2024 Collegiate Wind Competition

Report 2

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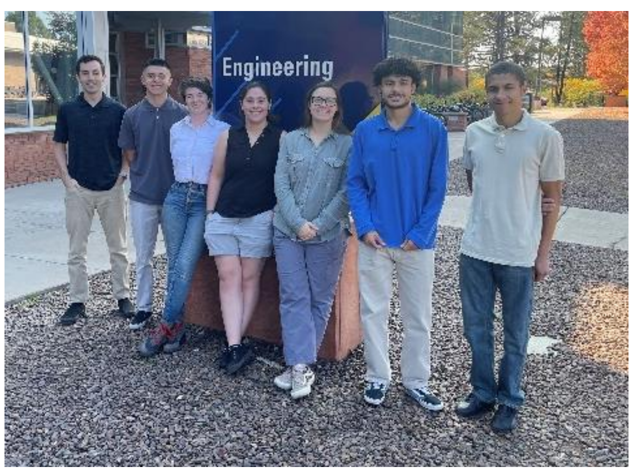

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DISCLAIMER

1 EXECUTIVE SUMMARY

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2 BACKGROUND

The following section introduces the project and what is required of the team in order to create a successful design, as well as how that success is ultimately measured.

2.1 Project Description

Late in the spring of each year, twelve universities nationwide are selected to compete in the Collegiate Wind Competition – a contest wherein each team tests a small-scale, off-shore, horizontal-axis wind turbine in a wind tunnel against requirements set out in that particular year's rulebook. The CWC begins with Phase 1 the summer before. At this stage, any motivated university can apply for a spot in competition. Of the applicant teams, as was mentioned, only twelve will be selected to compete (Phase 3). This selection is done through the mid-year report (Phase 2), which outlines any and all progress made toward the design of a turbine.

This project is important for a multitude of reasons. For one, renewable energy is one of the fastest growing engineering disciplines. Through this project, each teammate will gain skills that can be directly applied to industry. Along those same lines, it exposes future engineers to alternative energy sources, something sorely needed as the world faces the negative impacts of climate change. For NAU's capstone team specifically, it is important as it presents an opportunity to physically apply coursework from the last three years of school.

NAU's CWC team began the semester with a $2000 grant from the Department of Energy following approval of the team's application. Gore, a local engineering firm, has also donated funds in the amount of $5000. This brings the current budget to $7000. Assuming NAU advances to Phase 3, the DOE will allocate additional funds to the project, as is protocol for all teams that earn one of the twelve spots. For this competition cycle, the grant is $15000. Therefore, the total projected budget is $22000. Capstone now requires internal fundraising in an amount equal to 10% of total funds. This equates to $2200. The current plan for obtaining this money is multifaceted, with most of the required fundraising coming from university grants like ASNAU or the Office of the Dean.

The DOE's goal is to prepare engineering students for industry. In their words, "...the CWC's objective is to prepare students from multiple disciplines to enter the wind energy workforce by providing real-world experience for researchers, scientists, engineers, educators, project managers, and business and sales forces. Wind-energy-specific advanced degrees are not required for many of these jobs, but having wind-related experience is highly valuable" [1]. This is ultimately accomplished through the three contests – turbine design, connection creation, and project development. Turbine design allows the team to learn application skills like manufacturing, failure analysis, and prototyping that directly translate to industry. Connection creation allows professional networking, which is necessary in today's collaborative world. Opportunities may present themselves based on who you know. Additionally, it gives insight into what renewable energy engineers are working on right now, which could direct a team member's career goals. Project Development allows the team to learn all the logistical decisions involved in getting a wind farm operational. While the design of the turbine is, of course, important, equally as important is where it will be placed and how its electrical output will best set aside for use. It is useful for students to be exposed to both the design aspect of wind energy as well as the more administrative aspects like cost and location.

2.2 Deliverables

The major deliverables for the 476C course include: three presentations showcasing the research and development of the project as the semester progresses; two reports which condense the information presented in the presentations into a technical report; two physical prototypes near the last quarter of the semester; finally a website which will be there for the public to see what the project is about and to give information/contact information about each team member.

The major deliverables for the client/competition can be split up into two sections of the competition: the turbine design contest and the turbine testing contest. For the turbine design contest there are two main submissions: the phase 2 midyear milestone submission and the phase 3 final turbine design submission. The midyear milestone submission consists of a one page write up highlighting the team's design progress and prototype fabrication, the main point of this being a short summary of our progress made towards the assembly of a prototype. The final turbine design submission consists of a 15-page technical design report which explains the entire design process as well as foundation structure, a 10-minute presentation and Q&A at the final event talking about the technical design, and an overall competition poster which will be shared with project development and connection creation.

The turbine testing contest also has deliverables due at the middle and final phases of the academic year. The midyear consists of a video submission which will be five-minutes describing and showing the team's progress on a working prototype, as it is important for the team to iterate and produce a couple of prototypes before reaching the final design. The final turbine testing submission before the actual competition will be a three-minute timed assembly video which "must include everything from after the foundation has been installed and aligned and the stub placed on top by the competition staff up until the team declares they are ready for testing," the video is required this year because there will only be an allotted three minutes to assemble the turbine at the actual competition, and an additional three minutes for turbine commissioning.

Finally, a midyear connection creation report and final connection creation report will also need to be submitted. Both sub teams will work together to create stronger connections with folks in the wind industry and our local communities as per the competition. All midyear submissions will be due on December 14th, 2023, while all final submissions will be due April 14th, 2024.

2.3 Success Metrics

Most of the success metrics can be measured quantitatively and linked to our Customer Requirements and Engineering Requirements, where major design requirements such as max rotor plane area and max voltage are discussed. Though this is obvious, having good working prototypes by the time they are due will be a great success metric, even better would be having at least two iterations of a prototype made by the time they are due.

Team success can be found in setting up testing rigs and learning how to use certain testing devices. Each of the members should become familiar with the testing apparatuses to be able to conduct additional testing if needed by someone else but they are not available. Once we have a good idea of testing, we will be able to refine our calculations to produce "goal values" which the team will strive to achieve.

In general, the biggest success metric would be making it past phase 2 and earning the $15,000 cash prize to continue development towards bettering our design to compete at the phase 3 final evaluation. If this is to occur, the next biggest success metric would be placing at least in the top 5 at the final competition.

3 REQUIREMENTS

3.1 Customer Requirements (CRs)

The customer requirements are the specifications of our project that are deemed necessary by our customers, specifically the DOE. This team's customer requirements include not being able to excavate sand when placing an anchor foundation in the sand. This is a new rule that the DOE have included in the past few years of the competition where the team cannot use any tools to move around sand for the foundation. Something that goes along with this requirement is that the team is also not allowed to touch the water with their hand or tool when placing the anchor into the sand. The next requirement is that the turbine must be of an original design, which means that the teams cannot take to design of a past turbine and reuse it for this competition. The next requirement is that the team also cannot use primary components from previous teams. This means that the team will not be able to take certain designs or components of past teams and use them in this turbine, like taking the blades from a previous design and use them for this turbine. An exception to this is if the team can back up decisions with mathematical reasoning of why the team used a similar motor or blade shape after doing an analysis of that particular part. Another requirement is that the design is safe and is designed within high factors of safety to ensure the turbine is safe. The design should also be durable because one of the DOE tests for the wind turbine is durability test so this team must make sure that the turbine is durable and will be able to pass this test. The next requirement is that the turbine needs a generator that produces power output at variable wind speeds. This is important because a part of the turbine testing is being able to produce a consistent power output at different velocities. Another requirement is that there is a convenient base plate attachment for the three testing bolts. This is important because the team will need to create a base plate that can attach to the test bolts in order to qualify for testing the turbine in the wind tunnel. The next requirement is that the turbine can be assembled quickly because this year the assembly will be timed, and the team will have a limited amount of time to assemble the turbine. The last customer requirement is that the design is weight conscious which means that each part is designed correctly for what the best weight is needed for each sub-part. The anchor should be designed to be as light as possible so the team can get the max number of points for it while having the turbine to be designed heavy to support the foundation.

3.2 Engineering Requirements (ERs)

The engineering requirements are the quantifiable requirement specified by the DOE for the wind turbine competition. The first requirement is that the whole turbine profile must fit within a 61cm x 122cm door to be placed into the wind tunnel. The next requirement is that the rotor and non-rotor system must fit within a max $45cm^3$ volume. This means that the blades and nacelle cannot be greater than 45cm. The next requirement is that the anchor dimensions must be less than 30cm in length and width. Another requirement is that the turbine must have a braking capability for 3 different scenarios. The first one is for when a stop button is pressed, the second one is for a loss of power and the third one is for when the PCC had a voltage greater than 48V. The next requirement is that the tower baseplate thickness must be less than 16.1mm. Another requirement is that the anchor must be made from a ferrous metal and can only have a thin coating if the team would like to put a coating on the anchor. The next requirement is that the anchor cannot penetrate the sand more than 20cm. So, from the all the requirements for the anchor, the max dimensions will be 30cmx30cmx20cm for the length, width, and height of anchor foundation. Another requirement is that the top 8cm of the turbine tower diameter must be less than or equal to 3.81cm. In relation to that the rest of the tower diameter must be less than 15.8cm. This means that the entire tower can have a diameter of 3.81cm or have two different diameters for the top and bottom of the tower. The next requirement is that the power curve fluctuation may not exceed a 5s interval of ±10% power average at wind speeds of 5-11m/s. Another requirement is that the noise from the power electronics must be between 50-22.5kHz. The next requirement is that the rotor midplane must be 60cm±3cm above the flange top. This just gives the team the specified dimensions of how tall the tower and nacelle should be. Another requirement is that the power must be at equal value or close to for the 11m/s bin compared to the 12-14m/s bin. Having the power be similar for different speeds will mean a better score for the turbine. This is similar for the rotor RPM where is must be the same or close for different velocities to get the best score. Another requirement is that the cable passthrough must use cable glands, quick connections at the cable end and is a 4.5m minimum cable length. Another requirement is that the electrical systems must be ground through the baseplate with 100kohm resistance. The last engineering requirement is that there needs to be a 4mmx20mm open rotor area for reflective tape placement. This is for the tachometer reader so the judges can measure the RPM of the turbine during testing.

3.3 House of Quality (HoQ)

The full House of Quality shown in **Appendix A** was largely built based on the CWC 2024 Phase 2 Rules and Guidelines document provided by the Department of Energy. Engineering requirements are explicitly generated using scoring criteria and requirements from the durability testing, safety check, and power performance sections of the competition. As described thus far, the engineering requirements vary from binary criteria to ranged values, where in most cases the team will achieve favorable testing numbers based on an analytical performance approach towards these ranged requirements. A majority of customer requirements were generated based on non-quantifiable maximum point scenarios described in scoring sections of the competition. The remainder are concerned with the ease of use and safety of the device.

Relationships among the engineering requirements and customer requirements are built on how well correlated the two are, on a scale of 0-10, using only 0, 1, 5, and 9 for simplification. The engineering requirements are compared similarly, using a plus (+), minus (-), or period (.) to represent a positive, negative, or no correlation respectively. It should be noted that most of the engineering requirements are uncorrelated. This is due to their specificity, where most of the requirements are geometric or electrical and the team has the flexibility to design around both.

Other quantitative measurements are listed at the bottom of the HoQ: technical importance, importance as a percentage, priority, rank, and difficulty rating. Percentage importance and difficulty are of particular interest. One purpose of the HoQ is to provide a quantitative method for analyzing a set of requirements. For this project, importance is calculated in a range of 1% to 12%, however all engineering requirements and most of the customer requirements are mandatory per the competition guidelines. If the team aims to score with distinction, the importance of all engineering requirements must be equal. Perhaps the importance rating might give the team a quantitative reason for approaching certain design choices in a specific order. The difficulty of each engineering requirement is equally affective to the team’s success. If a difficulty value is congruent to its importance the team should focus on that element of the design first while approaching less complicated and integral aspects later in the project.

4 Research Within Your Design Space

4.1 Benchmarking

Benchmarking has proven to be very important for the turbine design team. The point of the competition, according to its organizers, is not to reinvent the wheel each time. Rather, each team is meant to learn from previous submissions. Past turbines have served as inspiration and insight for design decisions and general concept acquisition. Additionally, it is important to be aware of previous designs so as to not inadvertently copy configurations.

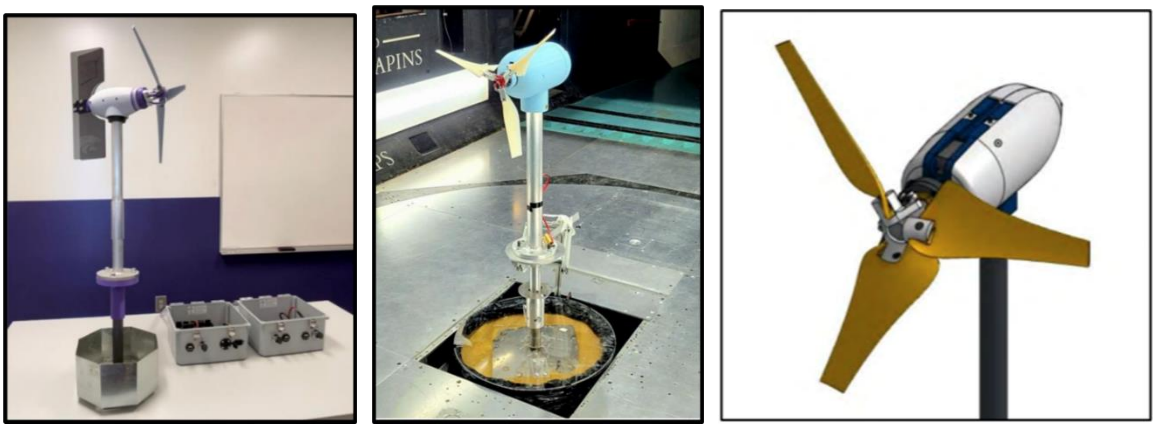


Figure [1] - From left to right: Kansas State 2023, Johns Hopkins 2023, NAU 2022.

Figure [1] shows three assemblies that the team considers state-of-the-art. First is the most recent competition's overall winner – Kansas State University. The CWC handbook has not drastically changed from 2023 to 2024; thus, Kansas' turbine is a great study tool for subsystems like the anchor, which has relatively strict requirements. Next is Johns Hopkins University, who placed first specifically in turbine design during the 2023 competition. This turbine can serve as a comparator for what works and what does not based on the DOE's requirements. Additionally, the team can review what of their design won them the most points and how NAU's 2024 turbine might follow suit. Lastly is NAU's 2022 submission, which placed second overall. This is, perhaps, the best resource the design team has simply because there is physical access to it. It has been hugely useful to understand a complete turbine iteration through taking it apart and putting it back together. Its benefit is the team can more closely study certain geometries and interactions between subsystems. Looking at the 2022 report, the team can improve upon anything that fell short in its respective category. What stood in the way of NAU taking first place that year?

4.2 Literature Review

4.2.1 Tower and Anchor – Ellie Freeman

Tower and Anchor

Model tests on performance of offshore wind turbine with suction caisson foundation in sand [5]

When designing an anchor system there are many different types that could be used in this project. This source is an article specifically about a suction caisson foundation in sand for an offshore wind turbine. The calculations and information for this article is for a full-scale foundation while for the project the foundation will only be 30x30x20cm for the max volume. But this article is still relevant for designing a suction caisson foundation because it gives good information on how to design one even if it is on a smaller scale. This article goes through the performance of a steel caisson after installation and analysis the foundation design for different penetration velocities in the sand. So, this is relevant information when considering to make the foundation a suction caisson foundation for this project.

Dynamic penetration of a flying wing anchor in sand in relation to floating offshore wind turbines [6]

This dissertation is about a different foundation system for offshore wind turbines called a flying wing anchor. This anchor is a kite-shaped plate anchor that is installed by free-fall penetration and then is rotated in position to anchor itself into the sand. The anchor is launched into the sand and follows a curved path until it reaches the desired depth and then is rotated until the anchor is in the position to lock itself into the sand an provide the forces necessary to keep the foundation from moving. This is a good article for generation different designs for the foundation/anchor system because it discussed a specific anchor design for an offshore wind turbine. It helped with the concept generation for creating a bunch of different designs.

Evaluation of theoretical capacity models for plate anchors in sand in relation to floating offshore wind turbines [7]

This is another dissertation about three different anchor types, a vertically loaded square plate anchor, an inclined square plate anchor, and a drag embedment anchor. The objective of this paper was to analyze existing theoretical and empirical capacity prediction models for vertical and inclined plate anchors in sand. Having three different anchor types in a source is very helpful because the dissertation discussed a few different anchor designs that this team will be able to consider and create different concepts from this. The dissertation also provides valuable information about what to consider when design an anchor and foundation system for an offshore wind turbine. For example, the dissertation mentions that when designing or considering a certain anchor type you must look at the soil conditions. Each location for an offshore wind turbine will have different soil conditions so each one will have a different anchor type that will work better than others. This is something that this team will have to consider why designing an anchor system.

Shigley's Mechanical Engineering Design [8]

This source is a book about the fundamentals in mechanical engineering design and some standards of industrial components. This book was very helpful for designing the best tower design for this project. The book has many formulas and equations for find the normal, shear and bending forces on the tower which was important in calculating the overall bending moment that the tower goes through from the forces on the turbine thrust and drag forces. Using this book and the Wind Energy Explained book the calculation for the tower and some helpful calculations for the anchor systems were found, which helped in the concept generation process for these two systems. From these overall forces on the tower system and with the equations in the book the team will be able to also find the stress and strain for the tower with different materials to find the best material and size for the tower within the constraints given from the DOE rules.

Wind Power [9]

This book discusses many things for designing and building a wind turbine but there are also specific sections for designing the anchor/foundation system of a wind turbine whether it is on land or offshore. There were many different anchor types discussed in this book which was very helpful when generation concepts for this project. While the book does focus on full scale wind turbines these is still a lot that can be learned from this book when considering and generation different anchor designs.

Wind Power Generation and Wind Turbine Design [10]

This book goes into the different foundations that could be needed for a wind turbine. While for this project the foundation and anchor system are the same, rather than two different systems for full scale wind turbines, there is still something to learn and consider for designing the foundation/anchor from other full-scale foundations. Because the foundation and anchor are going to be built as one system, it will be important to study both different foundation and anchors to create one functional and safe foundation/anchor system that will support the turbine at different velocities.

Wind Energy Explained [11]

This book has a lot of the fundamental concepts and equations that are needed when designing a wind turbine. This team was able to use this book for many of the different calculations and formulas needed when generation concepts for the different subsystems. For the tower and foundation there were and few formulas that were used from this book along with the formulas from Shigley's Mechanical Engineering Design book to make the calculations necessary to design the tower and foundation/anchor and justify those calculations mathematically.

4.2.2 Blades – Holden Gardner

Structural Design of a Composite Wind Turbine Blade Using Finite Element Analysis [12]

A 5kW wind turbine is the subject of a study to increase power output while decreasing construction costs for similar systems. The blades were developed using the blade element theory and iterative finite element analysis (FEA) techniques. The iterative process similarly considers much of what the CWC24 team is looking towards in their upcoming design evaluations: material properties, aerodynamic loads, static and dynamic analyses, and optimal blade stacking arrangements. Additionally, the article describes a few details required in making composite blades and how the process can be improved for future iterations. Overall, the team has much to learn from this paper due to its comprehensive coverage on small-scale wind turbine optimization.

Finite Element Analysis of Composite Wind Turbine Blades [13]

Like the previous paper, this article delves into a numerical method for solving optimization issues in wind turbine blade geometry. The materials used in this analysis are the largely similar as well, leaving the FEA methodology worthy of inspection. ANSYS finite element software is shown via meshing, property selection, and boundary condition identification steps for multiple materials. The article concludes that blade mass decreases 442.6% compared to steel alternatives and maximum principal stresses occur at only 11.54MPa. While few conclusions extend beyond these basic facts, the blade design team finds invaluable advice from the order of events and analysis details expressed in the article. It is likely that a very similar process will be taken to complete blade root optimization in the coming weeks.

4.2.3 Braking and Motor – Holden Gardner / Niki Wilson

Braking System

Wind Turbine Trailing Edge Aerodynamic Brakes [14]

Overspeed protection is an important factor in protecting the structural integrity of a wind turbine at high wind speeds. Trailing edge devices are a focus of researched around the 1995 release date because more sophisticated analytical models were beginning to develop solutions to aerodynamic problems. It is concluded in this paper that trailing edge configurations are favored among other systems such as full-span or partial-span pitch control systems because of their cost efficient and integrable designs. It is important for new systems to be adaptable to existing active pitching systems to give an element of active and passive control to wind turbines. In general, trailing edge devices are not as structurally intrusive as other methods and the aerodynamic properties (low lift/drag ratio and high drag) present conclusive data towards their effectiveness in overspeed protection. This paper is particularly useful to the aerodynamics design team because it well defines dual blade characteristics, allowing aerodynamic braking and efficient power production in the same geometries.

Method and Apparatus for Wind Turbine Braking [15]

Many current utility-scale wind turbines have redundant braking systems which includes actuated brake pads from hydraulic, spring, or battery power and a pitch-to-feather system. Such systems, once in combination, allow the turbine to brake under power failure scenarios but strongly neglect subsequent vibrational stresses while in a feathered position. Additionally, quick braking is common among these systems and provokes additional stresses to arise in the turbine rotor. This patent details a system in which a processor will selectively control blade pitching based on force feedback from a specific component on the turbine. This system is in place to reduce forces imparted on the rotor due to braking. While the force concentration analysis section of this paper is useful for utility-scale turbines, the team may overlook this analysis for the time being and focus on the sections which detail how electronic parts of the turbine communicate to allow passive and active braking.

Designing Wind Turbines [16]

The "Engineering and Manufacturing Process in the Industrial Context" textbook is one source used by the team due to its comprehensive coverage of practical concepts in designing and manufacturing a wind turbine. The book itself was derived from the practical aspects of real development projects and focuses on drive train engineering while supplementing with manufacturing techniques. Like most textbooks, it begins with basic concepts and theorems then expands on them with a modern analytical perspective. The main focus remains on utility scale turbines, however the concepts covered are easily scaled and applied to the team's purposes. Most of the book's use will come in later stage prototyping and testing brakes and shaft supports.

WC Branham Website [17]

WC Branham is an industry professional who specializes in pneumatic and hydraulic machinery. Automated components such as linear actuators, gearboxes, and caliper disk brakes. This company produces components unique to wind turbine systems. Ones usable in the team's small-scale nacelle. Their options are not limited to a strict geometry as well, they supply air cylinders and pneumatic actuators of cable-type and round-rod categories. Should the team choose this method of actuation for the braking and pitching system, this company will be an excellent resource for selection and potential purchasing.

Regal Rexnord Article [18]

Rotor and yaw braking systems are explained based on utility necessity in this brief article. Much of the main rotor braking system is described in emergency braking context. Determining the necessary braking torque requires equating it to load torque with considerations to other mechanical factors such as disc temperature. The yaw brakes are released when the anemometer signals a change in wind direction. Load on the yaw motor from the brake creates a clamp on the system thus preventing erratic motion from wind loads. Many yaw systems are operable under power loss conditions. This article gives great context to the team on mechanical considerations for braking systems as whole, how they can fail, and what design elements to incorporate into the design of a wind turbine to accommodate for adequate braking power.

Shigley's Mechanical Engineering Design – Chapter 16 [19]

This chapter describes the function of brakes and introduces several of their available configurations. The most common application of these assemblies is in motor vehicles. However, the concept can be applied to any machine in need of braking. Section 16-6 specifically details disc brakes, which are the chosen type for the CWC wind turbine. It includes an example that walks through the calculations for pressure, actuation force, and force location.

Brakes 101 [20]

This short article introduces the braking system on a full-scale turbine. It describes where the assembly is generally located along the shaft and how that affects overall performance. It also explains possible constraints and restrictions. It is important to understand what braking systems in standard wind turbines look like and how they work in order to effectively design a brake for the CWC's scale model.

Front DISC Brake System for the V4 RC Car [21]

This video records the creation and assembly of a disc brake system for a remote-controlled car. Although the application is very different, the concept is relatively identical. It is a useful reference for how to scale down a configuration that already exists as well as any design adjustments that need to be made in order to more specifically optimize the configuration for the project at hand.

Motor System

Fundamental and Advanced Topics in Wind Power [22]

This textbook is standard in comparison to other wind power texts. Blade element theory, the Betz equation, tip speed ratios, lightning protection measures, and foundation mechanics are some of the many topics covered in this textbook. What will be most helpful to the team is its comprehensive coverage of induction motors, electric generators, and static converters. Understanding these aspects of a wind turbine will prove to be beneficial in communicating to the Electrical Engineering sub-team as well as performing our own analysis backed motor selection. The textbook provides equations for power and torque which will allow the team to quantify and make clear conclusions from rotor performance.

Development of Wind Turbine Simulator for Wind Energy Conversion Systems based on Permanent Magnet Synchronous Motor [23]

The most likely motor type to be used in this project is a permanent magnet synchronous motor (PMSM). This paper describes a table-top method for simulating wind turbine output to a generator. By using an original power and torque equation, wind shear torque oscillations can be plotted over time. Similarly, wind speeds, theoretical torque, output torque, power coefficient, and tip speed ratios can be plotted over time for comparison to real wind turbine values. The conclusion of the paper states the PMSM, intelligent power module (IPM), and PC connection for wind turbine simulation is a success. This paper is important to the team to best understand how a PMSM can be linked to analysis tools such as an IPM or dynamometer then connected to analysis software, MATLAB/SIMULINK for example. The team will have much to learn from these techniques once testing begins in the Spring.

Ecology Center DIY Article [24]

This brief article focuses on the differences between PMSM's and alternators in wind turbine motor application. The writer weighs voltage output, efficiency, RPM, size, weight, and ease of maintenance when comparing the two and concludes that choosing one motor over another completely depends on the budget and goal turbine size of the builder. Amazon is a perfect place to compare and purchase motors however a warning is given towards using eBay. The capstone goals outline a do-it-yourself project, thus the team can benefit significantly from the practical nature of the article. Motor output in the testing phase may use the voltage and RPM relation outlined in the article to simplify testing conclusions.

4.2.4 Pitching and Yaw – Niki Wilson / Ellie Freeman

Pitching System

Wind Energy Systems [25]

This textbook details all relevant components included in a wind turbine and their use. It also describes the processes involved in wind conversion. Chapter four outlines the difference between pitch regulation and stall regulation. In essence, stall regulated turbines have fixed blades that organically slow down when the fixed angle of attack is not at optimum. In contrast, pitch regulated turbines feature blades that can be adjusted through actuated linkages. This information is useful as a baseline in our preliminary pitching system designs as it parses the benefits or limitations of each configuration.

Blade-Pitch Control for Wind Turbine Load Reduction [26]

There are several different pitching system configurations in use today. This thesis reviews each and their respective design cycle. This is useful for the team in terms of the concept generation as it acts as a reference for which geometries are popular in industry and their relative benefits. Their geometry largely affects the range of angle of attacks allowable.

Wind Turbine Aerodynamics [27]

This is a lecture series detailing the aerodynamics involved in the operation of a wind turbine. One such lecture explains the importance of pitch regulation through fluid mechanic principles. When a turbine blade's angle of attack is too high, the air separates from the surface of the blade and increases in turbulence. This significantly increases the drag and decreases the lift. It is important to fundamentally understand what is physically happening when the rotor is rotating so as to more innovatively apply the concept.

Determination of the Angle of Attack on a Research Wind Turbine Rotor Blade Using Surface Pressure Measurements [28]

As has been previously mentioned, adjustment of the angle of attack is one of the main purposes of a pitching system. The angle itself is hugely important in the optimization of the turbine as it affects power extraction. This article explains how one calculates the angle of attack. It should be noted that much of the data available to estimate optimal angle of attack was developed empirically per airfoil.

Mathematical Model of Variable Speed Pitch Regulated Turbine in a Wind Energy Conversion System [29]

This succinct article provides a comparative method of calculating angle of attack using trigonometric relationships between the pitch angle and tip speed ratio. The optimal angle of attack of a wind turbine falls in the range of 25°–35° with a tip speed ratio of about 7 at Betz. Though many of the calculations are a bit complicated at this point in the project, it is useful to know where it's headed.

Actuonix Motion Devices [30] - Ellie

This is a website for micro linear actuators and is the type of actuator that the 2022 team used. There are many different micro actuators that this company sells, each one has specific dimensions and stroke lengths. The one that is needed for this project must have a stroke length of at least 20mm and has a force between 12 N to 50 N and on this website, there are a few options that can be used for the pitching system.

McMaster - Ball Bearings [31] -Ellie

This website has several ball bearings that we can use for the swash plate. There are many different types of ball bearings and dimensions for these bearings. So, this website is helpful with finding which dimensions would work the best for the swash plate and the shaft size. For prototype 1 the team has to use a ball bearing that wasn't the best size for the shaft and other dimensions so for prototype 2 searching for the proper sized ball bearing would be beneficial in the long run.

Wind Energy Explained - Aerodynamics of Wind Turbines [32] -Ellie

This specific section of the book was helpful for the pitching calculations that are needed to figure out the max force that the linear actuator will need for the team to use for the pitching system. There is the pitching moment that needs to be calculated from the moment coefficient that the team will be able to find from QBlade. This section of the book helps explain the different formulas and the overall pitching system.

Yaw

Yaw Systems for Wind Turbines [33]

This article provides a brief overview of what a yaw is in terms of a wind turbine. Wind is multi-directional. A turbine best extracts kinetic energy from the wind if it is facing it head-on. Therefore, a series of gears and bearings at the intersection of the tower and the nacelle rotates the nacelle and the rotor until it is optimally located. Understanding the basics of yawing is useful as a baseline as the team sets out to design a system.

SKF Bearing [34]

This website is a digital library of standardized bearings across all categories. Yaw systems are primarily composed of bearings. Therefore, this is good reference for bearing selection as it contains all relevant data like bore diameter or load rating. Rather than completely starting from scratch, it is more efficient to design a system with a few bearings in mind and then iterate until satisfied.

Review of Control Strategy of Large Horizontal-Axis Wind Turbines Yaw System [35]

This article details the key differences between active and passive yaw systems. Active yaws are those with a yaw drive that is purposefully manipulated to turn the turbine. Passive yaws simply use the aerodynamics of the turbine's overall geometry to adjust its location relative to the wind's direction. As per the handbook, the wind generated by the wind tunnel will not change direction. However, the platform the turbine must be on may not face the wind head-on. Thus, some sort of yaw is necessary to ensure the most power extraction. This article can be used to best decide which route to go – active or passive.

Developing Wind Power Systems Using MATLAB and Simulink [36]

This website walks through the process of using MATLAB to simulate wind conditions for a given configuration. This is hugely useful for prototyping purposes as the team can use it to collect quantitative data on design decisions like active versus passive yawing.

4.2.5 Nacelle, Shaft ,Mainframe - Sergio Zuniga

Shigley's Mechanical Engineering Design - Chapters 7 and 11 [37]

Chapter 7 of this Mechanical Engineering design textbook describes the entire shaft design process in a way that is helpful for new designers such as us. The chapter talks about shaft material selection, layout, designing for stress, some of which will be seen in the mathematical modeling section of this report. The last section of the chapter goes into limits and fits which ties into chapter 11 of the book titled "Rolling-Contact Bearings." This chapter helps a new designer make an informed decision on what kind of bearing is necessary for the application they are using it for depending on the results. This is useful as the turbine will need at least one bearing to help mount the shaft and rotate it with little friction.

Machinery's Handbook [38]

Machinery's handbook goes into depth more than Shigley's book does on similar topics. The book covers subjects such as mathematics, mechanics, materials, machining processes, fasteners, machine components, and much more in detail, so much so that the book is about 3000 pages. This handbook will be good to reference once a proper shaft analysis has been done following the method found in Shigley's and the machining process on the shaft begins. Not only does it offer calculations and advice, but it also includes information about various standards and guidelines that should be used during the design and manufacturing process.

The Engineering Toolbox [39]

The Engineering Toolbox is a website with various resources, tools and information for engineering applications. This website was referenced when doing the calculations for the initial shaft analysis as it has material properties for various commonly used machinable metals. Further down the line a more proper shaft analysis will be conducted, and again engineering toolbox will be heavily referenced again to calculate factors of safety and make sure desired materials will not fail.

Wind turbine nacelle testing: State-of-the-art and development trends [40]

This article provides an overview of current and emerging trends in nacelle testing, the nacelle being what houses the drivetrain system. With factors such as wind loads, emergency stops, rotor dynamics, the nacelle subsystem experiences significant loads, which the team's turbine will experience to some degree. Though the article is talking about testing on utility-scale turbines, the team can still draw inspiration for different testing methods for the nacelle system and its components. It also describes challenges that arise whilst testing, which hopefully our team can do its best to avoid if the testing methods described here are employed.

Wind Energy Explained: Theory, Design and Application – Chapter 6 [41]

Chapter six of the Wind Energy Explained book lists out the different machine elements and wind turbine components. Though at this point most of the components and their functions are known, it is good to have a reference to go back to which clearly explains them and how they tie into each other. The chapter also provides useful information. The most equation-dense portion of chapter 6 involves gear speed relations and loadings, which could provide some inspiration for a gear drive train if it is more efficient, though this would not be necessary, if it is feasible then it would be nice challenge to attempt it.

Wind Turbine System Design. Volume 1: Nacelles, drivetrains and verification [42]

This book offers valuable design knowledge and optimization written by turbine experts. It provides methods of validation, models and simulations, various concepts and designs for different subsystems of the nacelle. The book also provides similar information for the pitching and yaw systems, proving valuable for the team members tasked with those. It is another good resource to make sure the correct approach is being taken in the overall design process of the nacelle system.

Tyto Robotics Database of Drone Motors, Propellers & ESCs [43]

This webpage provides a database of drone components. Seeing prior competition turbine designs, it seems that it is typical to go with drone motors as the application of that and turbine design are fairly similar. The database currently has data on 71 brushless motors, including things such as weight, KV values, number of magnetic poles, all of which will be useful for the both the ME and EE team to come to choose motors for testing. It will also prove useful for nacelle design as it will provide dimensions necessary for the nacelle's overall geometry.

Tyto Robotics: How Brushless Motors Work & How to Test Them [44]

Following the same page as before, Tyto provides an article which gives one a quick crash course on brushless motors. The article is broken up into four parts, 'how brushless motors work,' 'inrunner vs outrunner motors,' 'Efficiency and Performance,' and 'Choosing a motor.' While some of this information has already been discussed by ME and EE team members, such as the KV rating of a motor being the most important characteristic, other information such as the difference between inrunner and outrunner motors was not known and could prove useful in the future.

Fracture analysis of wind turbine main shaft [45]

Provides an in-depth fracture analysis of a wind turbine shaft as a reference for similar analyses. The shaft is hollow and composed of 34CrNiMo6 steel with heat treatment. The results showed that the high stress concentration of the change in inner diameter accelerated the failure. This is important because, although the team's turbine will be solid, the plan is to machine a "Double D" profile onto one end of the shaft to secure the brake disc onto, and this will have a similar effect in creating a high stress concentration at that point. One part of the study included making theoretical stress concentrations which will also be useful to look at when creating a shaft analysis for the desired turbine.

Facts About Wind Energy and Noise [46]

A brief article that speaks about noise production from wind turbines/ wind farms. It describes the difference in wind turbines that produce broadband noise vs tonal noise, where broadband noises are the swishing and whooshing sounds, while tonal noise is a hum that's produced from mechanical components. A CWC wind turbine is most likely going to produce tonal noise as the rotor is not big enough for broadband noise to overcome the tonal, although it could be a mix of both. In one section they speak about streamlining the nacelle to reduce noise and vibration, which can be taken into consideration when creating a small-scale turbine, such as one that the team will create.

4.3 Mathematical Modeling

4.3.1 Blade Material – Holden Gardner

The largest stresses found in the turbine are a result of the frontal wind velocity contacting its faces. Important stress factors to consider are those found in the blades as the wind meets their geometry. Though the perpendicular forces, i.e., drag forces, found on wind turbine blades are small, their presence cannot be neglected. A strike on the turbine tower by a blade will lead to catastrophic failure. While the team determines a conceptually sound design, the distance between the rotor plane and turbine tower is unknown. Therefore, this analysis model will be conducted by comparing blade material costs, density, safety factors, and deflection. Firstly, the deflection can be calculated using cantilever analysis,

$$\delta_{max} = \frac{11wL^4}{120EI} \tag{1}$$

however, this is a gross overcomplication of the math needed to compare materials. Geometric qualities and wind forces can be generalized for the sake of comparison resulting in a deflection equation simplified to a function of only Young's Modulus. A modulus datum is chosen, PLA, and divided into each modulus value to give a normalized set of values.

$$E_{norm} = \frac{1}{E_{datum}} \tag{2}$$

Normalized modulus values are summarized below.

Table 1 – E_{norm} Values

Carbon	**Glass**	**Onyx**	**PLA**	**ABS**	**Al**	**Steel**	**Ti**
18.2	6.4	0.7	1.0	0.6	3.2	56.1	33.3

If the non-dimensional value is less than 1, it has a greater quality to deflect and strike the turbine tower. If the number is greater than one the opposite is concluded, and if the number is greater than one by a significant magnitude the blade can be assumed to be perfectly rigid under low wind velocity values.

This process is, in effect, comparing the stiffness of the materials in a way that can be transferred quantitatively to future decision processes. Other quantitative comparisons such as material density, price per mass, and modulus were modelled using MATLAB graphing capabilities. These graphs can be found in **Appendix A**, Figures 31, 32, and 33.

4.3.2 Airfoil – Holden Gardner

Airfoil design is a comprehensive and complicated process. Due to the time-consuming nature of airfoil creation, an existing airfoil, among the thousands that exist, will be selected based on criteria determined important for wind turbine blade performance. The two most important criteria are a low coefficient of drag (C_d) and a high coefficient of lift to coefficient of drag ($\frac{C_l}{C_d}$). Additionally, a Reynolds number must be calculated to locate accurate C_d and $\frac{C_l}{C_d}$ values,

$$RE = \frac{U_{rel} \cdot c}{\nu} \tag{3}$$

where c is the local chord length, ν is the kinematic viscosity of air, and U_{rel} is relative wind velocity denoted by,

$$U_{rel} = \frac{U_{wind}(1-a)}{\sin(\phi)} \tag{4}$$

This equation considers a, the induction factor, ϕ, the angle of relative wind, and U_{wind}. Utilization of an induction factor allows the calculation to be completed at Betz efficiency or an expected efficiency value per evaluation of competition antecedents. Once the Reynolds number is calculated coefficient curves are more accurately analyzed within the proper design space.

Plot	Airfoil	Reynolds #	Ncrit	Max Cl/Cd	Description
☑	naca0015-il	50,000	9	24.7 at α=6.25°	Mach=0 Ncrit=9
☐	naca0015-il	50,000	5	26.9 at α=6.25°	Mach=0 Ncrit=5
☑	naca0015-il	100,000	9	37.5 at α=6°	Mach=0 Ncrit=9
☐	naca0015-il	100,000	5	37.8 at α=6.25°	Mach=0 Ncrit=5
☑	naca0015-il	200,000	9	49.6 at α=6.25°	Mach=0 Ncrit=9
☐	naca0015-il	200,000	5	48.6 at α=7°	Mach=0 Ncrit=5

Figure [2] – airfoiltools.com Reynolds Number Ranges

Initially, a tool called airfoiltools.com should be used to make observations on public airfoils, however the website utilizes Reynolds ranges too high compared to calculations presented from equation (3), and the graphs cannot be referenced. QBlade software and its embedded XFOIL analysis must be used instead. The proper Reynolds number is then inputted into XFOIL to develop coefficient curves more accurate to their application.

4.3.3 Braking System – Niki Wilson

As wind moves past the blades, the difference in pressure around the airfoil creates lift, which causes the rotor to spin. That rotation can quantitatively be described by torque. The turbine's braking system ultimately needs to overcome this torque value in order to slow the rotor down. Torque can be calculated multiple ways depending on your relevant inputs. To start with, it is necessary to estimate max rotor torque, as this will be the largest numerical rotation that the brake will have to oppose. Torque is defined as the ratio of turbine power and rotational speed through the following equation,

$$\tau = \frac{\frac{1}{2}C_P \rho A U^3}{\Omega} \tag{5}$$

where C_P is the coefficient of power, ρ is the air density, A is rotor plane area, U is wind velocity, and Ω is the angular velocity in rad/s. The resulting torque values can then be used to calculate clamping force. Torque as a function of wind speed is a positive exponential. This relationship is established in Figure 28 in **Appendix A**. The current numbers are too big. Realistically, max torque for the turbine at 22 m/s should be quite small, in the range of 1 or 2 Nm. However, being that the calculated torque is under 5, they still provide a reasonable jumping off point. In fact, static testing revealed the 5 Nm was a realistic max value.

It should be noted that angular velocity is a function of tip speed, which is a function of tip speed ratio.

Units must be closely paid attention to in these calculations as Ω must ultimately be in rad/s. This is all summarized in the following equation,

$$\Omega = \frac{2\lambda U}{D} \tag{6}$$

where D is the rotor diameter.

In general, wind turbines have two options in terms of braking systems – disc brakes, which is a disc attached to the rotating shaft that is squeezed on either side by brake pads, or clutch brakes which use hydraulics or compressed air and are a bit too complicated for this application. Clamping force, an important value for disc brakes, is the force pressing each brake pad against the moving disc. This can be estimated with the following equation,

$$CF = \frac{T_B}{\mu r_m} \tag{7}$$

where μ is the brake pads' coefficient of friction and r_m is the effective disc radius (see Figure 3). e relationship between torque and clamping force is linear. As torque increases so must the force to overcome it. The resulting graph can be referenced in **Appendix A**.

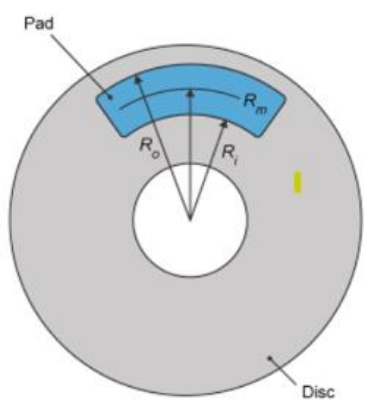


Figure [3] - Disc brake geometry

4.3.4 Tower – Ellie Freeman

The tower, along with the anchor, is meant to keep the turbine upright for the max velocity that the turbine will be tested at. To find the best dimensions that the tower should be built at there are a few different forces that act of the tower to consider. There is the thrust force from the wind that acts on the turbine and some small drag forces that act on the tower that will cause a moment force that will knock over the turbine. To make sure the turbine will not fall over these different forces will be needed to be calculated. Starting with the thrust force equation (8) will be used.

$$T = \frac{1}{2}\rho A U^2[4a(1-a)] \tag{8}$$

Where a is the axial induction factor, where $a\_betz = \frac{1}{3}$ and in order to find the max thrust the coefficient will be used from the Betz limit. ρ is the air density at sea level and for this calculation, $\rho = 1.225\ [\frac{kg}{m^3}]$. The area, $A = \pi\left(\frac{.45m}{2}\right)^2$, where .45m was taken from the DOE rulebook for this competition. Lastly there is the velocity, U, for which the thrust will be calculated with a range of velocity values from 0m/s to 22m/s which will produce a graph as seen in **Appendix A** Figure [25]. The $22\frac{m}{s}$ is the max velocity that the wind turbine will be tasted at during competition.

This shows the different thrust forces that will act on the turbine for different velocities. Using the graph, the max thrust force at the Betz limit that will act on the turbine at $22\frac{m}{s}$ is $T_{betz} = 41.7\ N$. The next for that needs to be considered is the drag force acting on the turbine. Using equation (9),

$$F_d = \frac{1}{2}\rho U^2 C_d A \tag{9}$$

Where C_d is the coefficient of drag for a cylinder, $C_d = 1.16$. The area is $A = \frac{\pi d h}{2}$, where d is the outside diameter of the cylinder and h is the length of the cylinder. In the DOE rulebook the top .08m of the tower must have a diameter of less than or equal to .0381m and the bottom section of the tower can have any diameter that is less than .158m. To pick a good diameter for the section of the tower a graph, shown in Figure [26] from **Appendix A**, was made with a range of diameters from .0381m to a max of .158m.

From Figure [26], it shows that the bigger the diameter the larger the drag forces are and the more material that will be needed so for the next calculation a diameter of .05m will be considered for the lower part of the tower. The two drag forces that were calculated gave the results, $F_{D_1} = 1.64\ N$ for a diameter $d = .0381m$ and $F_{D_2} = 12.69\ N$ for a diameter $d = .05m$.

$$M = T_{thrust} * l_1 + F_{D_1} * l_2 + F_{D_2} * l_3 \tag{10}$$

From both the calculated thrust forces and the drag forces and using equation (10) where l is the different lengths from the sand to the different centers of where the force is action on the turbine and tower. The overall moment force is $M = 53.21\ N * m$. In conclusion the diameter that is consider for the lower part of the tower is .05m and the max moment at the Betz limit was calculated from the thrust and drag forces on the turbine from the wind to find the forces that will knock over the turbine at 22m/s. Using this moment in the anchor calculation in the next section will help in determining the best anchor design.

4.3.5 Anchor – Ellie Freeman

To design a foundation/anchor for this project there is the overall moment from the turbine that anchor needs to overturn for the anchor to be successful. To find that overturn moment all the forces from the different weights of the tower will be considered and the moment created from the size of the anchor itself is considered. Equation (11) was used to find all the forces in the y direction, F_y, from the weights, where m is the mass of the different subsystems and g is the acceleration due to gravity. Equation (12) is then used to find the overturn moment, $M_{overturn}$, and w_{box} is the width of the anchor system.

$$F_y = g(m_{tower} + m_{turbine} + m_{anchor} + m_{stud} + m_{sand}) \tag{11}$$

$$M_{overturn} = F_y * \frac{w_{box}}{2} \tag{12}$$

The overturn moment was calculated for three different anchor volumes, $V_1 = 0.2x0.2x19(m)$, $V_2 = 0.25x0.25x.19(m)$, $V_3 = 0.3x0.3x.19(m)$. Also because of the different volumes there were also three different masses for m_{sand}, the different masses for different volumes were $m_{1_s} = 12\ kg, m_{2_s} = 19kg$, and $m_{3_s} = 27kg$. These sand masses is the weight that the sand will produced if the volume is filled completely by the sand. By finding the overturn moment for different volumes and sand masses it will help with determining what will be the best size that the anchor should be designed to. The overturn moment for the three different volumes were $M_{overturn_1} = 109.9Nm$, $M_{overturn_2} = 121.4Nm$, $M_{overturn_3} = 137.8\ Nm$. Once the overturn moment was calculated then the factor of safety was calculated using equation (13) and the moment that was calculated for the tower system in the previous section.

$$S_f = \frac{M_{overturn}}{M} \tag{13}$$

For calculating a reasonable factor of safety, a graph was created see in Figure [27] in **Appendix A**. This graph is the percent of sand captured vs overturn moment. In a realistic world the mass forces from the sand would be 100% because the volume won't have a 100% of that sand in that volume. To find more reasonable numbers, the moment forces on the graph were compared to the percent of sand that was captured in a volume. This way it will show a range of how much sand in captured in the volume. The better the anchor design, the better percentage of sand that will be captured in the volume.

Since there were three different volumes and sand masses there are three different factors of safety and the factors of safety at 50% of sand captured with in the volume are ${S_f}_1 = 1.032$, ${S_f}_2 = 1.141$, and ${S_f}_3 = 1.2950$. At a 100% of sand captured with in a volume the factors of safety are ${S_f}_1 = 2.065$, ${S_f}_2 = 2.281$, and ${S_f}_3 = 2.590$. In conclusion the bigger the volume and the better percent of sand captured with that volume will give the biggest overturn moment and will be more likely to keep the wind turbine from falling over due to the thrust and drag forces acting of the turbine from the wind. So, the anchor system will have to be designed with these calculations in mind.

4.3.6 Shaft – Sergio Zuniga

The analysis for the shaft where the components will be mounted included the following assumptions: a bet limit coefficient of power ($C_p = 0.59$), done at STP ($\rho = 1.225\ kg/m^3$), a rotor plane area that's the upper limit allowed by the competition ($A = 0.159\ m^2$), wind speed of $U = 22\ m/s$, and an angular velocity range of 3000 RPM – 5000 RPM. For simplification purposes, the brake disc section is treated as a fixed end when coming to a complete stop, which would be the moment that the maximum torsion is happening on the shaft. First, the power with these given conditions was found using the equation:

$$P_{T,max} = \frac{1}{2}\rho C_p A U^3 \tag{14}$$

Where $P_{T,max}$ is the maximum power found from the listed ideal conditions. From there, a simplified method of finding torque was employed where torque was calculated by

$$T_{max} = (P_{T,max})\omega \tag{15}$$

Where ω represents angular velocity. After finding the values for torque, torsional shear stresses for the different angular velocities can be found.

$$\tau = \frac{T_{max}c}{J} \tag{16}$$

$$J = \frac{\pi}{2}c^4 \tag{17}$$

Where τ represents torsional shear stress, J represents the shafts polar moment of inertia, and c represents the outer radius of the shaft; as seen in equation [17] the torsional shear stress is only dependent on the shafts. Using MATLAB, a code was created to produce a plot of τ vs C, as seen in Figure [4]

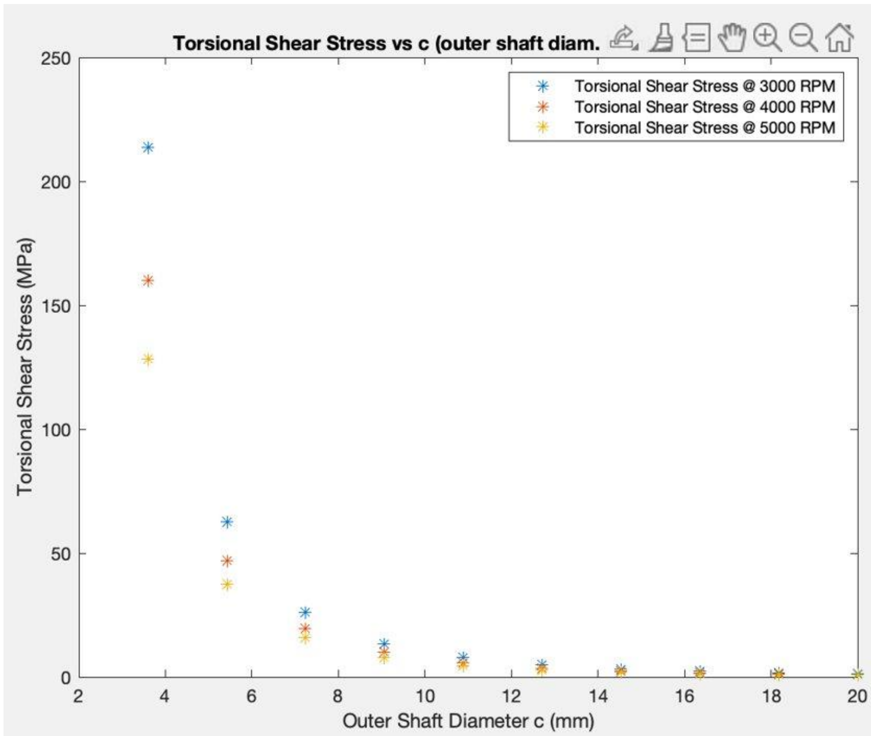


Figure [4]- Plot of Torsional Shear Stress vs Outer Shaft Diameter

Originally, c values ranging from 10mm-15mm were chosen to be displayed on the plot, but seeing as how the stress was low for typical metals such as steel and aluminum, the radius was made small enough to be able to produce factors of safety less than 1; though a shaft with that small of a radius would not be implemented, the purpose of this analysis was to find out the most extreme case where failure could occur, and the analysis shows that the shaft would likely not fail given its application. A table of safety factors for a shaft of 10mm diameter can be seen in Table 2 below where the torsional shear stress is about 10 MPa.

Table 2 - Factors of Safety for different metals (D = 10mm, τ = 10 MPa)

Material	FOS
Aluminum 2024	29
Aluminum 2024	24.1
Steel AISI 1045	31

5 Design Concepts

5.1 Functional Decomposition

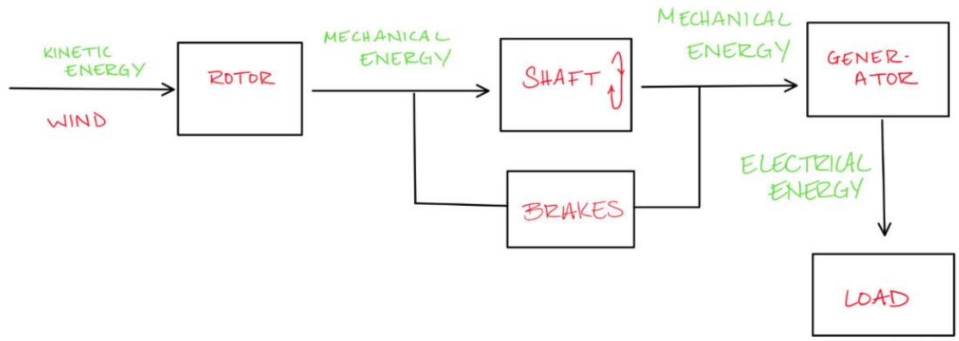


Figure [5] - Functional Model

Functionally, a wind turbine operates by the rotation of the rotor as result of head-on wind flow. This rotation continues through the shaft, which turns a generator that converts that mechanical energy into electricity. The most important subsystems are the rotor, shaft, brakes, generator, and load. This is all summarized in the functional decomposition in Figure 6. This model is useful because it visually breaks down the turbine into its essential components and very simply depicts where they are and at what stage of energy conversion they are used. Along those lines, a black box model is a useful way to depict exactly what is going in and what is coming out.

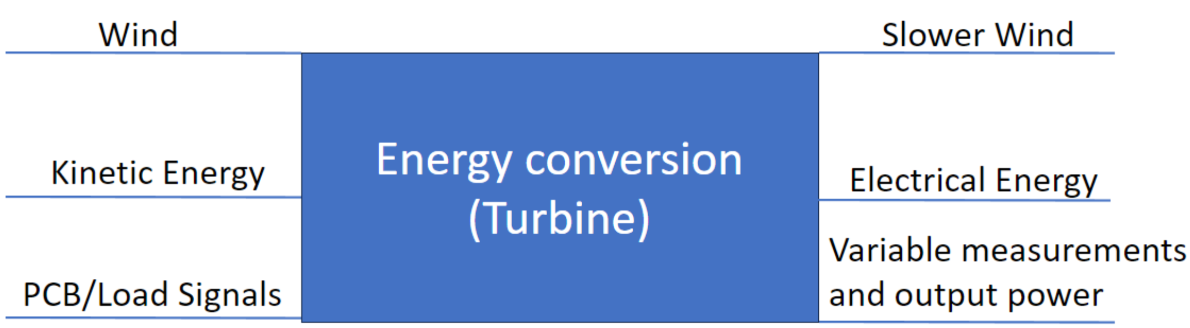


Figure [6] - Black Box Model

5.2 Concept Generation

5.2.1 Blade Material – Holden Gardner

Turbine blade materials require a narrow selection process. The highest-level materials are those that will deflect the least, can be fabricated in-house, and will prove cost efficient in the span of the project. Carbon fiber blades are an appealing option based solely on their mechanical properties and appearance. The projected cost of a full set of carbon fiber blades far outreaches that of any other material listed in Figure [7]. Glass fiber options yield similar mechanical properties to carbon fiber but are cheaper to fabricate. Most 3D printing materials available on the market deflect in unfavorable ways or are too weak in tension to behave suitably as a spinning element. Combination and blended materials such as carbon-nylons and polycarbonates behave favorably under stress but are expensive and unique to 3D print. Onyx is a carbon blended printing material which the NAU campus IDEA Lab can print. While the team's designs may be submitted to a convenient third party for printing, it is an expensive material, and the blade will deflect a greater amount compared to composite materials on the list. Steel blades are plausible only if hollow. Solid steel weight is too high to be safely spinning in testing or competition environments. However, the material is cheap and can be manufactured in-house.

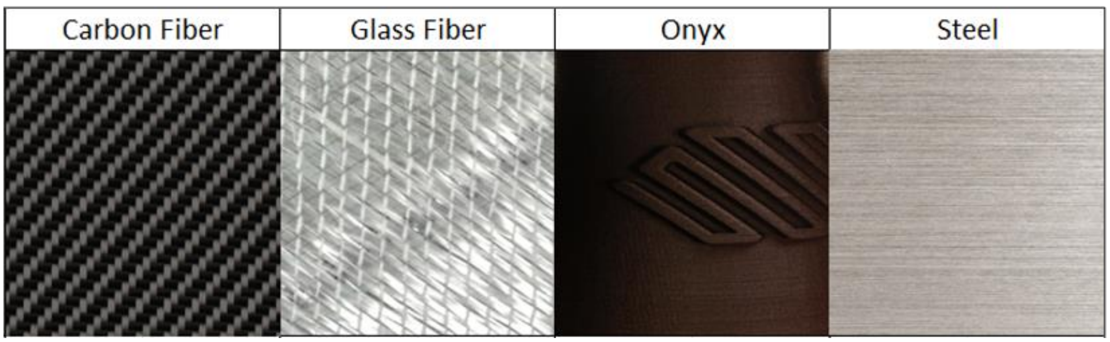


Figure [7] – Top Level Materials

5.2.2 Airfoil – Holden Gardner

XFOIL software and an accurate Reynolds number produces realistic C_d and $\frac{C_l}{C_d}$ graphs for the purpose of airfoil selection. Ten airfoils were narrowed to six by coefficient comparison. At this stage of analysis, coefficient evaluation is the only precise method for selection, and it should be noted that most top-level selections shown in Figure [8] have varying but appealing values. The short airfoil list generated thus far contains options based on the team's airfoil analysis learning process. The most important conclusion being that airfoils pre-made for small Reynolds numbers are the best place to begin analysis. This satisfies one design requirement and allows for easier synthesis of later-stage XFOIL results. A common advantage of all airfoils listed below is their narrow thickness and slight camber. Secondary conclusions like these give the intuition necessary to qualitatively evaluate whether a small-scale wind turbine will be effectively pitch regulated or may output power at variable wind speeds. This is speculation until XFOIL analysis supports these conclusions.

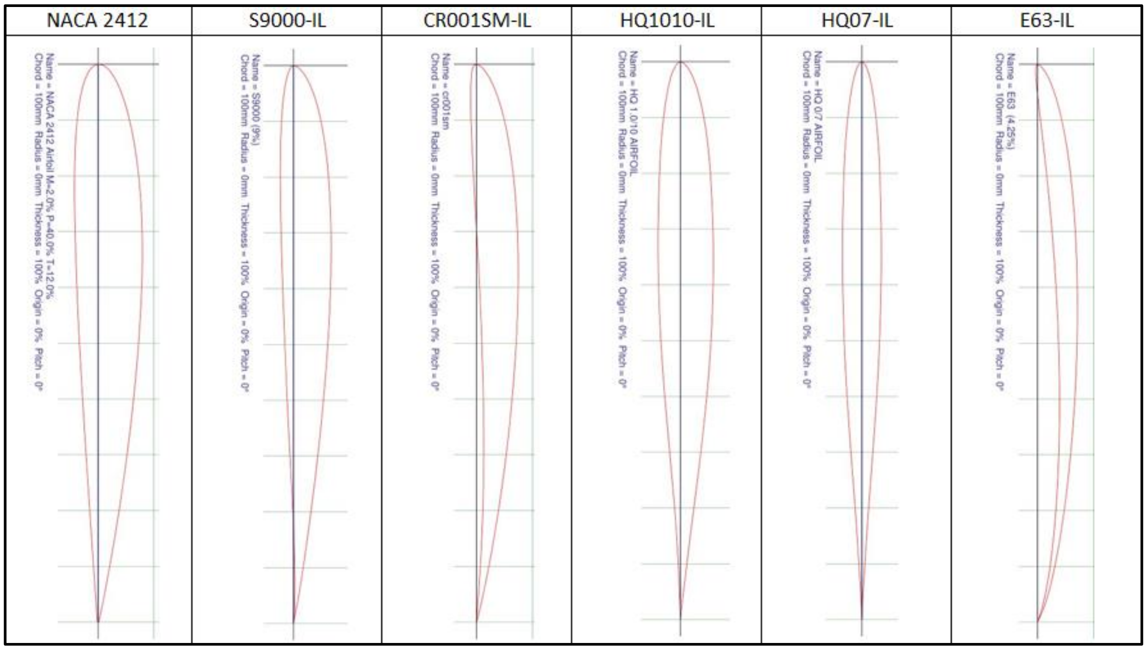


Figure [8] – Top-level Airfoils

5.2.3 Braking – Niki Wilson

As was previously mentioned, realistically, the CWC team is limited in its brake configurations. Thus, initial concepts were inspired by previous examples, as well as general braking systems presented in Shigley's Mechanical Engineering Design.

A rotor disc brake, fundamentally, is a disc connected to the rotor shaft that rotates at the same rate as the rotor. Brake pad(s) push against the spinning disc and slow it down by friction. Figure 9 contains all generated concepts. They are numbered from 1-6 starting from the upper left-hand corner and continuing from left to right. Concept #4 is the simplest model of a disc brake based on the above definition. It is a representation of the system used in the 2022 turbine. Concept #2 is a similar construction to #4. However, this concept explores pulling the brake pad towards the disc rather than pushing it into the disc. Concept #5 includes two identical discs that are stopped with a total of 4 brake pads. Concepts #1 and #3 include spring actuated braking systems. #3 is inspired by clutch brakes used in scale wind turbines. Though the configuration is effective and popular in industry, its complexity as well as space requirements ruled it out quickly. Concept #6 was inspired by drum brakes, maximizing contact area by utilizing 360* of arc.

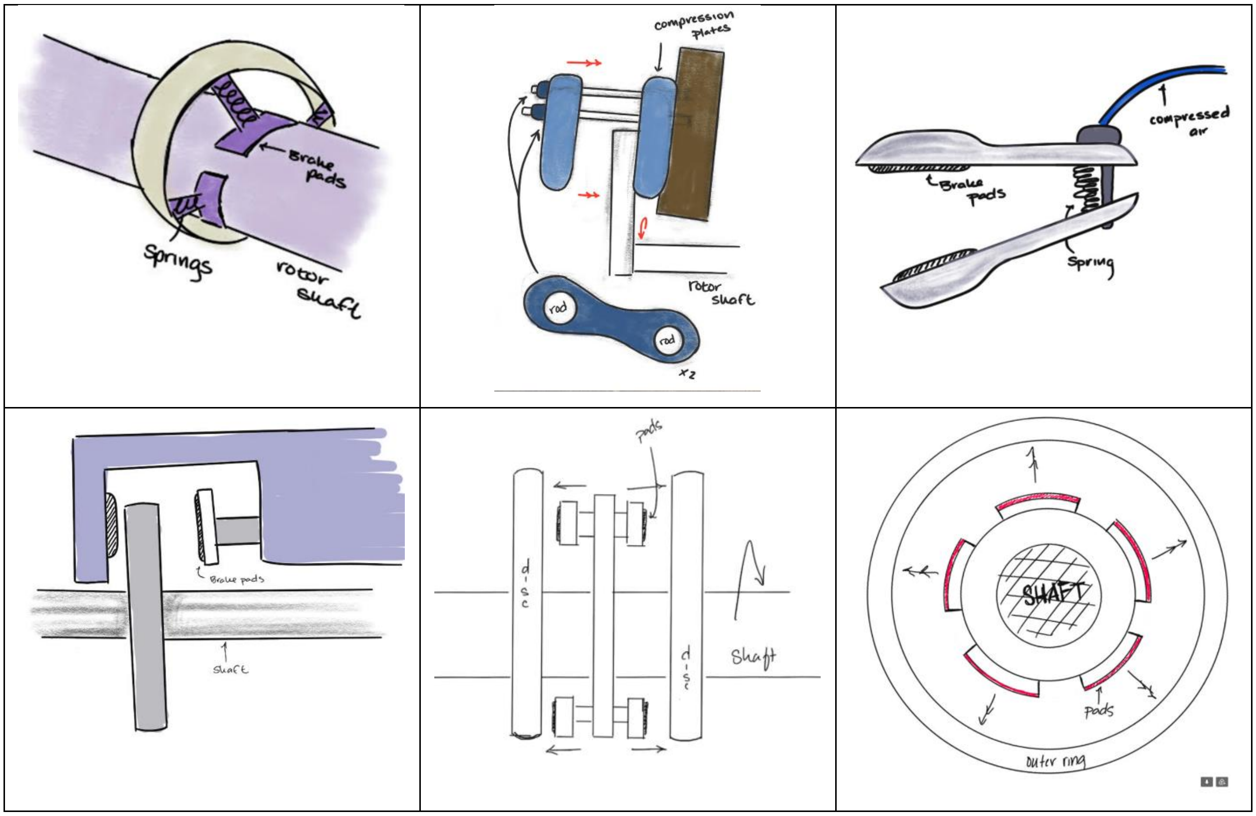


Figure [9] – Braking System Concept Generation

5.2.4 Tower – Ellie Freeman

The tower selection is limited for concept designs because the only thing that this team has control over for the tower design is the lower diameter and the material. Because of this the generation for the tower will be based on some different lower tower diameters and a few different materials. The first diameter of the lower part of the tower is the same as the top part, with a diameter of .0381m which is similar to a design 2 years ago. This means that the higher part if the tower and the lower part are the same and don't need to be connected and has the least amount of drag force. The only downside would be the lack of extra space for wires and connectors and less weight for a weight force to help the anchor system. The second option is a diameter of .05m which is only slightly bigger than option one and will have a little more drag force and will have to be welded together. But it will increase the space for wires and connectors and increase the weight of the overall turbine. The last option is a diameter of .1 which is a lot bigger than the other option and will have the most amount of weight and space for wires. But being able to connect the top and bottom part together might be difficult and it would have a large drag force.

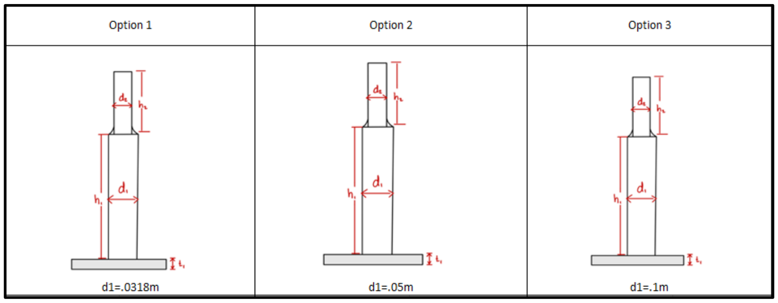


Figure [10] - Tower Diameter Concept Generation

There are only a couple of materials that will work for the tower and those are steel and aluminum. From this it would be more beneficial to use steel as the material for the tower because it is heavier that the aluminum and more structurally sound than the aluminum. Also welding steel would be easier when connection the base plate with the tower compared to welding aluminum what requires advances skills.

Figure [11] - Tower Material Concept Generation

5.2.5 Anchor – Ellie Freeman

The anchor concept generation has a lot of different types of designs where, based on the calculations, the designs were generated on the idea of how to best capture the most amount of sand. This is because if the sand is allowed to move then the sand starts action like a non-Newtonian fluid and will allow the turbine to fall over. This idea led to the process to come up with designs for this idea. These designs were also inspired by previous years designs which is why the main part of the designs are based on a box foundation. The drill anchor was one of the first concepts that were generated, and the idea is that the part inside the box can be twisted into the sand to dig itself the sand and capture most of the sand within the box. The small lip anchor is one of the more basic ideas and would most likely be the lightest, but it will also capture the least amount of sand in the box because there is only a small surface area keeping the sand in while a large area that is letting it move. The square and circle mesh anchor are similar in that they both have an open and closed section. The ides are that when the meshes are open they will allow sand to go through to place the foundation in the sand and when it is placed then the mesh in closed to not allow any sand through and trapping the sand into the box. The only differences are that the square will be able to capture more sand but will also be harder to place into the sand while the circular mesh is the opposite. Also, to close the square mesh you will have to push the connector from side to side and for the circular you will have to twist. The plate suction anchor is a more basic idea of pushing the foundation into the sand with the plat at the bottom of the box and when it is in the sand you try and pull up the plate to pull up at much sand into the box as possible. This design doesn't seem as likely to capture a lot of sand. The last design is a suction caisson anchor where the box design will have a pump that is attached to the top and will try to suck as much water and sand as possible to create an anchor that is pressurized. The math helps supports the idea of these concepts but in order to know for sure which one is better or worse there has to be some physical test to determine the best concept.

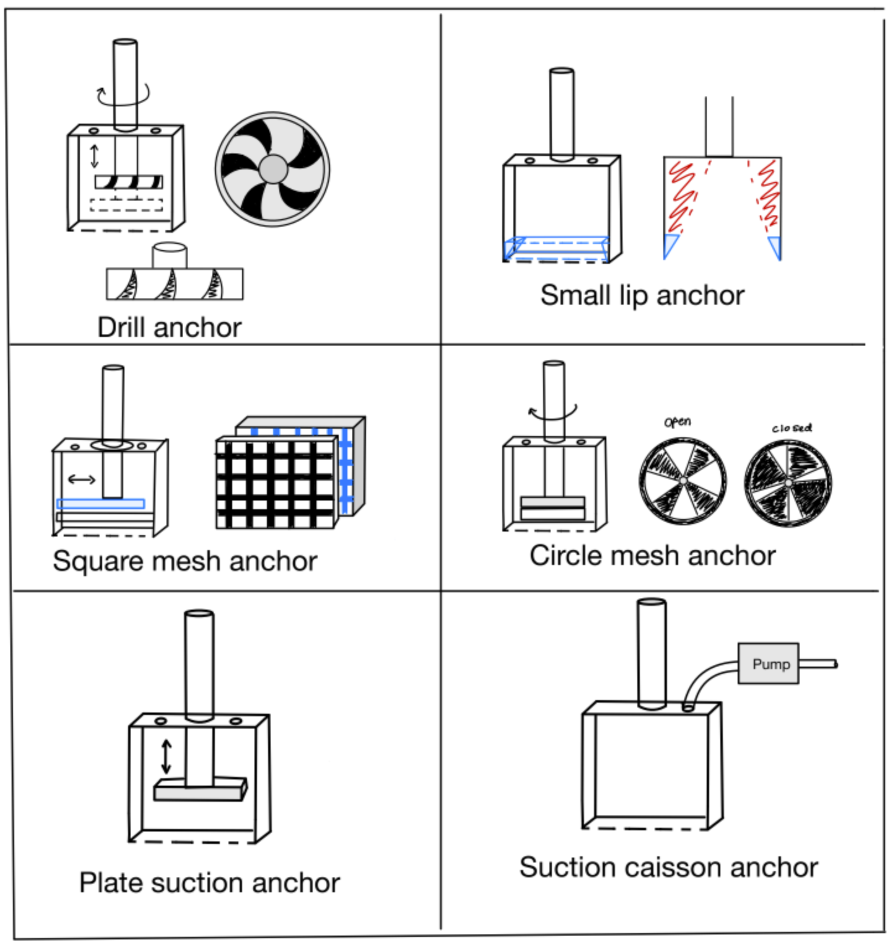


Figure [12] - Foundation/Anchor Concept Generation

5.2.6 Shaft – Sergio Zuniga

The top three deciding factors for shaft material selection include cost, strength, and weight as having a lighter design could add some points to the competition score. Four materials that come to mind are carbon fiber, steel, aluminum, and 3D printed plastics. A pro and con of each (respectively) include carbon fiber, strongest axially of the four, not easily machinable; Steel, most inexpensive (apart from 3D printed plastics), but heaviest/densest of the four; Aluminum, easiest to machine, but weakest and most susceptible to deformation of the two metals; 3D printed plastics, widely available and inexpensive, weakest of the four materials. As mentioned in the mathematical modeling section, the torsional stress on the shaft is only dependent on the shaft's radius and not the material properties, therefore both the metals are the most likely to be good fits for this application.

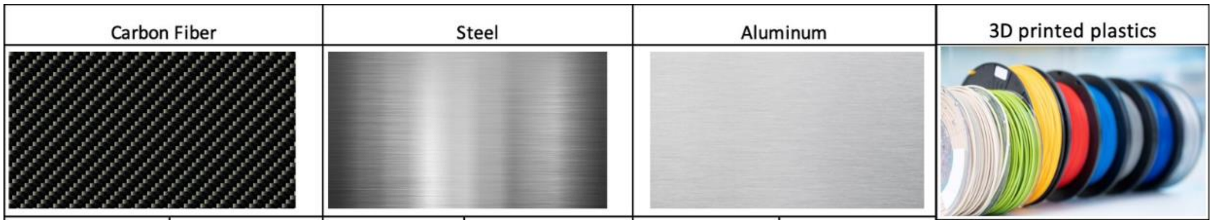


Figure [13] - Shaft Material Concept Generation

5.3 Selection Criteria

5.3.1 Blade Material – Holden Gardner

Blade material criteria are generated with respect to testing and competition aspects. Certain customer requirements influence testing factors such as material safety and post processing time, but the remaining criteria are inferred and mathematically supported from competition handbook requirements. Due to the complicated nature of turbine development, thorough analysis cannot be completed until a product is developed. Hence the theoretical and generalized selection criteria shown in the blade material section. All the low-level materials are viable for testing but unrealistic at competition standards, thus weights ascribed to their criteria later in the selection process are organized based on these competition standards. Deflection values are an excellent example of this: the normalized modulus values are directly proportional to positive and negative weight, and since blade strikes at the competition would result in catastrophic failure, the weighting is high. Costs and material weight values are determined proportionally, with reference to the budget and the turbine design dimension engineering requirements respectfully. Remaining criteria such as strength are specified such that if a tensile strength value is too low, the option should be removed based on projected stress concentrations at blade root. A simple bearing stress calculation is used to support this conclusion.

5.3.2 Airfoil – Holden Gardner

Airfoil selection criteria are still developing and require analysis the team must self-teach later in the design process. In the current state, the coefficients C_d and $\frac{C_l}{C_d}$ are the only criteria to be compared. However, after determining airfoil design must be taken with complete consideration to the working Reynolds number in the correct design space, a new factor, qualitative Reynolds number is developed. This criterion considers the history of an airfoil and its intended use. Based on these facts, an airfoil will receive a positive or negative score. Further selection should not be made based on this essentially qualitative factor. Instead, XFOIL analysis techniques should be studied further, and new criteria will be made.

5.3.3 Braking System – Niki Wilson

The selection criteria were based on the customer and engineering requirements. However, the competition handbook does not offer anything significant in the way of guidance for this system. The only explicit requirement is the turbine must come to a full and complete stop either when an emergency stop is pressed or when the rotor spins too fast. Therefore, some creative liberties had to be taken to increase criteria. First, the system must be compact. Per the rules, all rotor and non-rotor parts must fit within a 45 cm3 box, so a bulky brake might compromise that. Next, the brake must be easily adjusted. The reason behind this criterium is two-fold. One, should something go wrong (e.g., fail, get stuck, etc.) it is important that the team be able to solve the issue efficiently and effectively, especially if that issue happens at competition. Two, the team has a time limit for assembly, so any overcomplicated systems in multiple pieces will take much of the limited time given. Next, the assembly should be simple. This is for similar reasons previously stated – so it will be easily adjusted and put together. Then, the system should have sufficient resistive torque to overcome the rotor's rotation. It should also include high contact area since the torque is opposed through friction. Braking torque is a function of clamping force. Therefore, an effective design should have a high clamping force. Lastly, torque is a function of radius, thus, a braking system that includes a higher mean radius will produce higher torque.

5.3.4 Tower – Ellie Freeman

The selection criteria for the tower are based on the engineering and customer requirements where there are a few specific criteria that must be followed. The first one is that the top .08m of the tower must have a diameter that is less than or equal to .0381m. The lower half of the tower must have a diameter that is less than .158m. Another criterion is that the base plate must have a thickness of less than. 0161m and it must have convenient 3 bolt attachment so that the baseplate can be connected to the given testing foundation. Lastly electrical systems must be ground through baseplate with 100kohm resistance. Based on these requirements and the calculations made for the tower, a smaller diameter either .0381m or .05m will be used for the lower part of the tower.

5.3.5 Anchor – Ellie Freeman

The selection criteria for the anchor are based on the engineering and customer requirements. The first one is that the anchor must be made from a ferrous metal and can only have a thin coating. Another criterial is that the max area for the anchor is 30cmx30cm and cannot penetrate the sand more than 20cm. Another big rule for the anchor is that the sand cannot be excavated when placing the anchor system and hands cannot touch the water when placing the anchor into the sand. Based on the calculation that were made for the anchor the anchor should be designed as close to the max dimensions as possible in order to produce the best overturn moment and largest factor of safety.

5.3.6 Shaft Material – Sergio Zuniga

The selection criteria for the shaft material selection were dependent on the decision matrix criteria, Pugh chart criteria and the mathematical modeling results. Neither the engineering requirements nor the customer requirements listed require a specific type of material to be used, therefore the results of the mathematical modeling heavily influenced which materials should even be considered as it gave a good sense of what the extreme case that needed to be designed to would be. One sort of "stretch" customer requirement that did end up being one of the criteria of the Pugh chart and decision matrix was the mention that the lightest turbine design would get additional points, which is where the "density" category came from, where something that's less dense/lighter was positive.

5.4 Concept Selection

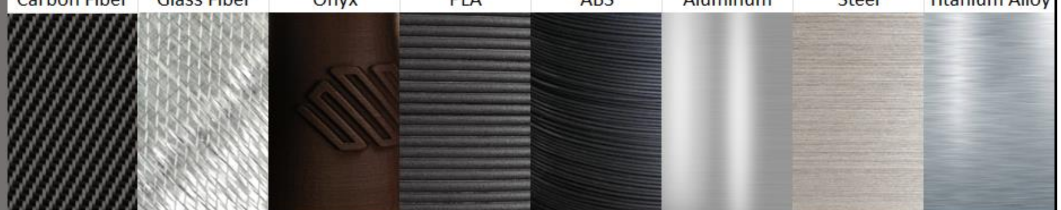
5.4.1 The Top-Level

The top-level system shown in **Appendix A,** Figure [36] displays the current CAD model at its highest level of analysis-supported design. This model includes a pitching assembly (Figure [37]), current blade models (Figure [38]), and arbitrary swashplate and anchor models.

5.4.2 Blade Materials – Holden Gardner

Specification tables are few and far between at ground up design levels within blade material and airfoil selection steps. Pugh charts and decision matrices will be the primary reference tables for these concept selection processes. The top-level materials and their criteria selection have been discussed previously; their final selection justification will be discussed in the following sections. Initially, a Pugh chart is developed, touching on the three main categories of materials. 3D printed materials, two composites, and a variety of metals are considered in the chart to provide a comprehensive decision-making process. Materials weak in tension, those displaying high bearing tension values, and excessively difficult to machine materials are omitted from the process.

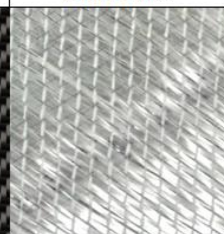
Table [3] – Blade Material Pugh Chart



	Carbon Fiber	Glass Fiber	Onyx	PLA	ABS	Aluminum	Steel	Titanium Alloy
Criteria								
Deflection	+	+	-		-	+	+	+
Cost	-	+	-		0	-	+	-
Strength	+	+	+		0	+	+	+
Operational Safety	+	+	+	Datum	0	-	-	-
Weight	0	0	0		0	-	-	-
Post Processing	+	+	+		0	+	+	+
Lead Time	-	-	0		0	-	-	-
+	4	5	3	0	0	3	4	3
0	1	1	2	0	6	0	0	0
-	2	1	2	0	1	4	3	4
Total	2	4	1	0	-1	-1	1	-1

Moving on to the decision matrix are the composite options, a carbon-based 3D printing material, and steel. Both composites hold favorable characteristics in tension and operation safety while maintaining a relatively low cost compared to Onyx. Steel is eliminated with respect to safety factors and material density.

Table [4] – Blade Material Decision Matrix

		Carbon Fiber		Glass Fiber		Onyx		Steel	
									
Criteria	Weight	Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted
Deflection	25	1	25	1	25	0.75	18.75	1	25
Operational Safety	25	1	25	1	25	0.8	20	0.1	2.5
Strength	20	1	20	1	20	1	20	1	20
Lead Time	10	0.1	1	0.1	1	1	10	0.5	5
Cost	10	0.5	5	0.4	4	0.1	1	0.25	2.5
Post Processing Capable	5	0.5	2.5	0.5	2.5	0.4	2	1	5
Weight	5	0.75	3.75	0.75	3.75	0.7	3.5	0.1	0.5
Total			82.25		81.25		75.25		60.5

While Onyx remains the most conveniently manufactured material, its cost and deflection variables are too high to be considered outright for final design prospects. Nonetheless, it is not eliminated from the final decision-making process for the purposes of design flexibility in future team testing. Composite materials remain the most reliable option for final competition performance. Carbon and glass fibers are highly resistant to tensile stresses and resin bases are capable of withstanding bearing stresses found in blade root connections even at the highest projected wind speeds.

5.4.3 Airfoils – Holden Gardner

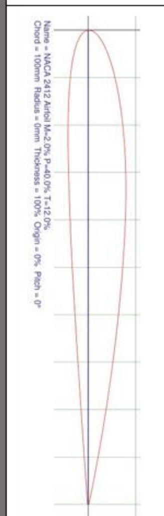
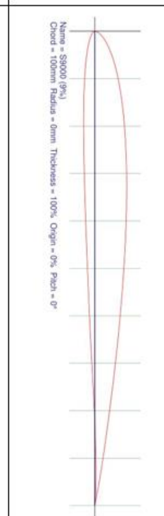
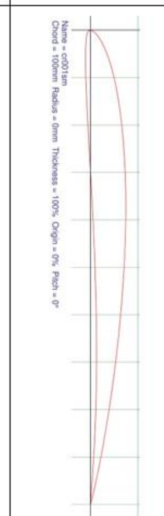
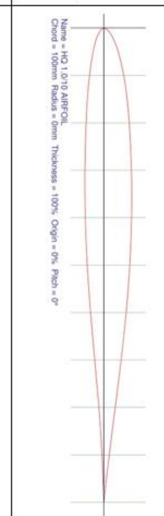
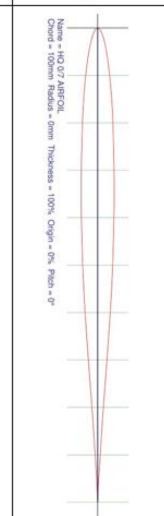
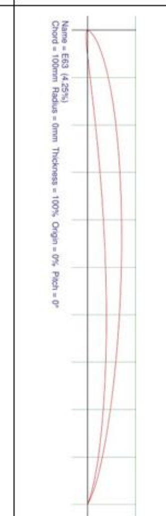
Equally important factors, coefficient of drag, coefficient of lift to drag, and design Reynold number, are the only criteria utilized in determining airfoil viability. They are weighted equally, and only the coefficient values are compared.

Table [5] – Airfoil Pugh Chart

	NACA 2412	S834-NR	S9000-IL	NACA 0015	CR001SM-IL	HQ3510-IL	HQ1010-IL	HQ07-IL	CH10SM-IL	E63-IL
Criteria				Datum						
C_l/C_d	+	+	+		+	+	+	+	+	+
C_d	-	-	-		-	-	-	+	-	-
Qualitative RE	+	-	+		+	-	+	+	-	+
+	2	1	2	0	2	1	2	3	1	2
0	0	0	0	0	0	0	0	0	0	0
-	1	2	1	0	1	2	1	0	2	1
Total	1	-1	1	0	1	-1	1	3	-1	1

The four airfoils with the lowest coefficient values are removed from the decision-making process and the remaining six move on to the decision matrix.

Table [6] – Airfoil Decision Matrix

		NACA 2412		S9000-IL		CR001SM-IL		HQ1010-IL		HQ07-IL		E63-IL	
													
Criteria	Weight	Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted
C_l/C_d	33.3	1	33.3	0.5	16.7	0.7	22.2	0.2	5.6	0.3	11.1	1	33.3
C_d	33.3	1	33.3	0.7	22.2	0.5	16.7	0.7	22.2	1	33.3	0.8	27.8
RE	33.3	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
Total			66.7		38.9		38.9		27.8		44.4		61.1

It is with these six similar, but qualitatively different, airfoils that decision processes are halted for the sake of accurate conclusions. Additional XFOIL analysis is needed, in addition to prototype testing to single out an airfoil that is completely suited to the team's competition needs.

5.4.4 Braking System – Niki Wilson

After the criteria were chosen, both a Pugh chart and decision matrix can be made to quantitatively see which concepts are viable prototype options and which should be eliminated. Starting with the Pugh chart, all concepts were compared against a datum. A "+" indicates the design ostensibly functions better than the datum under that criterium, - indicates worse function, and 0 indicates about the same. There are six different concepts shown here – a clutch brake, a spring-actuated annular brake, two horizontal compression disc brakes, a double-sided disc brake, and a drum brake. Each concept's score was based on their estimated alignment with the following: less spatial requirements (i.e. more compact) as there are very strict size requirements stated in the CWC handbook, less internal parts (i.e. more easily adjusted) so as to more effectively diagnose problems and fix them, less overall parts (i.e. simpler) since more parts means a greater opportunity for failure, greater resistive torque, high contact area, greater pressure, larger radius (within reason; the system must still be as compact as possible), and a higher clamping force, which is a function of the coefficient of friction and torque. Mathematical analysis to support concept selection was presented in section 3.

Because the Pugh chart was not hugely conclusive - many of the designs earned a score of 0, indicating they are no better or worse than the datum - all generated concepts advanced to the decision matrix, which includes the same criteria. Unsurprisingly, the simplest assembly ultimately accrued the highest score. Therefore, concept 4 was the basis for prototype 1.

However, after prototype 1, it was apparent that a redesign was necessary to solve the many geometry issues that ensued. The adjusted configuration is modeled in SolidWorks in Figure [14].

Table [7] – Braking System Pugh Chart

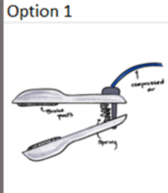
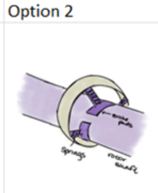
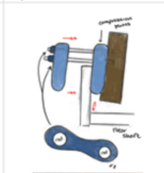
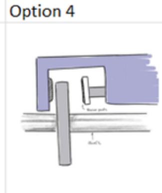
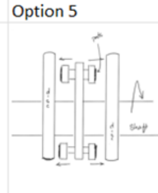
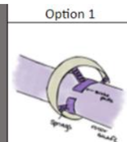
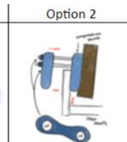
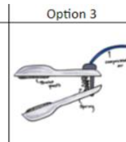
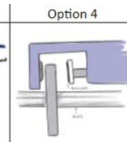
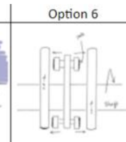
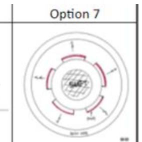
	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6
						
Criteria						
Compact	-	-	0		-	-
Easily adjusted	-	0	0		-	-
Simple	-	-	0		-	-
Resisitive torque	+	+	0		+	+
Contact area	0	+	0	Datum	+	+
Pressure	+	+	+		+	+
Radius	0	-	0		-	0
Clamping Force	+	+	+		+	+
+	3	4	2	0	4	4
0	2	1	6	0	0	1
-	3	3	0	0	4	3
Total	0	1	2	0	0	1

Table [8] – Braking System Decision Matrix

		Option 1		Option 2		Option 3		Option 4		Option 6		Option 7	
													
Criteria	Weight	Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted
Compact	0.1	5	0.5	9	0.9	2	0.2	10	1	6	0.6	5	0.5
Easily adjusted	0.05	7	0.35	8.5	0.425	3	0.15	10	0.5	6	0.3	5	0.25
Simple	0.05	6.75	0.3375	9	0.45	3.5	0.175	10	0.5	5	0.25	5	0.25
Resisitive torque	0.35	9	3.15	7	2.45	9.5	3.325	9	3.15	9	3.15	9	3.15
Contact area	0.15	10	1.5	6.75	1.0125	8.5	1.275	7	1.05	9	1.35	10	1.5
Pressure	0.0875	9.5	0.83125	8.5	0.74375	10	0.875	7.5	0.65625	9	0.7875	9	0.7875
Radius	0.0875	4	0.35	8	0.7	9	0.7875	8	0.7	8	0.7	8	0.7
Clamping Force	0.125	8.5	1.0625	8	1	10	1.25	7.5	0.9375	9.5	1.1875	9.5	1.1875
			0		0		0		0		0		0
			0		0		0		0		0		0
			0		0		0		0		0		0
	1		0		0		0		0		0		0
Total			8.08125		7.68125		8.0375		8.49375		8.325		8.325

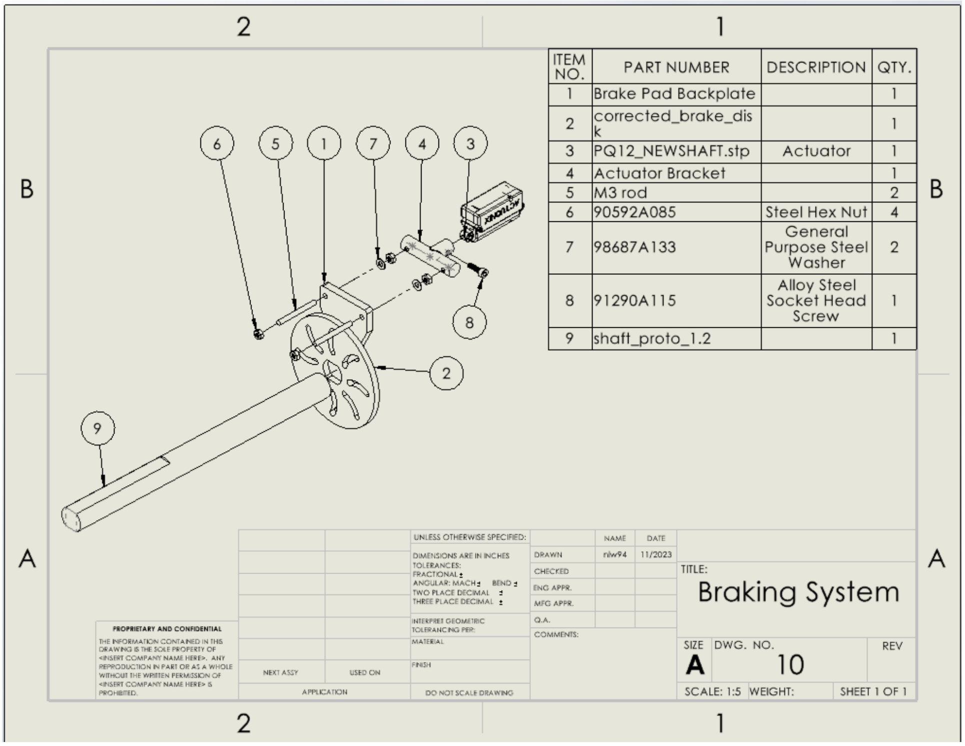
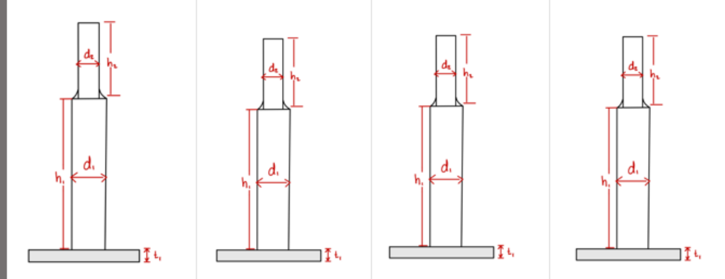


Figure [14] - Current CAD model

5.4.5 Tower – Ellie Freeman

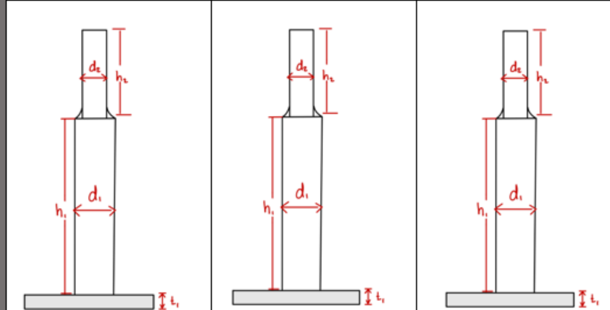
The concept selection will help narrow down the different options for the tower. A Pugh chart and decision matrix were created to help narrow down the different options for the tower dimensions. For the criterial there were too many things to consider so there is only the drag force material and weight being considered. The drag force criteria are the amount of for that the specific diameter will create which is something that this team doesn't was for the turbine design. So, based on the calculations, a larger diameter means a larger drag force. The next criteria are the material which means that the less material that is being used the better, so the smaller diameter is using less material and get a better score. Lastly there is the weight, for this criterial the more weight of the tower from the bigger diameter will get a better score.

Table [9] - Tower Pugh Chart

	Option 1	Option 2	Option 3	Option 5
				
Criteria	d1 = .0381m	d1=.05m	d1=.07m	d1=.1m
Drag Force	+	+		-
Material	+	+		-
Weight	-	-		+
			Datum	
+	2	2	0	1
0	0	0	0	0
-	1	1	0	2
Total	1	1	0	-1

For the decision matrix the criteria are the same as the Pugh chart and the weight for the different criteria is the same because all oof the criteria are equal. According to the decision matrix the first two options have the same score so conceptually these two designs will work for the team and the team will be able to pick a design between the two after some of the other sub-assemblies are more fleshed out.

Table [10] - Tower Decision matrix

		Option 1		Option 2		Option 3	
							
		d1=.0318m		d1=.05m		d1=.1m	
Criteria	Weight	Score	Weighted	Score	Weighted	Score	Weighted
Drag Force	0.33	9	2.97	8	2.64	4	1.32
Material	0.33	7	2.31	6	1.98	6	1.98
Weight	0.33	3	0.99	5	1.65	8	2.64
			0		0		0
			0		0		0
Total			6.27		6.27		5.94

From the Pugh chart and decision matrix as seen in Table [9] and [10] the most likely option would be a lower diameter of .05m and a material of steel because of the calculations which show that a diameter of .05m will have a little weight to help with the anchor but also little drag that will knock over the turbine. But both designs can be considered when the team creates prototypes and make a full assembly.

5.4.6 Anchor – Ellie Freeman

For the concept selection for the anchor there are 6 different options. There are 7 different criteria for considering these different designs which are: sand concentration, ease of use, design complexity machinability, ease of placement, weight, and stability. The first criteria are, sand concentration, which is the expected amount of sand that the design will be able to hold. Even through there isn't a way to know for sure how well the designs will be able to capture the sand an educated guess can be made to see if one is better than the other. The next criteria are ease of use, this refers to how easy the anchor will be able to be used and how difficult it would be to use the anchor. The next criteria is the machinability which means how easy the anchor will created. For example, the first option will have a low score for machinability because the drilling piece because it is difficult to design and manufacture while option 6 will have a higher score because it is only the box that will have to be welded with a hole on top. The next criteria are the ease of placement, which refers to how easily the anchor will be placed into the sand. For example, option 6 will be easy to place into the sand because there is a pump that will help. While option 2 will be harder to place because the suction force will be created by hand and not as effective. The next criteria is the weight, this is the opposite from the criteria for the tower concept selection because in the rulebook from the DOE the lighter the anchor the more amount of points the team will get. So, the lighter the anchor design the better the design is. The final criteria are the expected stability of the designs. This is also something that the team must make an educated guess about because without physical testing the team will not be able to know how well a design will do.

Table [11] - Anchor Pugh Chart

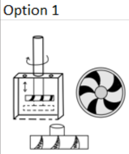
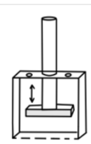
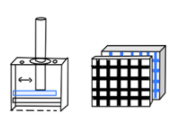
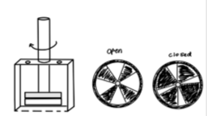
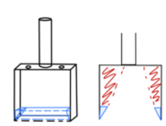
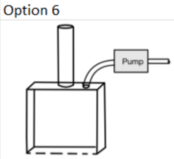
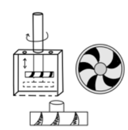
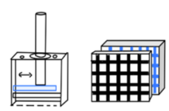
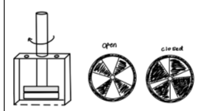
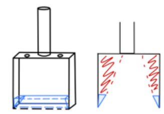
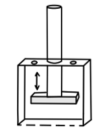
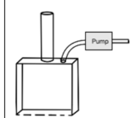
	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6
						
Criteria						
Sand Concentration	0	+	+	Datum	-	+
ease of use	+	-	0		+	+
design complexity	-	+	0		+	+
Machinability	-	+	0		+	+
Ease of placement	+	-	+		-	+
Weight	0	-	-		+	+
Stability	+	-	+		+	+
+	3	3	3	0	5	7
0	2	0	3	0	0	0
-	2	4	1	0	2	0
Total	1	-1	2	0	3	7

Table [12] - Anchor Decision Matrix

		Option 1		Option 2		Option 3		Option 4		Option 5		Option 6	
													
Criteria	Weight	Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted
Sand Concentration	0.45	8	3.6	10	4.5	8	3.6	3	1.35	4	1.8	8	3.6
Weight	0.25	5	0.25	3	0.15	4	0.2	8	0.4	6	0.3	9	0.45
Ease of placement	0.1	6	0.3	4	0.2	5	0.25	7	0.35	4	0.2	7	0.35
Machinability	0.05	2	0.1	6	0.3	6	0.3	7	0.35	6	0.3	8	0.4
design complexity	0.05	6	0.6	7	0.7	7	0.7	8	0.8	8	0.8	9	0.9
ease of use	0.05	8	2	6	1.5	7	1.75	8	2	4	1	8	2
Stability	0.05	7	0.35	9	0.45	7	0.35	3	0.15	4	0.2	9	0.45
Total			7.2		7.8		7.15		5.4		4.6		8.15

After looking at Table [11] and [12], it shows that the best overall anchor design is option 6 which is the suction caisson anchor. Even though the Pugh chart and decision matrix say that the suction caisson anchor is the best one, it would be beneficial to make prototypes for a few different ones and compare them that way there is some physical testing that will help determine the best anchor design.

5.4.7 Shaft Material – Sergio Zuniga

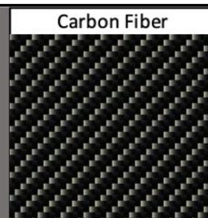
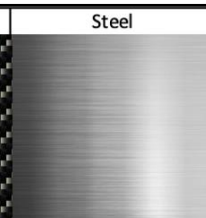
The six criteria for the Pugh chart include cost, machinability, strength, density, availability, and how repairable or not the material is. Steel was used as a datum as it is most widely used for rotary shafts. After going through the process, the 3D printed plastics ended up being left behind.

Table [13] - Shaft Material Selection Pugh chart

	Carbon Fib	Aluminum	3D Printed Plastics	Steel
				
Criteria				
Cost	+	-	++	
Machinability	--	+	-	
Strength	++	-	---	
Density	++	+	++	
Availability	-	0	+	Datum
Repairable	-	+	-	
+	5	3	5	0
0	0	1	0	0
-	4	2	5	0
Total	1	1	0	0

From there, to narrow down the selection to two materials, a decision matrix with the same selection criteria as the Pugh chart was created and the materials were run through. Due to carbon fiber's low ability to be repaired and machined, it ended up being dropped in the decision matrix process, leaving the two metals steel and aluminum as expected.

Table [14] - Shaft Material Decision Matrix

		Carbon Fiber		Steel		Aluminum	
							
Criteria	Weight	Score	Weighted	Score	Weighted	Score	Weighted
Cost	0.15	9	1.35	8	1.2	6	0.9
Machinability	0.25	3	0.75	8	2	9	2.25
Strength	0.25	9	2.25	8	2	5	1.25
Density	0.12	8	0.96	5	0.6	7	0.84
Availability	0.125	5	0.625	9	1.125	9	1.125
Repariable	0.05	1	0.05	8	0.4	8	0.4
Total			5.985		7.325		6.765

6 Schedule and Budget

6.1 Schedule

Throughout the course of this semester, the team closely followed a Gantt chart to keep track of scheduling. It can be seen below in Figure [15] This Gantt chart followed the ME476C class deliverables more than the client deliverables, which are more applicable to the second semester.

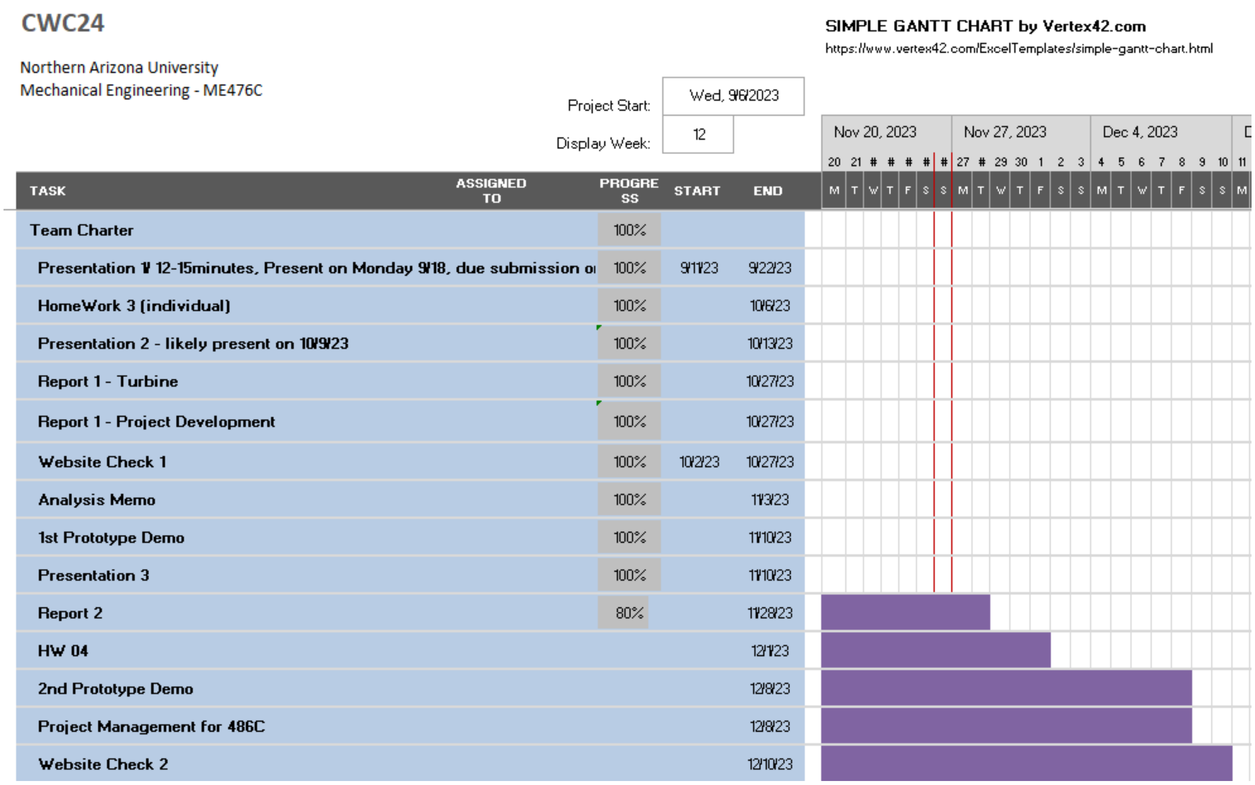


Figure [15] - First Semester Capstone Schedule

From the prior year's scheduling for ME486C, the team created an additional Gantt Chart for next semester. The days are rough estimates and will be updated when more information is made available. In the deliverables, there are five individual assignments, four of which are peer reviews, and the other is a self-learning assignment. The other deliverables fall into one of these categories: class submission, undergraduate symposium submission, Department of Energy Submission, and submission to advisor for review. Each of these tasks is essential in ensuring the CWC teams stay on track to be successful in the competition. This Gantt Chart is visible in the next page in Figures [16] and [17], which have been cropped for easier viewing. This schedule is applicable to both sub teams, and hence will be featured in both reports.

CWC24

Northern Arizona University
Mechanical Engineering - ME486C

SIMPLE GANTT CHART by Vertex42.com
https://www.vertex42.com/ExcelTemplates/simple-gantt-chart.html

Project Start: Mon, 1/15/2024

Display Week: 1

TASK	ASSIGNED TO	PROGRESS	START	END
Self Learning/ Individual Analysis	(Individual)		1/15/24	1/29/24
Hardware Status Update - 33+%	Team		1/15/24	2/12/24
Peer Eval 1	(Individual)		1/29/24	2/12/24
Website Check 1	Team Web Developer		2/12/24	2/26/24
Undergrad Registration	Team		2/26/24	3/5/24
Hardware Status Update - 67+%	Team		2/26/24	3/5/24
Peer Eval 2	(Individual)		2/26/24	3/5/24
Poster Draft for Ugrad	Team		3/19/24	3/26/24
Finalized Testing Plan	Team		3/5/24	3/26/24
DOE Submissions -1st Draft to Advisor for Review	Team		1/15/24	3/28/24
Hardware Status Update - 100% Build	Team		3/5/24	4/2/24

Figure [16] - Second Semester Schedule Part 1 of 2

TASK	ASSIGNED TO	START	END
Peer Eval 3	(Individual)	3/5/24	4/2/24
Final CAD Packet	Team	3/5/24	4/2/24
Initial Testing Results	Team	3/26/24	4/9/24
Final Poster and Powerpoint for Ugrad	Team	3/26/24	4/9/24
DOE Submissions - 2nd Draft to Advisor for Review	Team	3/28/24	4/11/24
Product Demo and Final Testing Results	Team	4/2/24	4/16/24
Final Report	Team	4/2/24	4/16/24
Final Website Check	Team	4/2/24	4/16/24
DOE Final Submissions	Team	4/11/24	4/18/24
Ugrad Symposium	Team	4/9/24	4/26/24
Peer Eval 4	(Individual)	4/2/24	4/30/24
Client Handoff - Spec Sheet and Op. Manual	Team	4/16/24	4/30/24
DOE Competition	Team	5/6/24	5/9/24

Figure [17] -Second Semester Schedule Part 2 of 2

6.2 Budget

As of this report, the team has received two grants totaling $7000 dollars from the Department of Energy and W.L. Gore. Should the team advance to Phase 3 after the submission of the mid-year report, the DOE will award a further $15000 grant. However, given that this is not a guaranteed amount, all budgeting is based on current assets.

Expenses				
Item	Quanitity	Price (per unit)	Shipping	Total Cost
Fish scale	1	9.99		9.99
Digital level	1	29.97		29.97
PLA Plus	1	25.98		25.98
Brake pad material	1	5.9	10.29	16.19
Female ball joint	3	12.5	9.37	65.61
Male ball joint	3	12.5	6.89	58.17
Prony Brake	1	120		120
Bearings (assorted)	1	49.31		49.31
Steel shaft	1	9.98	11.71	21.69
				0
				0
				0
				0
				0
				0
				0
				0
				0
				0
				0
Total				396.91

Funding			
Source	Amount	Foundation	Assets
Dept. of Energy	2000	100	1900
W.L. Gore	5000	250	4750
Team Donation	24	0	24
Team Donation	150	0	150
Team Donation	19.31	0	19.31
		0	0
		0	0
		0	0
		0	0
		0	0
		0	0
		0	0
		0	0
		0	0
		0	0
		0	0
		0	0
		0	0
		0	0
		0	0
Total	7193.31	350	6446.4

Internal Fundraising	
Source	Amount
Team donation	193.31
Total	193.31

Figure [18] - Current expenses and funding sources

Future Expenses			
Source	Amount	Percentage	
Competition	8000	124.100273	
Prototype 2,3,4	500	7.756267064	
Testing	1000	15.51253413	
Raw materials	350	5.429386945	
Final turbine	2000	31.02506826	
		0	
		0	Tot. w/o Comp. :
TOTAL	11850	183.8235294	59.72326

Figure [19] - Future expenses with corresponding percentage of budget

6.3 Bill of Materials (BoM)

An up-to-date Bill of Materials can be found in **Appendix A**, Table [17]. This BoM details the current cost to build the prospective design at current levels of analysis. All part numbers are in reference to Figure [37] and subsequent sub-assemblies. True fastener quantity, bearing selection, and mounting profiles are not considered at this stage of design.

7 Design Validation and Initial Prototyping

7.1 Failure Modes and Effects Analysis (FMEA)

Common failure modes in a small-scale wind turbine largely result from fatigue over time. As such, the do-it-yourself nature of this project will define a turbine that is built with few power tools, inaccurate screw torquing, and cheaply 3D printed components. Failures in these areas mean failures in basic systems that are easily replaced or modified. At this stage of the design process, it is understood that the most dangerous failure mode is withing the mainframe, often leading to an arbitrary loose component then failure within the rotating metal internals. If this is the case, and large structures such as the tower and anchor are designed for a factor of safety beyond that which is required, the turbine braking system should be the primary focus of the team's FMEA efforts. With a reliable braking system comes a reliable and safe turbine.

To avoid catastrophic failure and unnecessary mechanical stresses, many turbines at the utility scale and below incorporate dynamic braking systems. Use of a combination of active yaw control, pitch control, and mechanical braking create a safe and predictable turbine rotation. Design of a turbine with synchronous pitch control and mechanical braking is a significant focus of the team at present because it (1) satisfies braking requirements per the DOE rules and guidelines, and (2) defines a safe system even upon failure of one of the two robust braking systems. This is all to say if the pitching systems experiences one or more planar failures, the mechanical brake can be throttled to mimic similar rotor control. If the mechanical brake explodes, the pitching system can rotate the blades into stall, or whichever angle is appropriate per the present windspeed and RPM. While failure modes and mitigation brought the team to this conclusive design aspect, it has since been determined that a dynamically controlled system is necessary to best capture power and RPM curves in windspeed testing. So, the effects are two-fold.

By moving forward with this design, the team is accepting a larger workload and must perform dutifully in their braking component analysis. Where a safe turbine is ensured, a more complicated system is also guaranteed, thus future comprehensive FMEA must be completed to predict a stable system.

7.2 Initial Prototyping

7.2.1 Pitching – Ellie Freeman

For the pitching prototype the question that was trying to be answered is if the team would be able to use a linear actuator to create linear motion that can be transformed into rotation motion on the blades. To answer this question, the team made a pitching prototype that included a swash plate with a ball bearing, ball joints, a blade hub and a shaft/blade hub connector. For this prototype most of the parts were 3D printed except for the ball joints and the ball bearing. This specific prototype was based on a similar design from a few years ago but the team is planning to improve that design and allow a larger range of blade rotation. After putting together the prototype, the answer to our original question is that the team can use linear motion in order to create rotational motion and allow the blades to rotate. From making this prototype there were a few things that the team learned, first was that the total design of the pitching is extremely dependent on the ball bearing which is dependent on the shaft diameter. This means that before the team picks a ball bearing that will be used in the final prototype the shaft diameter needs to be known. Once that value is known then the appropriate ball bearing can be selected, and all the other geometry can be figured out. Something else that the team learned is that the blade hubs could be designed with less material to allow for a larger range of blade rotation.

In the future an analysis of the blade hubs strength could be calculated and from there the team can shave off material to make the design more efficient. Another thing that the team learned is when designing the swash plate, the connector between the ball joints and the ball bearing needs to have an outer diameter that is similar to the blade hubs. The team noticed that the ball joint connector on the swash plate was too close to the shaft while the blade hubs were further away, and this limited the range that the blade hubs can rotate from the ball bearing. If the dimensions were similar, then the ball joints should have more freedom to move. There was a lot the was learned from the pitching prototype. Some things that the team will be looking at in the future is to figure out what stroke length is needed to get a 110-degree range of blade rotation and add a linear actuator. Something else that the team will investigate is finding a way to support the swash plate so that it doesn't rotate around the shaft when it isn't supposed to. A couple ideas to do this would be to change the geometry of the shaft in the front so that it is hexagonal, and the swash plate won't be able to rotate along the shaft or add some brass bushings to support the swash plate.

7.2.2 Blades – Holden Gardner

Blade prototyping in this cycle of the project behaves as a 3D printing exercise. When designing a wind turbine rotor, all force values and trajectories must be considered implicitly in the geometry of the blade and rotor connections. With centrifugal forces presenting the largest values in the blade itself, it's worth inquiring if centrifugal force values can separate the 3D printed blade model at its layers. Two blades were printed, one vertically and another horizontally along the leading edge of the blade. Serious conclusions can be made from only handling the vertical blade post-production. The vertically printed blade broke in half after bearing its own weight from the tip where the horizontally printed blade could be bent to nearly 180 degrees before plastic failure.

This prototyping process was important because it validates the presence of centrifugal separation and informs how all blades will be printed for future revision testing. Additional analysis will need to be developed numerically using FEA software to best capture effects on a solid blade from all remaining force values. It is from this process that the design team remains open minded about changes to the airfoil, adding airfoils for different blade length characteristics, and potentially replacing printed blades from final design submissions with composite materials.

7.2.3 Braking System – Niki Wilson

The main question to be addressed by this first prototype was that of relevant geometry. The initial design and 3D CAD model contained floating parts, as well as parts that do not necessarily exist. Therefore, the physical model set out to define how the braking system would integrate into the nacelle and if the required components were manufacturable. The answer was not a simple yes or no.

First, it was discovered just how many geometrical issues needed to be solved. The configuration was simple enough in principle – two brake pads connected via a rectangular pin would squeeze rotating aluminum disk, that included cut-out slots for increased friction, by the execution of a linear actuator. The brake pads, and what the pads are attached to, need to surround the rotating disc without touching it unless actuated. This has been the biggest problem thus far. The actuator is simply a small gear box with a leadscrew. The leadscrew is the actuation arm with a predetermined stroke length. One can connect the actuator to the component in need of translation through an 1/8-inch hole in the actuation arm. The friction and pressure between the pin and the actuator arm are the only things holding it up. Therefore, in reality, there is a moment about that connective point due to gravity and the anterior brake pad rests on the disc.

Another issue concerned the manufacturing of the relevant components. The rectangular pin was a unique part. It was initially 3D printed. However, due to the extreme size constraints set by the actuation arm, the pin was quite brittle. It was effective for illustrative purposes but did not support the brake pads satisfactorily.

Next, the design originally had the actuator pulling the anterior brake pad toward the disc. However, upon further inspection and thought, this creates a shear stress on the connective point between the actuation arm and the pin. There is not a significant amount of material surrounding the hole in the actuation arm to prevent failure. So, moving forward, the design will likely be adjusted to push the brake pads into the disc.

The whole process of prototyping informed the future configuration in that it needs to be simplified and key elements need to be redesigned. The pin has been eliminated and replaced with M3 threaded rods as guide rails and a T-shaped joint that will screw onto the actuation arm. Previously, the actuator was, essentially, hanging from the ceiling of the nacelle. Future iterations will likely put the actuator on the bottom.

7.3 Other Engineering Calculations

7.3.1 Pitching – Ellie Freeman

Some engineering calculations that went into the pitching system used MotionGen online software to determine the overall system on a 2D scale then figure out the proper dimensions of the components that the pitching system will need to get a certain range for the blade rotation. From MotionGen you can figure out what lengths that are needed to get a certain range of blade rotation. As seen in Figure [20] you can see how MotionGen is used to find the dimensions needed for the pitching system. For this system, with a ball joint of 4 cm long, a blade hub that 2.5 cm from the center to the ball joint connection and a stroke length of 2 cm from the actuator will give a range of 101 degrees for these dimensions. This will give us a estimation of the range that the blades can move but isn't exact so with this and then prototyping the team will be able to get a larger range of blade rotation for the different dimensions.

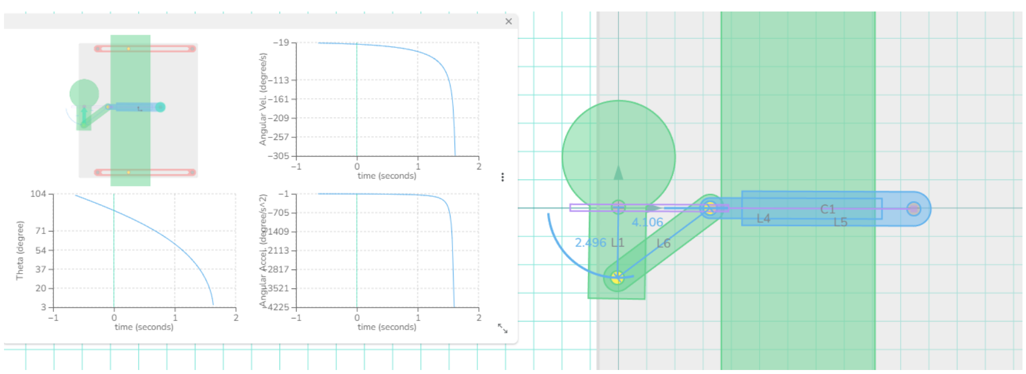


Figure [20] - MotionGen 2D pitching with 101-degree angle range

Figure [34] and [35] from appendix A shows how different lengths for the ball joints and stroke lengths will give different ranges for the blade rotation, giving the team different options for the sizes and capabilities for linear actuators so the team can make the best pitching system.

7.3.2 Brakes – Niki Wilson

The current, and most likely final, braking system design functions by way of a linear actuator. Linear actuators are rated for different actuation forces. To get an idea of what the max necessary force will be, a simple calculation was run in MATLAB based on the dimensions of the brake pad using the following equations,

$$p_a = \frac{2T}{(\theta_2 - \theta_1) f r_i (r_o^2 - r_i^2)} \tag{18}$$

$$F = (\theta_2 - \theta_1) p_a r_i (r_o^2 - r_i^2) \tag{19}$$

where f is the coefficient of friction and T is the torque. All other variables relate to the following graphic

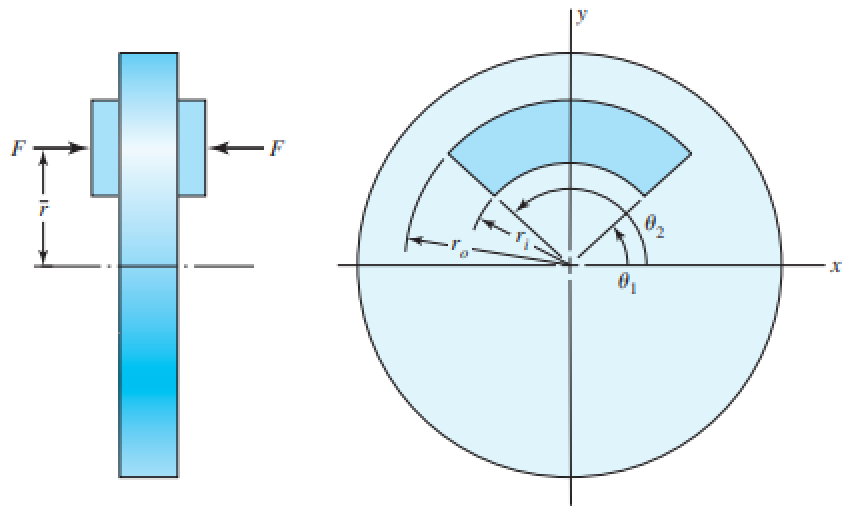


Figure [21] - Relevant geometry [19]

Results of the calculation are described in the graph below.

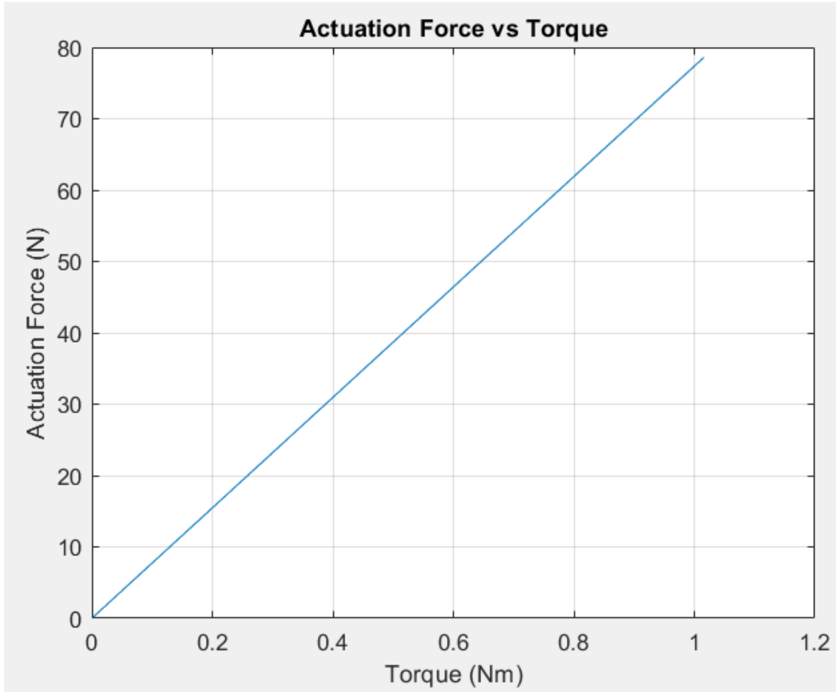


Figure [22] - Estimated Actuation Force

7.3.3 Shaft – Sergio Zuniga

Though the previous shaft analysis provided some insight, a more proper shaft analysis must be conducted for shaft diameter selection. A MATLAB code was produced where variables can easily be changed and calculations/results are given almost instantly. For torsional stress, equations (15), (16), and (17) were used again, however due to the team wanting to go with a double D profile to secure the brake disc, the stress increases due to stress concentration. This turns equation (15) into

$$\tau_{max} = K\left(\frac{T_{max}c}{J}\right) \tag{20}$$

To calculate the polar moment of inertia (J) of the notched section of the shaft, the J's from the segments that are to be machined off were subtracted from the full cylinder J, as can be seen in Figure [23]. This converts equation (16) into

$$J = \frac{\pi}{32}D^4 - 2A_{segment} \tag{21a}$$

$$A_{segment} = \frac{1}{2}r^2(\theta - \sin(\theta)) \tag{21b}$$

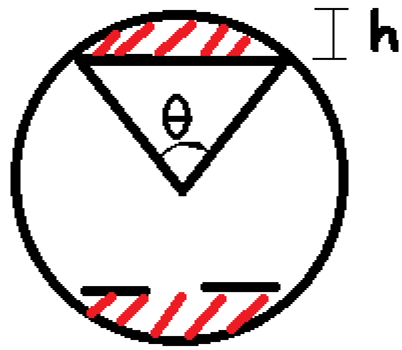


Figure [23] – Section cut of notched shaft section

From this initial revision of the shaft analysis, for a D of 10 mm and a h of 1 mm, a factor of safety of 23.3 is calculated for a shaft made of ASTM 1030 steel. This is a very rough estimate, but now this code can be optimized/modified to get the calculations as accurate as possible. Another analysis that must be done for the shaft is that of the cantilevered end where the weight of the rotor lies. This is being implemented and should be ready by the time homework 4, and upcoming assignment, will be due. Eventually, the code will also be modified to accept a vector of different diameters and spit out vectors as results, which will be nice to show graphical results such as factor of safety vs diameter size. To view the code, refer to **Appendix B**.

7.4 Future Testing Potential

A potential testing procedure that could be completed in the future is using a dynamometer to test a steel shaft at a certain RPM and apply a braking force to the shaft until the shaft stalls. This test uses a steel saft and a Prony brake to apply different forces to find the stalling force. This testing set up is shown in Figure [24] where everything has already been built and set up for this test, the team is only waiting for a steel shaft to come for the team to start testing.

Figure [24] - Dynamometer and Prony brake

Using the Prony brake to apply force and looking at the fish scales that are built into the brake the team will be able to find the force that caused the shaft to stall. After finding the force that it takes for the shaft to stall the team will be able to compare these experimental results with theoretical results that were calculated before the experiment took place and can determine if the team will be able to use the dynamometer as a replacement for wind power testing for early-stage designs for specific RPMs.

To test at what angular velocity the blades shear off the hub, the team will likely attach the rotor to the dynamometer and surround the assembly with a wooden box. Then, run the dyno at max rpms until the blades fail.

Another testing set up in mind is to use the same (or similar) dynamometer mentioned before to test different generators. To make sure that the most efficient generator is chosen, the team will buy and test a one or a couple of them versus a generator from previous years designs. From here, efficiency and performance curves can be created, which will heavily influence the generator selection. One other thing to monitor whilst testing the generators is making sure that they can produce a high amount of maximum power, as this will make the boost converter for the EE's less intensive and ensure that the motor will not overheat in competition to reach the required 48-volt limit.

7.5 DOE Midyear Report

The NAU CWC24 design team has successfully created numerous functional prototypes of integral HAWT components. All prototypes have utilized some form of data exchange among group members where strong communication and organization have defined the foundation for current successes. Thus far, prototyping efforts have been split among team members by interest and iterative technique: blade development, pitching systems, brakes, and nacelle configuration.

Analytical prototyping of blade geometries has shown that a realistic blade can be configured within software such as QBlade, conceptually checked with numerical methods within MATLAB, then transferred to CAD software for solid part creation. 3D printing blades lead to a new set of challenges. By printing multiple iterations of the same blade and remaining knowledgeable of rotor quantities such as rotational and centrifugal forces, a reliable printing orientation was determined for all future 3D printed blades to provide the most strength in necessary areas.

Where the team has found the most prototyping success has been in the pitching system. A fully functional pitching system is prototyped and ready for additional analysis at the time of recording. Currently, new iterations are being conceived and alternate ideas are being considered. 2D analysis using MotionGen browser software has allowed the team to discover a broader pitching angle compared to what the current pitching system allows for, ultimately allowing for a more flexible and effective wind turbine.

Mechanical braking systems within wind turbines can take many forms. First version braking systems utilized a pulling motion to press a brake pad into the brake disc. After several iterations and simplifications of this design's required geometry, it was determined a basic push-brake is the most space conscious and cost-effective method. One physical prototype of the pull-brake system demonstrated to the team the geometric complexity required for such a design. While the idea remains within option, the team looks toward as many nacelle mainframe space reductions as possible.

Prony Brake static brake testing is informing the team on exactly what static forces might be found between the braking system components. Validating key calculations such as torque is hugely important in the early stages of design, with most of its consideration to a safe design. Other results from static testing will inform linear actuator selection and mounting methods.

8 CONCLUSIONS

This report contains progress of the turbine design team at the current state of the design and ideation. Project background is divided into three sections: project description, deliverables, success metrics. The project can be simply described as an industry driven collegiate competition proposed to prepare students in industry-like outreach and design aspects of a small wind turbine. Many of the associated deliverables are assigned by the department of energy to maintain team perspective. The most important of these are the midyear report and final report submitted directly to the Department of Energy. Success within the team at the current stage of design is reliant on how capable members are to adapting to changing needs based on testing conclusions. Arriving at testing conclusions will require unique metrics and numbers to be developed and referenced throughout the project. The more accurate testing numbers can be the more precise the team can be in hitting their testing marks; however, realistic testing reference frames are just as beneficial to the team. Customer and engineering requirements are discussed rigorously. Most requirements are derived from the rules and guidelines document provided by the Department of Energy while few are determined with reference to what goals the team wants to achieve during testing and competition. The House of Quality will remain a living summary for these requirements. A detailed functional decomposition is also listed alongside a basic black box model of the wind turbine, from rotor to generator. Ultimately, each team member listed and defined their selection criteria and concept generation and selection rationale. Multiple top-level designs were determined through this process where the team has significant amounts of data to reason through in the upcoming testing stages of design. After determining the designs, a failure modes and effects analysis was made for the main parts of the turbine and prototypes were designed for the blades, pitching, and braking systems. This helped inform the team what needed more work for these designs with more calculations of these subsystems and how these designs can be improved in the future of this project. Along with prototypes for different subsystems there is also possible testing that can be completed in the future of this project once the calculations and subsystem designs are finalized.

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10 APPENDICES

10.1 *Appendix A: Descriptive Title*

Table [15] – Customer Requirements and Half Engineering Requirements

↑	↑	↑	↑	↑
Whole turbine profile: 61cm x 122cm	Rotor and non-rotor system volume: $45cm^3$	Anchor: ≤ $30cm^2$ length and width area	Turbine must have braking capability (1) by button (2) at loss of power (3) at ≥ 48V at PCC	Tower baseplate thickness ≤ 16.1mm
0	0	9	0	0
0	1	5	0	1
1	1	5	5	5
0	5	5	9	9
1	1	9	9	9
1	1	0	9	0
1	1	1	1	5
1	1	5	0	1
9	5	9	1	5
70	80	240	170	175
10%	9%	1%	3%	2%
15	**13**	**2**	**5**	**3**
16	14	3	6	4
5	7	4	6	2

Table [16] – Remainder Engineering Requirements

↑	↑	↑	↑	↑	↑	↑	↑	
Power (curve) fluctuation may not exceed a 5s interval of ±10% power average at wind speeds 5-11m/s	Noise from power electronics must be between 50-22.5kHz	Rotor midplane must be 60cm±3cm above flange top	Power must be at equal value for 11m/s bin compared to 12-14m/s bin	Rotor RPM must be equal or below value at 11m/s bin compared to 12-14m/s bin	Cable passthrough must use cable glands. Quick connections at cable ends. 4.5m min cable length	Electrical systems must be ground through baseplate with 100kohm resistance	4mm x 20mm open rotor area for reflective tape placement	Weighted Score
0	0	0	0	0	0	0	0	160
1	1	0	1	1	0	1	5	85
1	1	1	1	1	0	1	1	175
5	5	1	5	5	9	5	1	240
5	5	1	5	5	5	5	1	265
9	5	1	9	9	1	5	1	55
0	0	1	0	0	1	1	1	60
0	0	5	0	0	5	5	1	70
0	0	1	0	0	1	1	1	240
105	85	55	105	105	110	120	60	1350
5%	8%	12%	5%	5%	5%	4%	11%	100%
8	**12**	**17**	**8**	**8**	**7**	**6**	**16**	
9	13	18	9	9	8	7	17	
9	5	4	8	9	2	2	1	

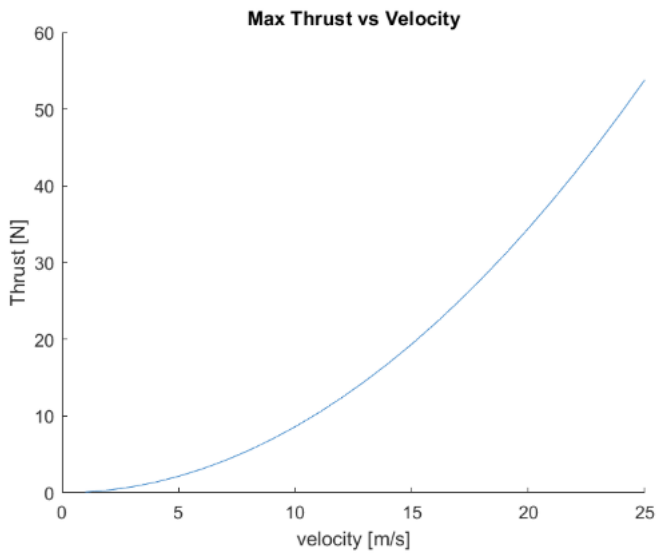

Figure [25] - Thrust vs Velocity

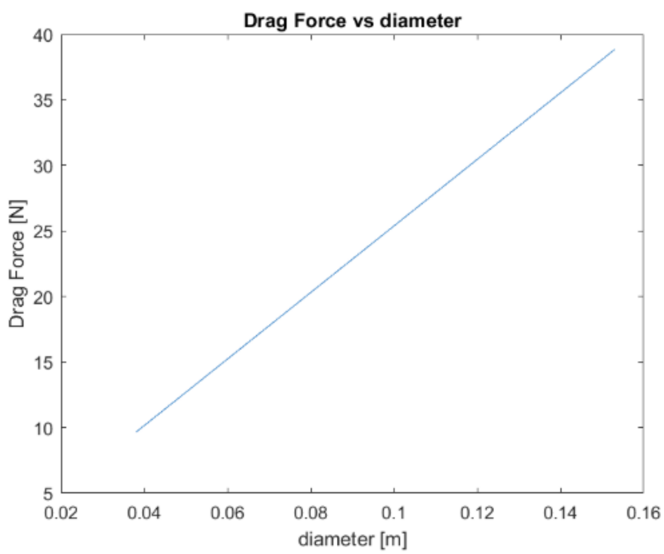

Figure [26] - Graph of drag forces vs diameter

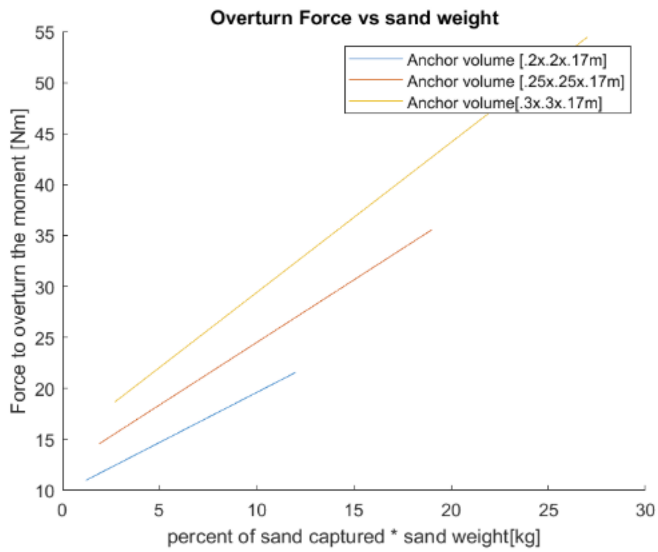

Figure [27] - Overturn Moment vs Percent Sand Captured

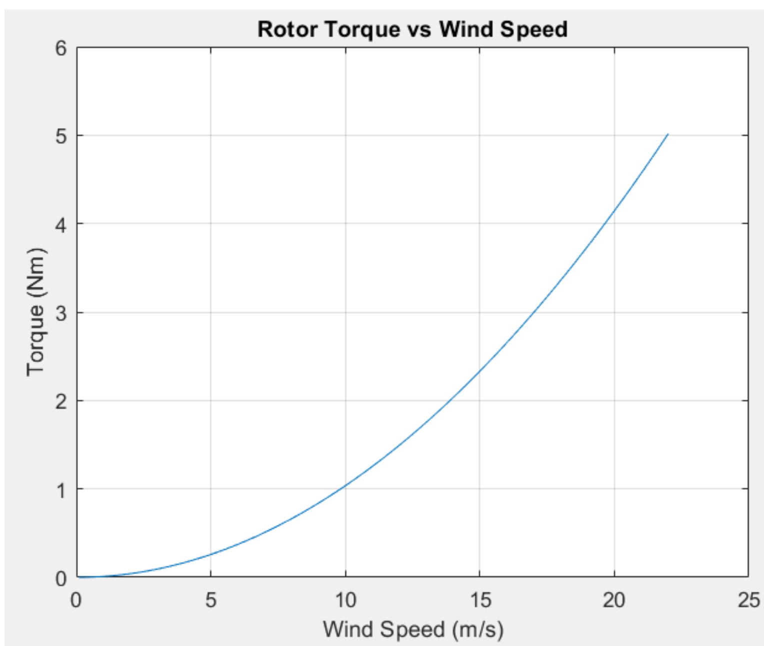

Figure [28] - τ vs U

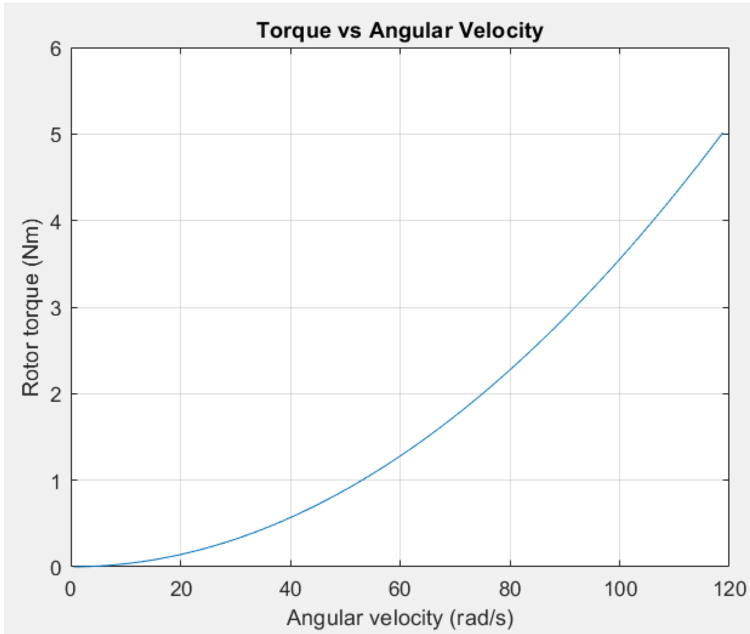

Figure [29] - τ vs Ω]

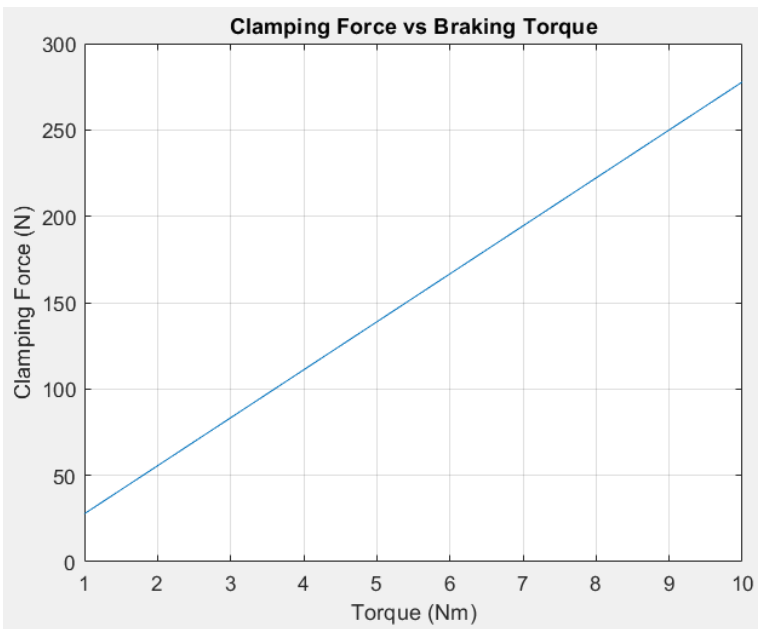

Figure [30] - CF vs τ

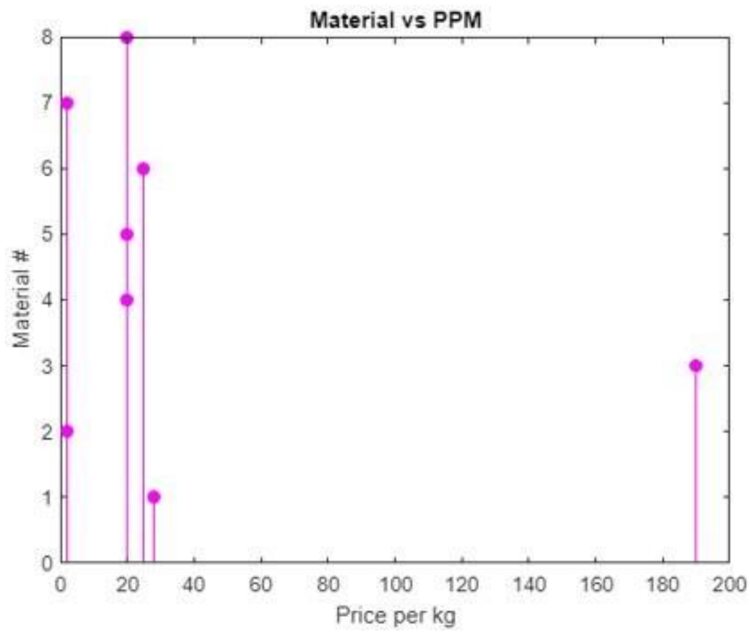

Figure [31] – Material # vs Price per kg

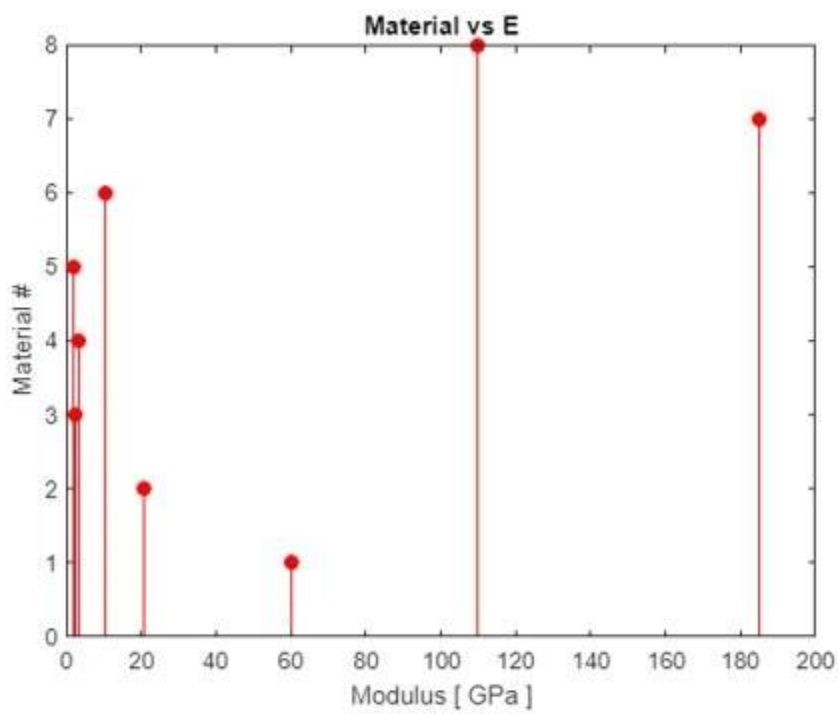

Figure [32] – Material # vs Modulus of Elasticity

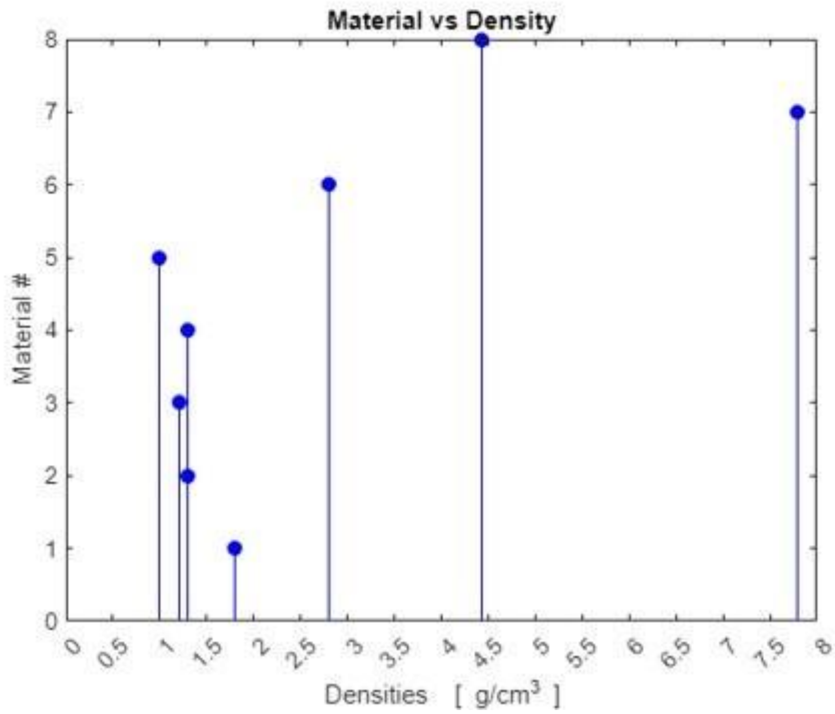

Figure [33] – Material # vs Density

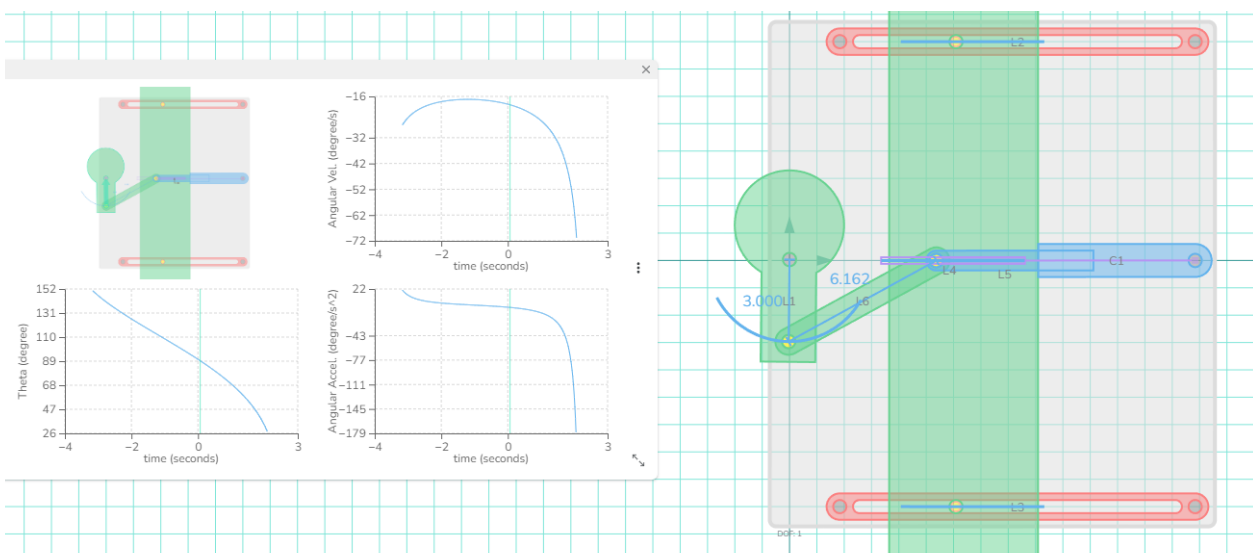

Figure [34] - MotionGen 2D Pitching with 126-degree Angle Range

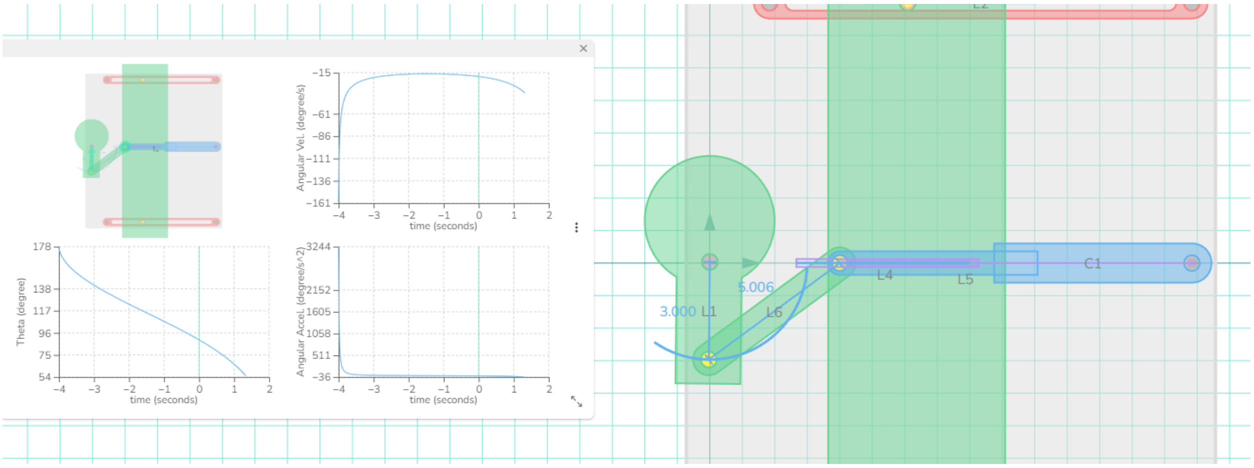

Figure [35] - MotionGen 2D pitching with 126-degree angle range

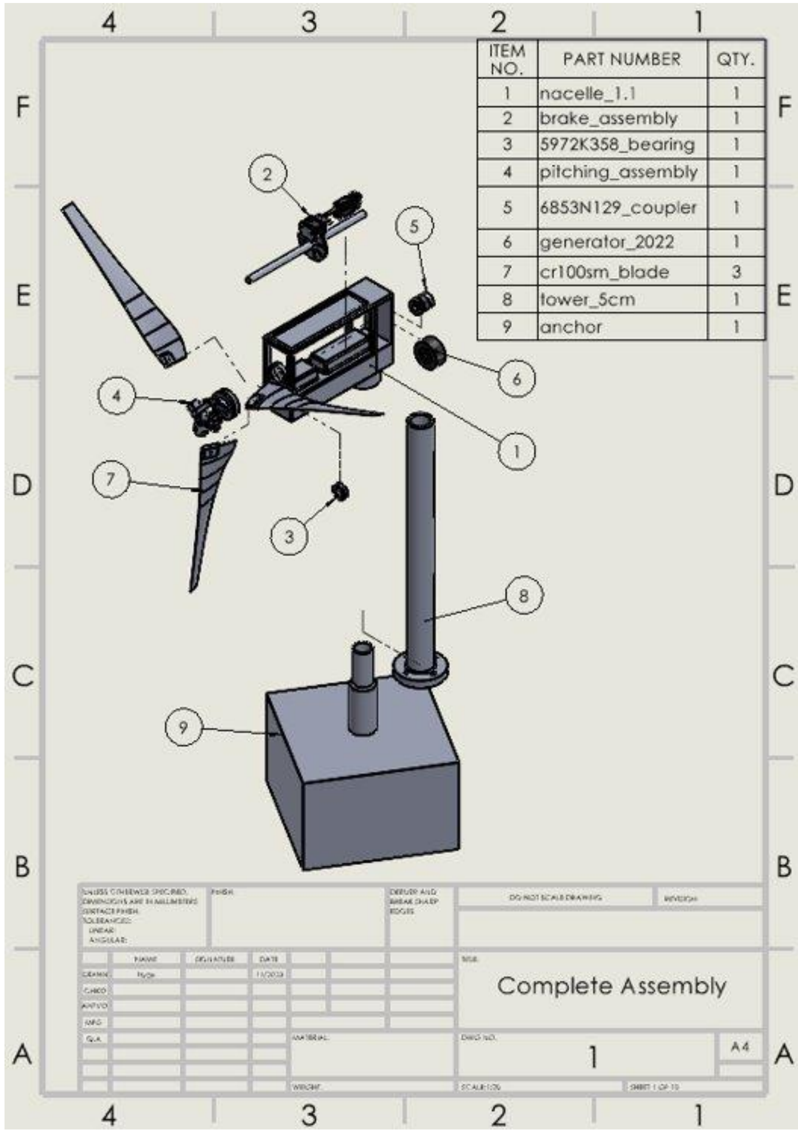

Figure [36] – Top-Level Assembly Drawing

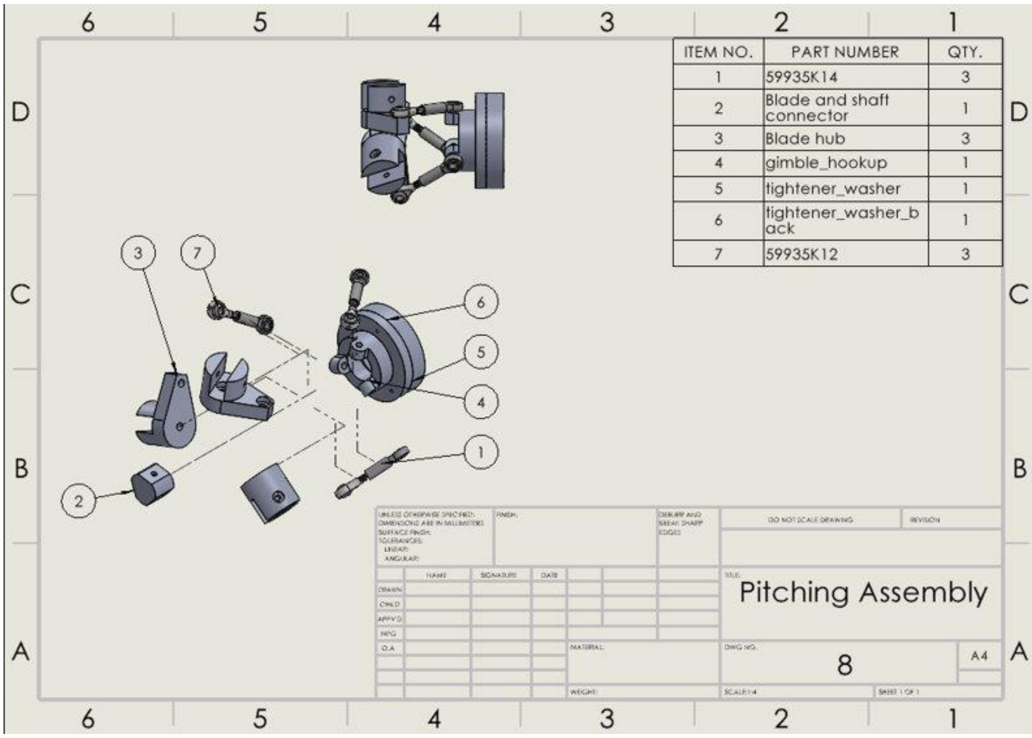

Figure [37] – Pitching Assembly Drawing

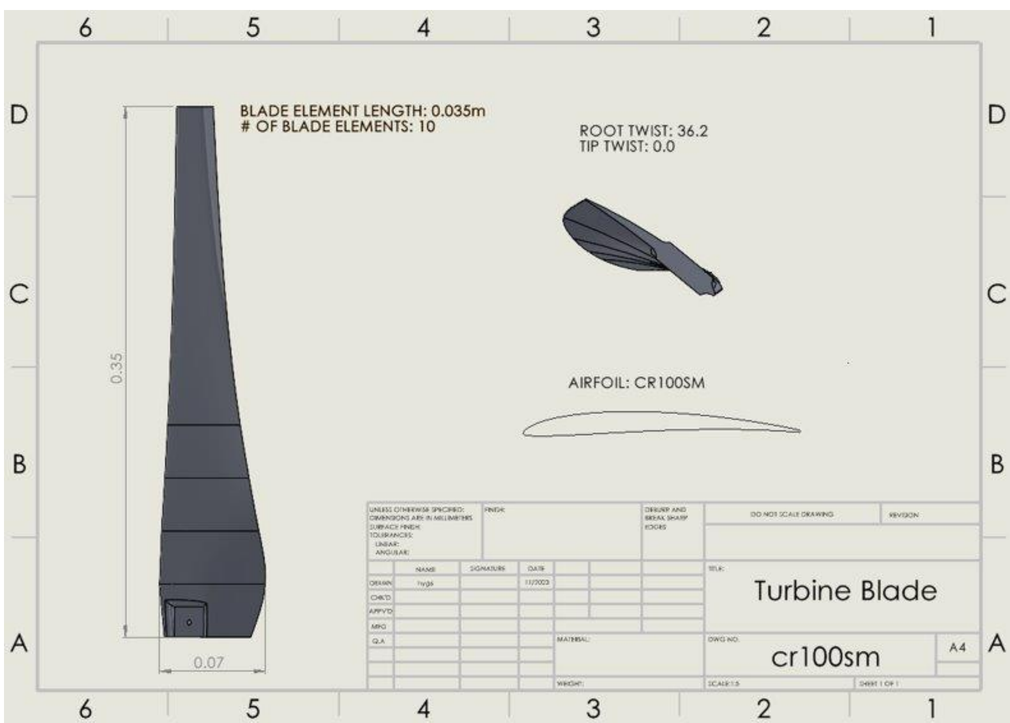

Figure [38] – Blade Drawing

Table [17] - BoM

Item #	Part #	QTY	Total Est. Cost ($)	Source
1	Nacelle	1	5	Team 3D Printing
2	Tower	1	10	Student Stock
3	Anchor	1	15	Student Stock
4	Blade	3	300	Team 3D Printing
5	Shaft	1	15	McMaster Carr
6	Brake Disc	1	10	Student Stock
7	Backplate	2	1	Team 3D Printing
8	Linear Actuator	2	70	Actuonix
9	Actuator Bracket	1	1	Team 3D Printing
10	Blade-Shaft Hub	1	1	Team 3D Printing
11	Blade Hub	3	3	Team 3D Printing
12	Linkage	3	110	McMaster Carr
13	Gimbal	1	1	Team 3D Printing
14	Front Washer	1	1	Team 3D Printing
15	Back Washer	1	1	Team 3D Printing
16	Interior Washer	1	1	Team 3D Printing
17	Fasteners	100	-	Donation

10.2 Appendix B: Relative Code