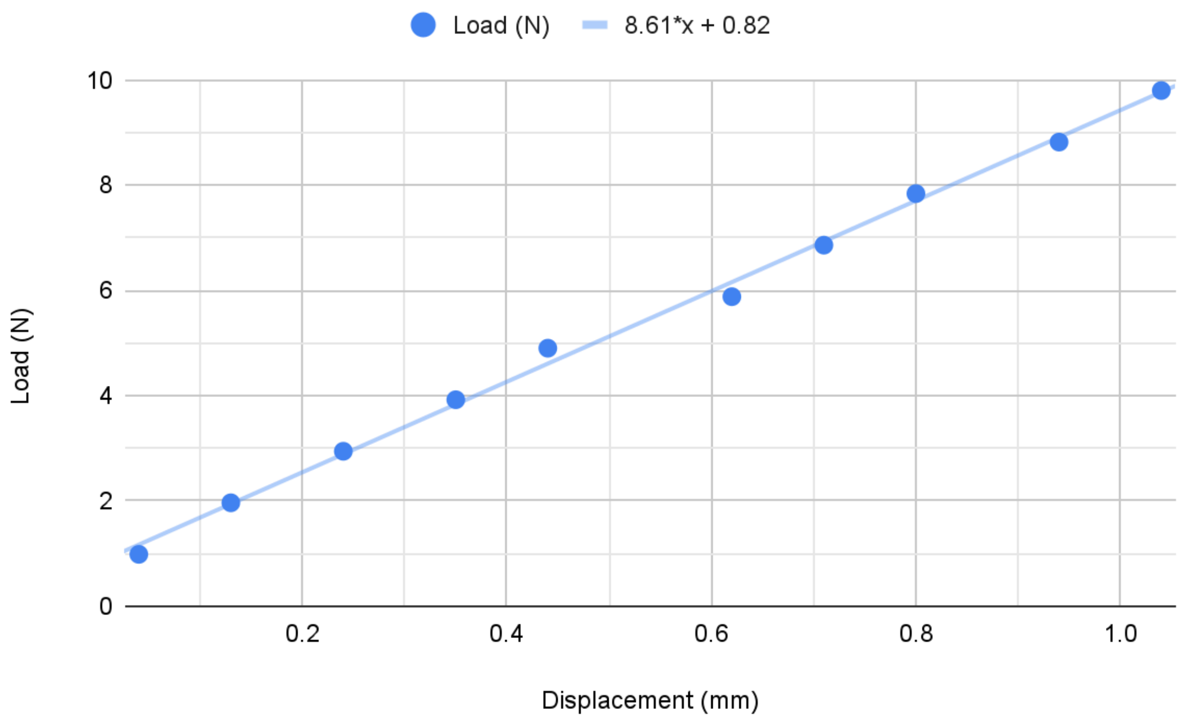

Figure 32: *Graph of Testing Results for Load v. Displacement*

Note. Stiffness is calculated by the slope of the best fit line between Load and Displacement. As shown in the figure, the slope of the line is 8.61, meaning the stiffness of our tower is approximately 8.61 N/mm.

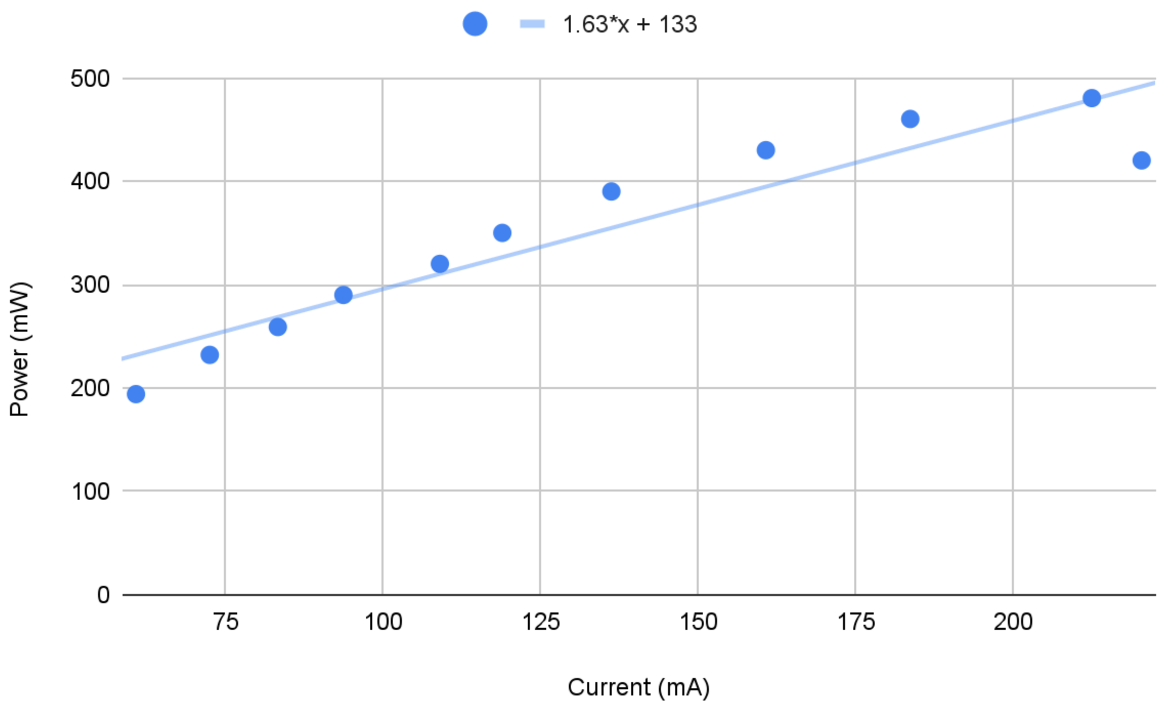

Figure 33: *Graph of Testing Results for Power v. Current*

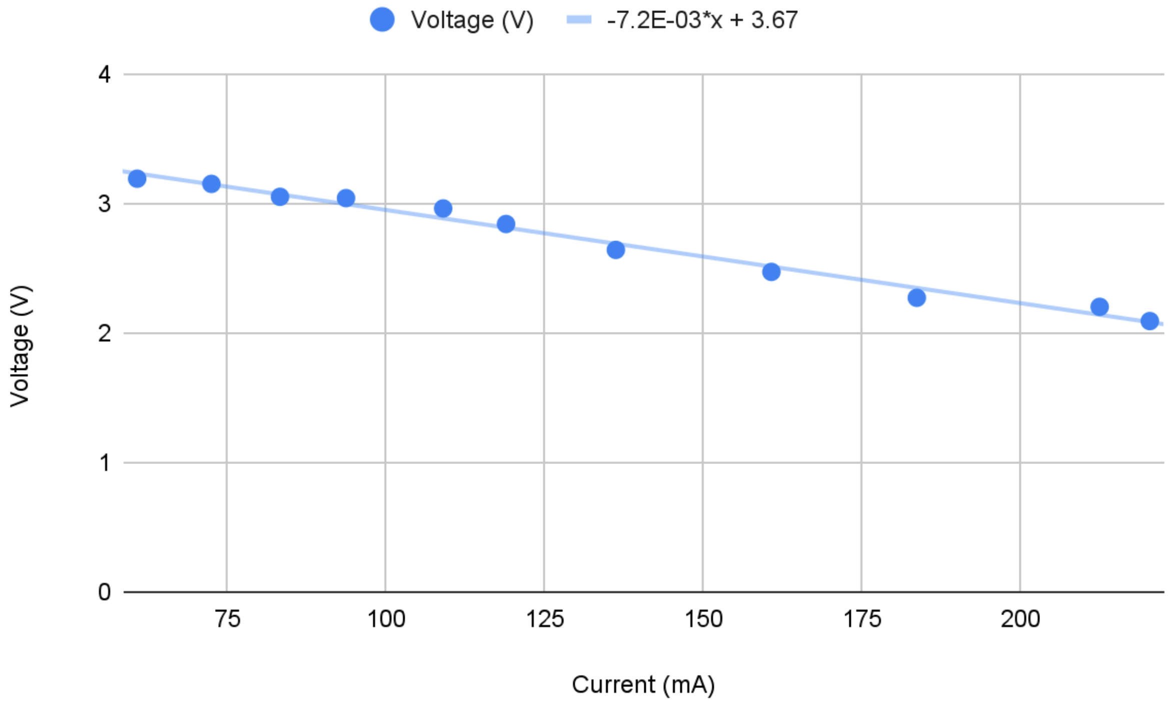

Figure 34: *Graph of Testing Results for Voltage v. Current*

Efficiency

As mentioned before, our turbine had relatively low efficiency. The equation of efficiency was:

$$Efficiency = ((Testing\ Output)\ /\ (Theoretical\ Power))\ *\ 100$$

The theoretical maximum power from the previously mentioned power equation in the theory section is 9.25W. Given our maximum watts produced was 0.48 W (From Table 4), this yields an efficiency of 5.29%. This poor result is likely due to significant mechanical losses in friction and generator inefficiency, electrical loss in the testing setup, and aerodynamic loss due to the blade design.

CAD Drawings

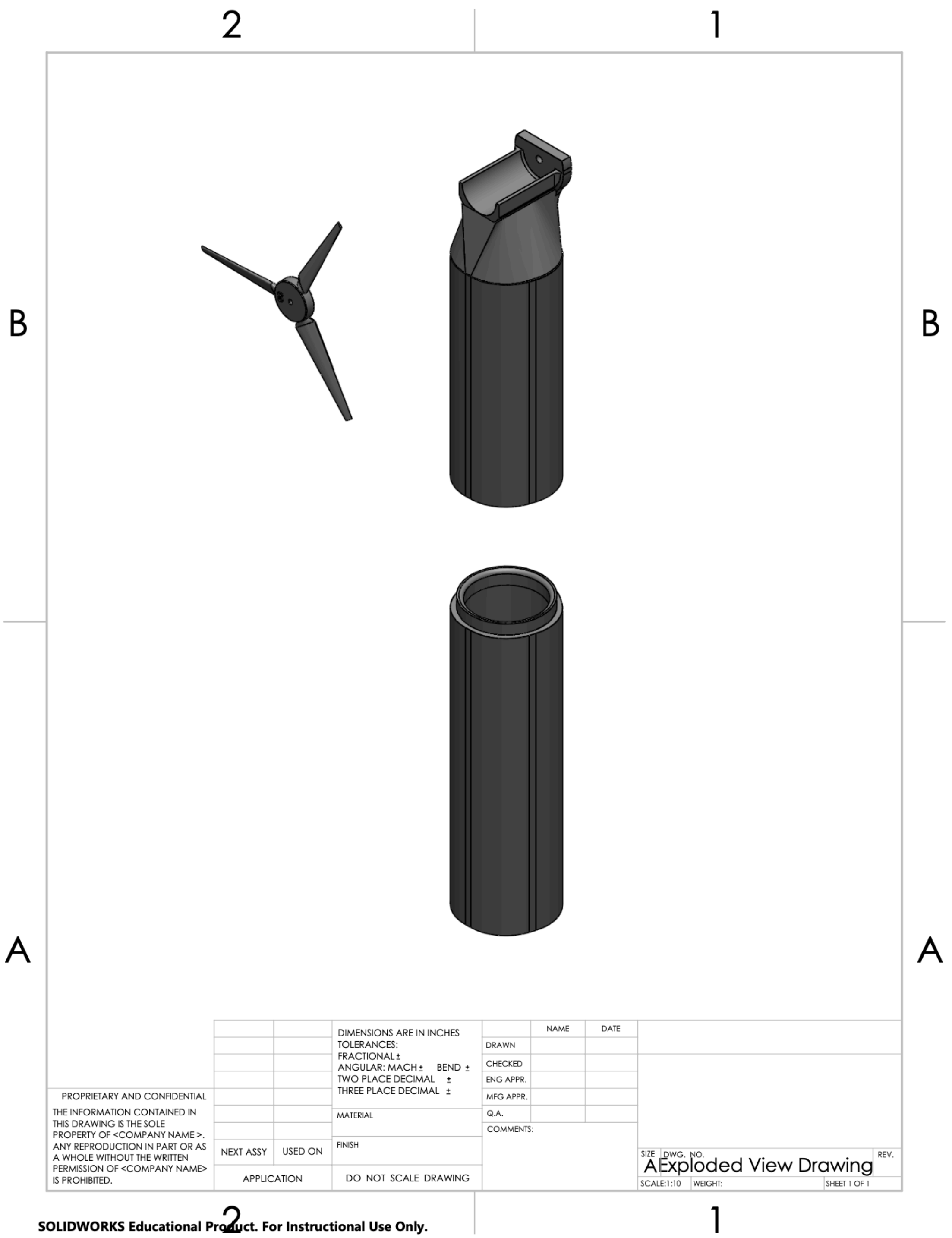

Figure 35: *3D Assembly Drawing of Designed Wind Turbine*

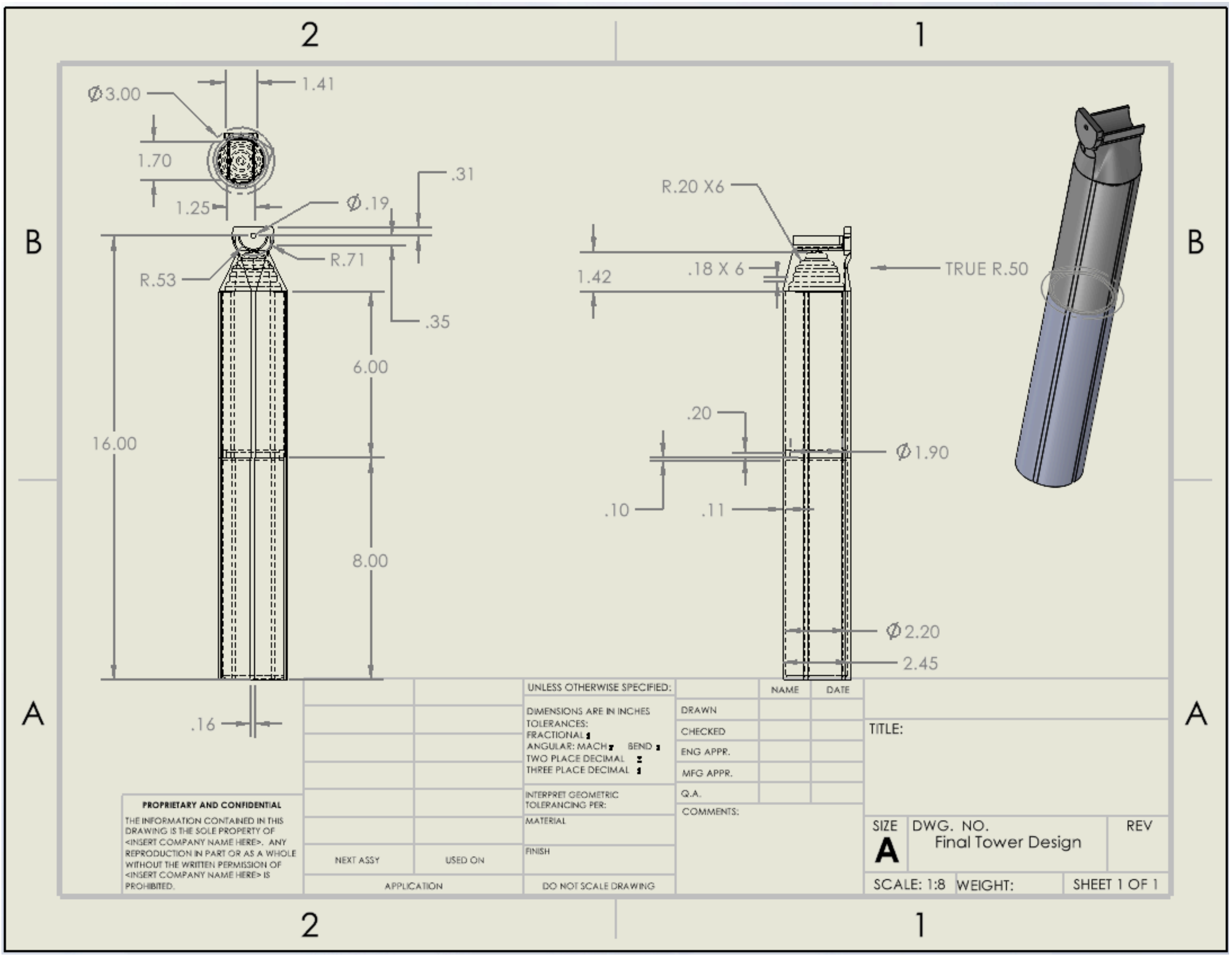

Figure 36: *2D Dimensioned Engineering Drawing of Tower*

Conclusions

After printing our final designs of the blade and tower design, we finally got to see our sketches printed and put to the test. Though we were confident with our blade design after our change from the initial NACA 4412 series profile to more closely mimic the DU97-W-300-flatback airfoil, which is known for its ability to maximize the lift coefficient while minimizing the drag, and had a sturdy base to help the blades generate the most power, unfortunately the results fell short of the requirements. To get full marks regarding the power category, our blade design was supposed to generate 2 watts which in reality it only generated .48 watts. On the other hand, the stiffness and weight of the tower exceeded their categories with the stiffness being over 8 N/mm and the weight being under 325 grams. Modern day wind turbines with efficiencies of around 25-45%, there is a lot of room for improvement through optimizing aerodynamic designs and stronger materials.

Though this wasn't the outcome we wanted, we walked away satisfied with the journey that ultimately led to making the final design. Most of us had to step outside of our realm of understanding and had to search for concepts and research done by professionals regarding how wind turbines worked to begin this project. We had to learn what the angle of attack and twist was on a blade and how they pertain to the power output of the wind turbine. In addition, we were learning how to operate a new CAD software which presented us with another roadblock. Regardless of these obstacles, we were able to make our sketch into a design within this foreign software and were able to print a fully operational wind turbine. This process we had to go through sharpened our CAD skills and gave us first hand experience with what it means to be an engineer which ultimately was the goal of this project. As a team of first years it also gave us our first experience as engineers in progress within the University of California, Berkeley.

Recommendations for Future Work

If we had more time, we would experiment further with the blade design. While we spent a significant amount of time working on the tower, it took away a little from the attention we gave the blade. Now that we know our power output of 0.48 watts was significantly lower than the target of 2 watts, we believe the blades likely played a role in this. In terms of specific changes, given more time, we would experiment with different blade profiles and further increase blade curvature since this can impact airflow. Additionally, we would also examine the angle each blade is positioned at and decrease it as needed to improve overall energy transfer.

One of the specific flaws with the blade we used was that the rough side of the blade was facing the wind instead of the smooth side. By being more strategic about the printing process, we can achieve a smoother blade without the use of sanding. Understanding different printing configurations and materials and their impact on power generation could help optimize the power generation output. The use of different tools resulted in a rough backside and edge of the blades from the supports. These imperfections created unexpected drag and were likely a main contributor to the lack of efficiency. Given the opportunity for future work we would like to explore the use of multiple higher end printers and material to get more precise prints, falling in line with our intended specifications.

Regarding the tower, we have already experimented with numerous models, but given more time, we would try a tapered design or lattice structure to observe how it affects power generation (KP Green Engineering, 2024). A tapered design would likely reduce wind resistance, leading to greater stability and better performance. A lattice structure could enhance the ratio of the tower’s strength to weight, giving us the ability to have a taller tower. Increased height would likely increase blade speed and rotations per minute, ultimately improving power generation.

Lastly, we would inspect how balanced the blades and turbine are together as a system since this likely affects power output through energy loss. This entails investigating how to evenly distribute the weight across both the blades and tower. Although our final design was mostly balanced and symmetrical, we were not able to spend as much time with it as a whole system since we worked individually with the tower and the blades.

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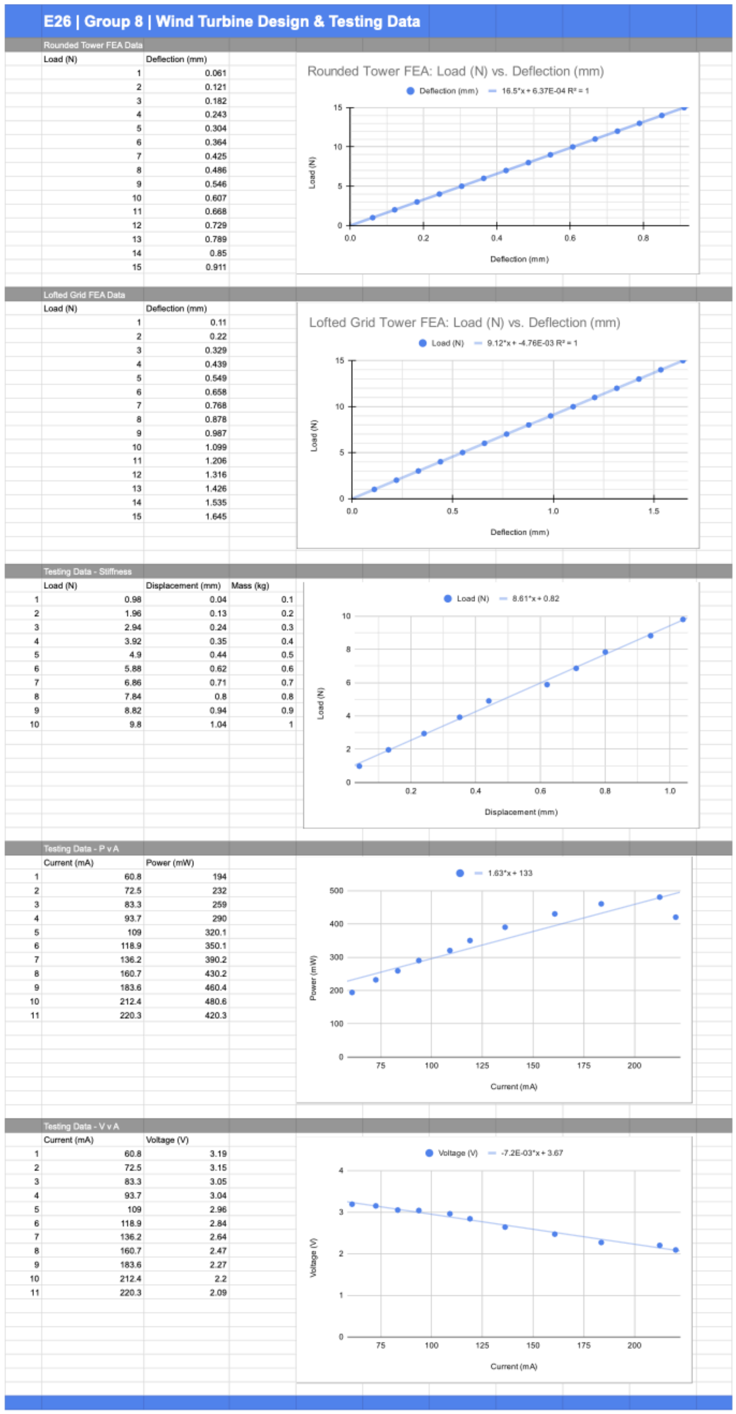
Appendices



E26 | Group 8 | Wind Turbine Design & Testing Data

Rounded Tower FEA Data

Load (N)	Deflection (mm)
1	0.061
2	0.121
3	0.182
4	0.243
5	0.304
6	0.364
7	0.425
8	0.486
9	0.546
10	0.607
11	0.668
12	0.729
13	0.789
14	0.85
15	0.911

Lofted Grid FEA Data

Load (N)	Deflection (mm)
1	0.11
2	0.22
3	0.329
4	0.439
5	0.549
6	0.658
7	0.768
8	0.878
9	0.987
10	1.099
11	1.206
12	1.316
13	1.426
14	1.535
15	1.645

Testing Data - Stiffness

	Load (N)	Displacement (mm)	Mass (kg)
1	0.98	0.04	0.1
2	1.96	0.13	0.2
3	2.94	0.24	0.3
4	3.92	0.35	0.4
5	4.9	0.44	0.5
6	5.88	0.62	0.6
7	6.86	0.71	0.7
8	7.84	0.8	0.8
9	8.82	0.94	0.9
10	9.8	1.04	1

Testing Data - P v A

	Current (mA)	Power (mW)
1	60.8	194
2	72.5	232
3	83.3	259
4	93.7	290
5	109	320.1
6	118.9	350.1
7	136.2	390.2
8	160.7	430.2
9	183.6	460.4
10	212.4	480.6
11	220.3	420.3

Testing Data - V v A

	Current (mA)	Voltage (V)
1	60.8	3.19
2	72.5	3.15
3	83.3	3.05
4	93.7	3.04
5	109	2.96
6	118.9	2.84
7	136.2	2.64
8	160.7	2.47
9	183.6	2.27
10	212.4	2.2
11	220.3	2.09

Figure A1: Google Spreadsheet with Data & Graphs[7]

7 https://docs.google.com/spreadsheets/d/1BaKugf-2CJw0IrfBl9hXFt-_8mM6RoC_HTh5rQ1Dj6w/edit?gid=0#gid=0

University of California
Mechanical Engineering Department – E26

Wind Turbine Tower stiffness test

Team member names: Jesus Cisneros Arreola, Helen Chang, Oliver Chang, Jeremy Cha, Urmi Sumant, Kalyan Piovesan Toussaint

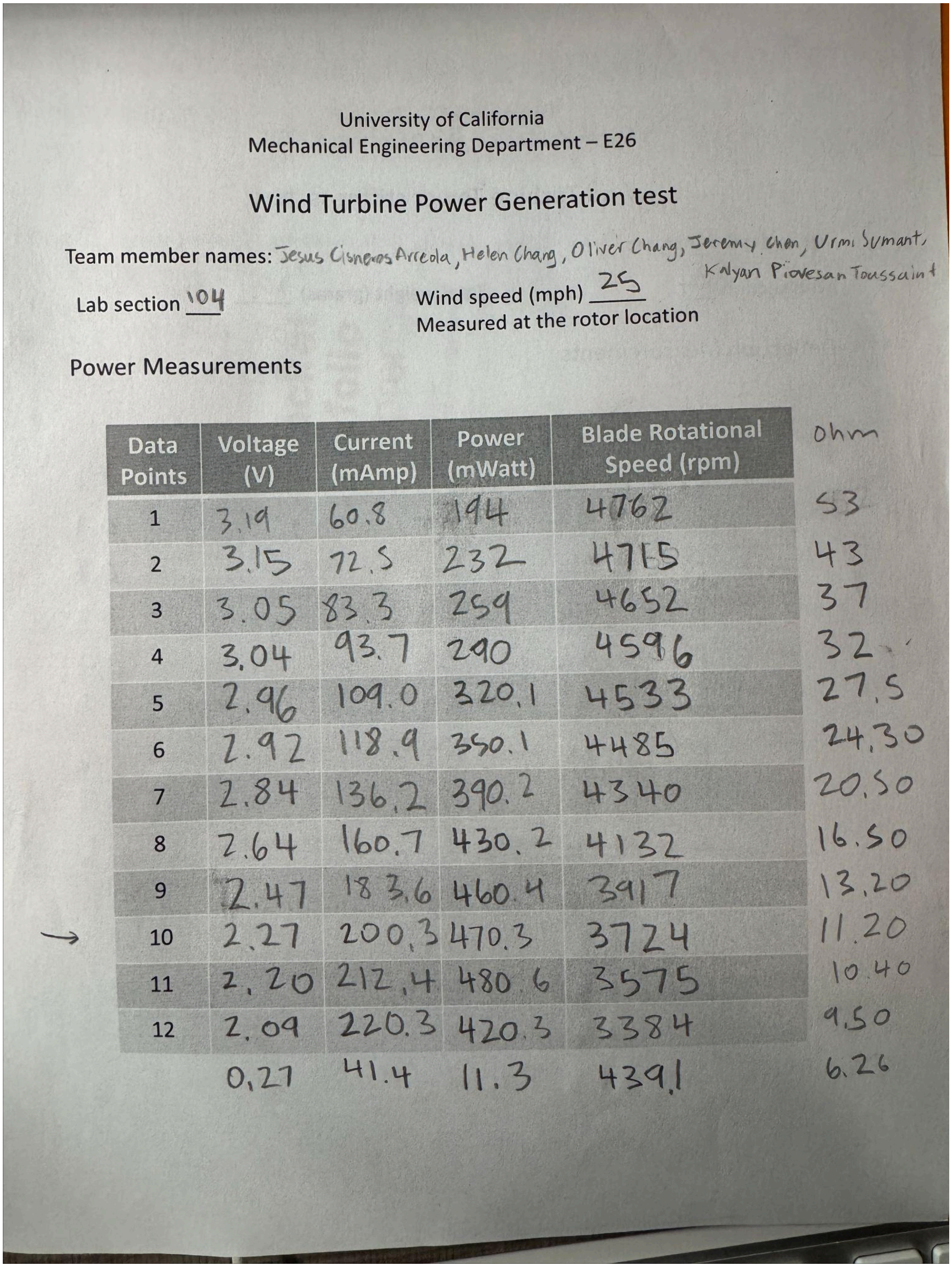
Lab section 104 Total weight (grams) 1077.8

1077.8 - 895
= 182.8

Deflection Measurements

Data Points	Load (N)	Displacement (mm)	Observation	Kg
1	0.98	0.04		0.1
2	1.96	0.13		0.2
3	2.94	0.24		0.3
4	3.92	0.35		0.4
5	4.9	0.44		0.5
6	5.88	0.62		0.6
7	6.86	0.71		0.7
8	7.84	0.80		0.8
9	8.82	0.94		0.9
10	9.8	1.04		1
11	19.6	2.39		2
12	29.4	3.8		3
	34.3	4.49		3.5

Figure A2: Stiffness Testing Data



University of California
Mechanical Engineering Department – E26

Wind Turbine Power Generation test

Team member names: Jesus Cisneros Arreola, Helen Chang, Oliver Chang, Jeremy Chen, Urmi Sumant, Kalyan Piovesan Toussaint

Lab section 104

Wind speed (mph) 25
Measured at the rotor location

Power Measurements

Data Points	Voltage (V)	Current (mAmp)	Power (mWatt)	Blade Rotational Speed (rpm)	ohm
1	3.19	60.8	194	4762	53
2	3.15	72.5	232	4715	43
3	3.05	83.3	259	4652	37
4	3.04	93.7	290	4596	32
5	2.96	109.0	320.1	4533	27.5
6	2.92	118.9	350.1	4485	24.30
7	2.84	136.2	390.2	4340	20.50
8	2.64	160.7	430.2	4132	16.50
9	2.47	183.6	460.4	3917	13.20
10	2.27	200.3	470.3	3724	11.20
11	2.20	212.4	480.6	3575	10.40
12	2.09	220.3	420.3	3384	9.50
	0.27	41.4	11.3	4391	6.26

Figure A3: Power Generation Test Data

NACA 4412	
1.0000	0.0013
0.9500	0.0147
0.9000	0.0271
0.8000	0.0489
0.7000	0.0669
0.6000	0.0814
0.5000	0.0919
0.4000	0.0980
0.3000	0.0976
0.2500	0.0941
0.2000	0.0880
0.1500	0.0789
0.1000	0.0659
0.0750	0.0576
0.0500	0.0473
0.0250	0.0339
0.0125	0.0244
0.0000	0.0000
0.0125	-0.0143
0.0250	-0.0195
0.0500	-0.0249
0.0750	-0.0274
0.1000	-0.0286
0.1500	-0.0288
0.2000	-0.0274
0.2500	-0.0250
0.3000	-0.0226
0.4000	-0.0180
0.5000	-0.0140
0.6000	-0.0100
0.7000	-0.0065
0.8000	-0.0039
0.9000	-0.0022
0.9500	-0.0016
1.0000	-0.0013

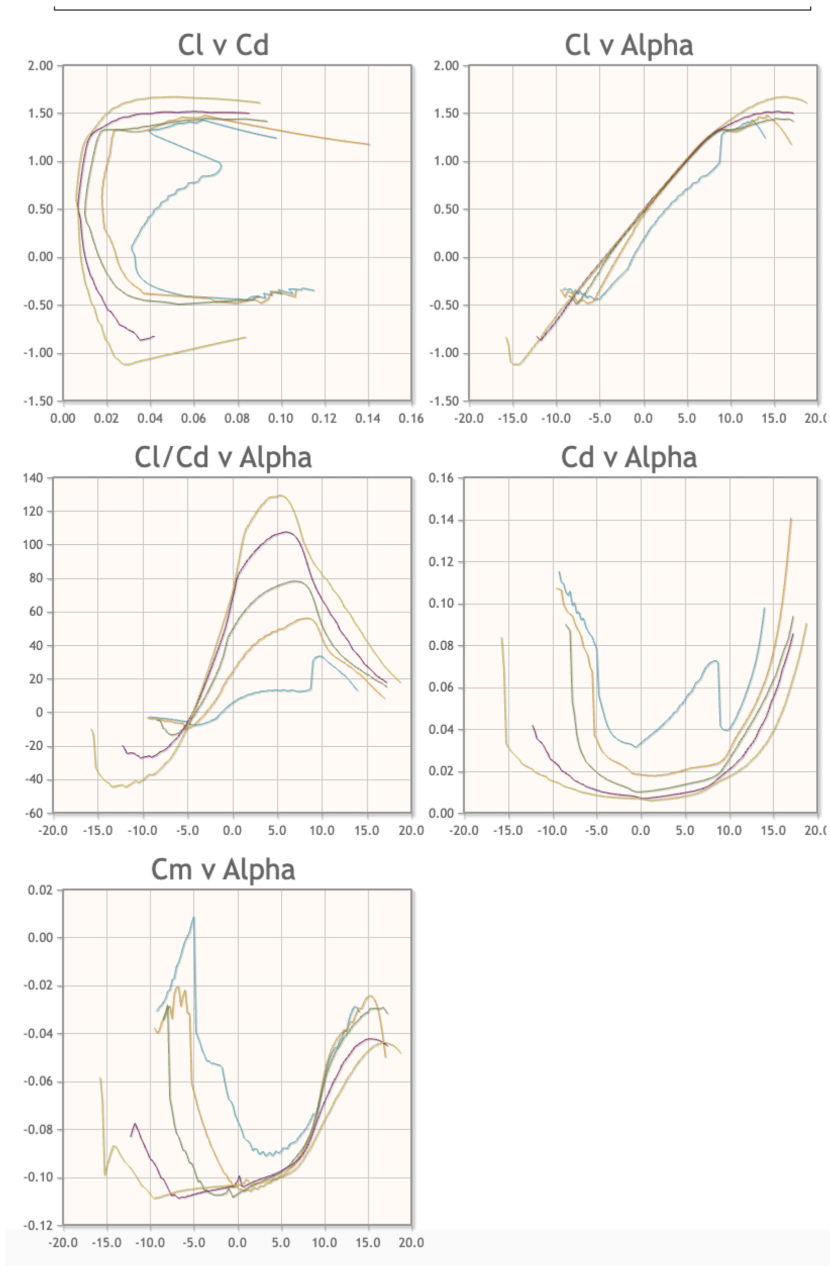


Figure A4: 4412 Profile Points & Graphs[8]

[8] http://airfoiltools.com/airfoil/details?airfoil=naca4412-il

Technical data sheet PLA

BCN3D

Description

PLA (Polylactic Acid) is a biodegradable, sustainable and food safe polymer made from organic sources.

It is the most common used filament in FFF 3D printers for its ease of use and awide range of applications, especially those not mechanically or thermally demanding. Definitely a good starting point to learn about the 3D Printing manufacturing process.

Properties

- Detailed and glossy surface quality
- Good tensile strength
- Rigid, fragile behaviour
- Good UV resistance
- Withstand operating temperatures up to 50 °C.
- Odor-free, ideal for educational and office environments
- Compatible with PVA supports
- Low humidity resistance

Recomendations

Plastics absorb moisture from the air. For long periods of time without printing, it is recommended to keep the PLA spools in a box or airtight container with desiccant to keep them dry.

PLA emits low levels of gasses and particles when printed. We recommend printing it in a well-ventilated area to ensure a healthy environment.

Filament specifications	
Diameter	Ø 2.85 mm
Max roundness deviation	≥ 95%
Net filament weight	750 g
Specific gravity (ISO 1183)	1.24 g/cm³

Mechanical properties	Typical value	Test method
MFR 210°C/2.16 kg	9.56 gr/10 min	ISO 1133
Tensile strength at yield	70 Mpa	ISO 527
Strain at yield	5 %	ISO 527
Strain at break	20 %	ISO 527
Tensile Modulus	3120 MPa	ISO 527
Impact strength-Charpy method 23°C	3.4 kJ/m²	ISO 179
Moisture absorption	1968 ppm	ISO 62

Thermal properties	Typical value	Test method
Melting temp.	115±35°C	ISO 11357
Vicat softening temp.	60 °C	ISO 306
Glass transition temp.	57 °C	ISO 11357

Printing settings	
Extruder temperature	190 °C - 220 °C
Bed temperature	65 °C
Speed	10-70 mm/s
Retraction speed	40 mm/s
Retraction distance	4 mm
Cooling fan	Yes
Minimum layer height	0.05 mm

More information about PLA: https://www.bcn3dtechnologies.com/en/3d-printer/filaments/#pla

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Figure A5: PLA Technical Data Sheet[9]

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9 https://www.bcn3d.com/wp-content/uploads/2019/09/BCN3D_FILAMENTS_TechnicalDataSheet_PLA_EN.pdf