Kansas State University
Wind Turbine Technical Report

WILDCAT
WIND POWER

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Executive Summary

Wildcat Wind Power is an extracurricular design team competing in the Collegiate Wind Competition (CWC). Our objective is to design and construct a scaled wind turbine as well as provide a siting and project development for a local wind farm. We are organized into three teams to face the challenges set by CWC; Electrical, Mechanical, and Siting team.

The Electrical and Mechanical teams collaborate closely to effectively produce a scaled wind turbine to meet the tasks set my CWC. The tasks include: Cut-In Wind Speed, Power Curve Performance, Control of Rated Power and Rotor Speed, Safety, and Durability. These are the same tasks as the year prior. Our previous turbine excelled during the Cut-in Wind Speed and Power Curve tasks. However, the inability to properly measure, control, and brake led to the turbine coming up short in the Control, Safety, and Durability sections.

Wildcat Wind Power's primary focus has been to improve upon the weaknesses of the previous year's designs without compromising the strengths that made it successful. To achieve this, the mechanical team has on focused implementing a new mechanical braking system, a nacelle design to house the additional components, and applying incremental optimizations the tail and blade design of the previous year. The electrical team has focused on tracking rotor speed and using that information to control the rotor speed and power output of the turbine through the intervention of the mechanical brake.

To measure the RPM of the rotor with our microcontroller, a photo-interrupter sensor and a custom printed code disc have been installed into the new nacelle. The information gained is used to control the position and torque required by the mechanical braking system. The mechanical braking system consists of a high torque servo motor, break arm, and brake disk. When breaking is desired, the servo motor rotates the brake arm to make contact with the brake disc. The addition of these 5 new components, and their associated wiring and mountings, has required a brand-new nacelle design which has been optimized to maximize space efficiency and simplify the assembly process.

In order to excel in control, safety, and braking tasks, our team has also worked on improving testing equipment and procedures used to simulate those tasks. Capability has been added to our Dynamometer stand and control and more data acquisition has been added to the wind tunnel. Our turbine design is the result of two strongly cooperative design teams, a limited yet specific goal, and a refined testing procedure to close the design loop and allow for continuous iteration.

Electrical Analysis

The electrical system is composed of several fundamental elements including the generator, three-phase rectifier, DC/DC converters, and load. Controlling the circuit is an Arduino microcontroller. Three-phase power is supplied when the generator captures mechanical energy and rectified to DC power. The DC power is then supplied to the load. The microcontroller will measure the power supplied to the load and control the function of the circuit. The microcontroller is able to implement the braking system and load detection.

Our team decided on the LD Power MT4114-320KV generator as it works efficiently for the application. The KV value is the relationship between the number of stator windings and gauge of the wires in the stator. The ability to produce higher voltages at low RPM is ideal for wind turbines; as wind turbines have large and heavy blades.

The main focus for our team was to solve the issues of previous competition failures. As our turbine was unable to complete the safety, control of rotor speed power output, and durability tasks. Our first challenge was to track RPM, which was achieved with a opto-interrupter sensor. The next task was to then brake and control the speed of the rotor. Our team researched two approaches: using back EMF and using a servo actuated brake to add more friction resistance to the rotor. Back EMF proved to be undesirable as it did not achieve our objectives. However, the servo provided the needed stopping power to meet our objectives. The servo is powered at five volts and current is pulsed to control the torque applied.

Using these tools, we can face challenges faced by actual turbines, including a steady power curve, control of rotor speed and power output, cut-in wind speed, enduring and persistent functionality, as well as safe shutdown systems. This section of the report will disclose the solution implemented to combat the challenges listed above.

Cut-In Wind Speed Task

Typically, turbines do not produce efficient power at low wind speeds. We can find the power generated by a turbine using the relation $P = 1/2 \, \rho \times A \times v^3$ where ρ is the air density, A is the swept area of the blades, and v is the wind speed. Operating at the lowest possible wind speed will allow us to get the most power output of our turbine for the range of possible wind speeds. Using a generator with a lower KV value allows us to lower our cut-in speed.

Power Curve Performance Task

The average wind speed across the continental United States is between 5 m/s and 8 m/s. Real turbines need to produce optimal power in this range of wind speeds, which is a parameter provided by the Collegiate Wind Competition. Table 1 outlines the scoring for power curve task. Figure 1 shows the power curve for our wind turbine

We designed our turbine and circuit to accommodate these parameters. Real turbines will also see a variety of wind speeds including storm winds and gusts from time to time but is not common practice to design a power generating turbine for these conditions.

Wind Speed (m/s)	Power Increase Factor
5	1.3
6	1.5
7	1.5
8	1.3
9	.9
10	.5
11	.3

Desired Power Curve
Table 1
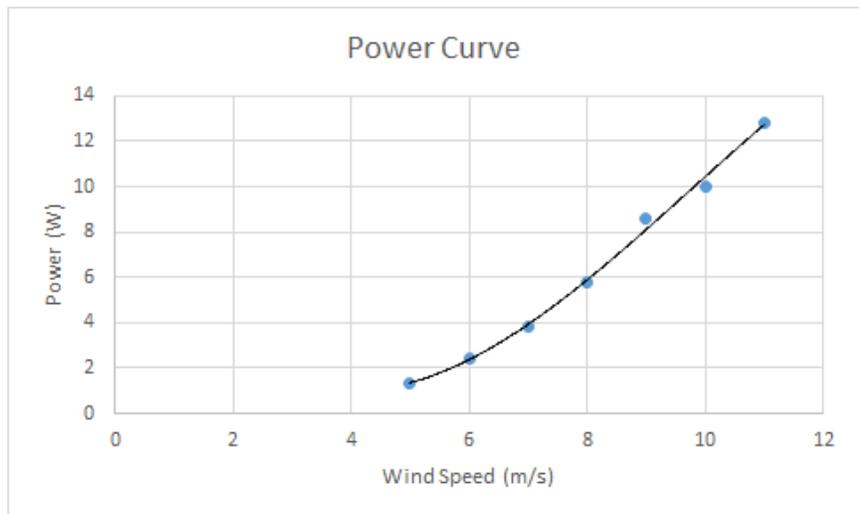
Turbine Output Power as a Function of Wind Speed
Figure 1

Safety Task

Safe construction and operation is the primary objective when designing any turbine. When the wind reaches speeds beyond the capabilities of the turbine, we need to be able to shut down the turbine. We are tackling this problem with a servo brake. The brake is programed for an off state and an on state. Using a MOSFET we are able to regulate the power supplied to the brake through pulse width modulation (PWM), in order to increase or decrease its torque. The brake will stay on as long as there is power supplied, keeping the turbine from reaching critical speeds from excessive winds or loss of loads. We signal the brake with a current sensor in series with a load and a manual switch. If the current sensor reads zero Amperes or the switch is set to on, then safety protocol is initiated. When the circumstances that initiated safety protocol become untrue, the turbine begins operation again. Significant time was spent researching a back EMF brake, and, while it performed well at wind speeds under 9 m/s, performance significantly declined at higher wind speeds.

Control of Rated Power and Rotor Speed Task

Sudden spikes in wind or power can be perilous for a wind turbine and power grid. The turbine is designed to operate in a certain wind range so being able to control the power output of a turbine when outside the rated wind range is an important task. We have two ways to govern the speed of our turbine: servo brake and pitch of the blades. When wind speeds exceed the desired range these two systems activate to slow the turbine.

To control power output and rotor speed, our team first found measurements for both current to the load and the RPM to find stable power and speed. Using the range for stable power output and rotor speed, the microcontroller communicates with a MOSFET to supply power to the servo. Duty cycle for the MOSFET is increased allowing more power to the servo. Once power output and rotor speed is brought to the optimal range the power to the servo is reduced.

Durability

Wind turbines will experience a wide variety of weather conditions throughout their lifetimes. Being able to provide reliable and sufficient power are vital to any generation scheme. When the wind is not able to provide the power needed, other sources such as solar, hydroelectric, nuclear, fossil fuel, and stored energy are implemented. The 58 Farad capacitor stores power to be used when power levels fall during wind energy production.

This test requires two states: charging and scoring. During the first minute of the task, we need to charge the capacitor as quickly as possible. Using a low resistance will result in a small time constant. The capacitor will act as a power bank for the second part of the test.

The second part of the test is a scoring period, our turbine will see a relative vast range of wind speed, along with a variable resistance load. Using the turbine and capacitor in tandem, we can supply a constant five volts. Our DC/DC converter will ensure a reliable five volts across the variable load, and we plan to regulate current by regulating the RPM speed of the turbine. We use a photo-interrupt sensor in the nacelle to read the RPM of the turbine, and the Arduino microcontroller utilizes this data to adjust the duty cycle of the power leading to the servo. This changing duty cycle will help us adjust the torque on the break and keep the RPM constant and keep relatively constant power across the load. Our current sensor, reading current through the load, combined with the photo-interrupt, will allow us to accurately adjust the brake torque to keep constant power during this task when the wind exceeds rated speed.

Mechanical Design

Major mechanical components for this year's wind turbine design include a mechanical braking system, twin plate tail, twisted blades, and an original nacelle design. The mechanical brake is a disc partnered with a brake pad designed to maximize the surface area of the surfaces the braking force is applied to. The twin wing tail is designed to maximize yaw rates and add the necessary damping to reduce swinging. This design has seen only minor modifications from the previous year. In addition to this, the twisted blades were designed to optimize both cut-in speed as well as power produced by the turbine between 5 and 11 m/s. Lastly, the nacelle was completely redesigned in order to incorporate the mechanical braking system, rpm sensor, and other electrical components of the wind turbine. Figure 2 shows a completed image of the turbine. Figure 3 shows an exploded view of the turbine.'
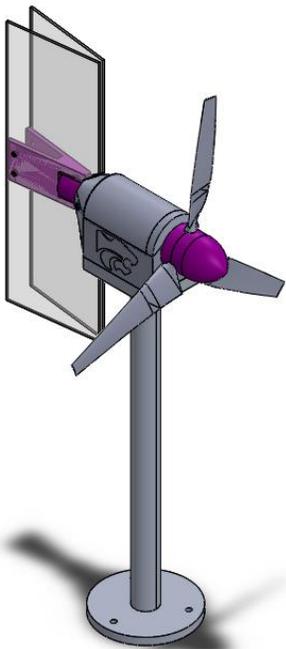
Turbine assembly

Figure 2
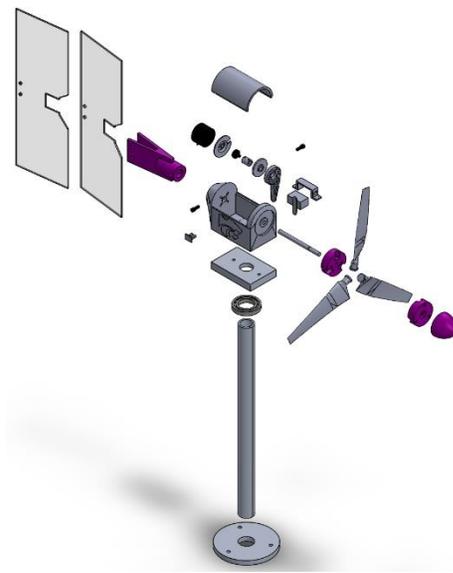
Exploded view of turbine assembly

Figure 3

Testing

Testing was a key component of the Wildcat Wind Power team's design process this year. The team makes countless updates and modifications through feedback gained from our two primary testing equipment: the dynamometer and the wind tunnel.

The dynamometer is used to simulate wind speeds condition, it achieves speeds up to 2400 RPM and torque as high as 2 N-m. By mounting a prototype nacelle with generator and drive-shaft to a testing plate, qualitative data could be gathered with quick set-up and few unknowns. Comparing qualitative observations in the wind tunnel to the quantitative values provided by the

dynamometer, context between the two measurements could be achieved. For example, the effect of breaking torque can be viewed in the wind tunnel and measured on the dynamometer.

The wind tunnel was built by the team in 2016 and was our second major resource for testing our prototypes and optimizing our final design. The tunnel produces wind speeds up to 16 m/s and can simulate changing wind directions through a bearing that the tower is bolted to at the bottom of the tunnel. A LabVIEW VI was developed to continuously control the operation of the tunnel and log data throughout the duration of the test. The data logged includes: tunnel wind speed, turbine RPM, load resistance, and power output. The VI allows the team to streamline the testing process and maximize the information received from testing runs. Additionally, the VI allows for data recording at a sampling rate of 100 Hz, allowing us to detect and remove noise in our power output readings.

The program receives a desired wind speed input from the user, runs it through a wind speed linear calibration, and sends the appropriate voltage signal to the wind tunnel's fan speed drive. Additionally, the program receives signals from the load and photo-interrupt and interprets those signals to calculate Power and RPM. During testing, live graphs of Wind Speed, RPM, and Power are seen on the block diagram. The programs reads 10,000 samples a second and populates an excel spreadsheet with averaged data once a second. Figure 4 Shows the LabVIEW Block Diagram and Front panel.
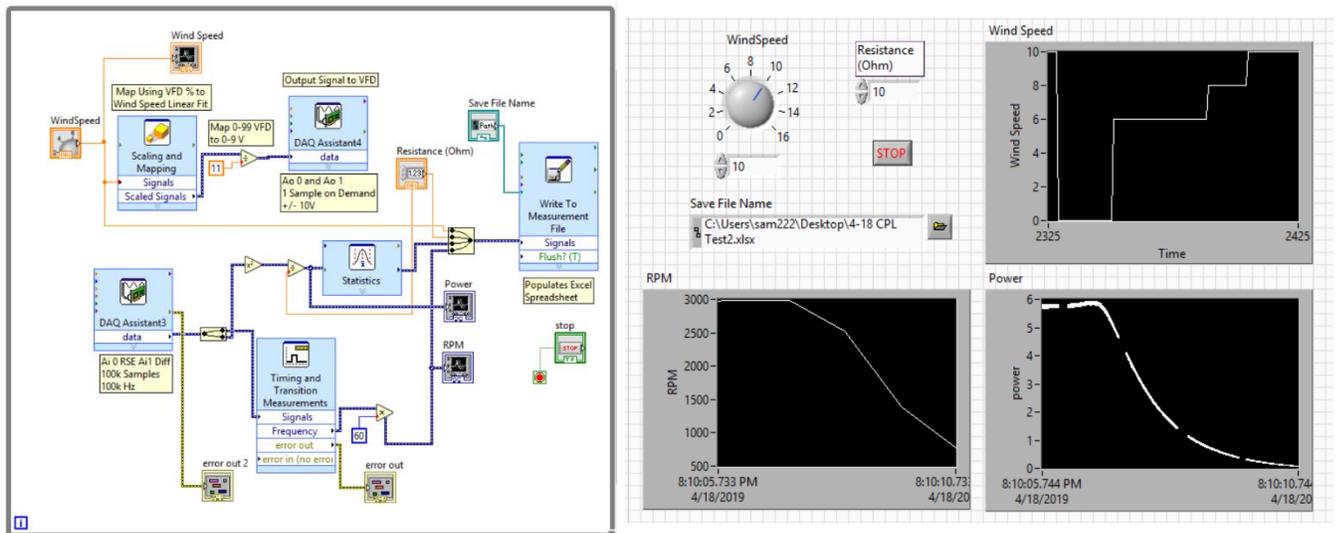
LabVIEW Program for Logging Wind Tunnel Test Data
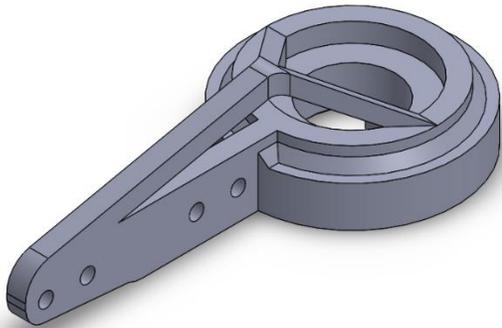
Figure 4

Another critical component of our design process is our 3D printers. Through partnerships with other organizations, Wildcat Wind Power was able to acquire and set up two 3D printers this year to assist our partner organizations in their outreach and improve our prototyping capabilities. The printer models we use are the Creality CR-10 and the Prusa i3 mk3. The printers allow us to go from 3D model to physical part quickly and easily. A significant portion of our turbine's design is 3D printed, particularly the pieces that have seen many design iterations.

Disc Brake

For industrial wind turbines, one of the most important features is the safety mechanism, something that is also of large importance for this competition. One of our main design goals for this year was to design a mechanical braking system that will be used for the safety test and controlling the RPM of our wind turbine. Our design is based off a basic disc brake, similar to those used on cars and large, commercial wind turbines, to bring the blades to a stop. Our version of this idea consists of a servo motor attached to an arm with a brake pad and a disc attached to the main drive shaft. The design is further optimized by using a double-sided servo horn, and making the brake pad the same size as the brake disc. The servo horn attaches the braking arm to the servo, and by using a double sided one, we are able to maximize the torque applied on the arm by the servo.

We chose to make the brake parts out of polycarbonate because it is stronger and more heat resistant than the PLA that our other parts are made of. These characteristics are especially important for this setup because the friction created between the brake pad and disc will generate heat, and the parts must withstand the high torque applied by the servo. In addition to this, a thin sheet of rubber was fixed to the brake pad to increase the friction and, as a result, the overall effectiveness of the braking system.

After multiple design iterations, and testing, this design was chosen because it maximizes the surface area that is applying pressure to the brake disc and maximizes torque applied by the servo. We determined that by mounting the servo directly underneath the shaft, making the brake arm vertical, was the optimal design for this system. This makes the force applied by the brake pad perfectly horizontal at the top, which is what we want. The arm was designed to translate torque from the top side of the servo horn directly, from the bottom through triangular members. Figures 5 and 6 illustrate the brake mechanism.


Brake arm/pad component
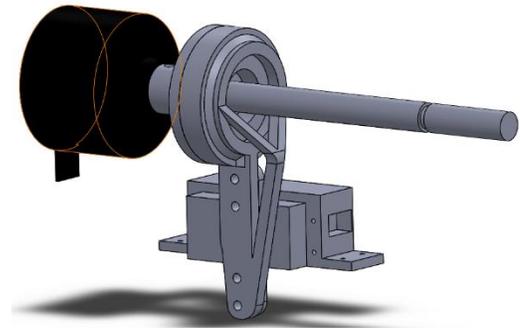
Figure 5
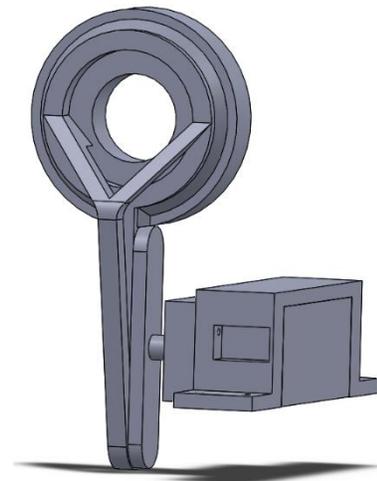
Brake arm mounted to servo

Figure 6

To save space in the nacelle, the brake disc was designed to fit onto the shaft coupler that connects our main shaft to the smaller shaft of the generator. It was designed to be a press-fit and utilize the same set screw as the shaft coupler to hold it in place and prevent rotation when the brake is applied. It also features a chamfer on the back side to add support and ensure it won't break under the high torque applied by the servo. Figures 7 and 8 show the shaft coupler and brake assembly, respectively.
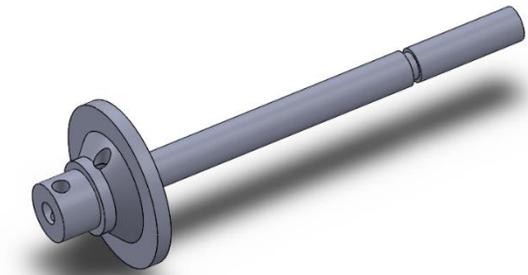
Brake disc mounted to shaft coupler

Figure 7

Disc brake assembly

Figure 8

After several iterations on the dynamometer, we found the best servo that could produce enough torque to braking to stop the turbine without taking too much power from the load. The servo we decided on is a Savox low-profile, high-torque servo. It puts out 8kg-in of torque at 4.8V, which is sufficient for our application. We needed a low-profile servo, so it would not to take up too much room inside the nacelle. It fits nicely inside the nacelle among the other additional assemblies added in the space. If the servo was any wider, the entire nacelle would have to be that much wider, taking from our swept area. Figure 9 shows the servo used.


Servo used for mechanical brake

Figure 9

Yaw Control – Tail

Our goal for the yaw system is for the turbine to turn to face into wind at 180 degrees/second and stay facing into the wind, with minimal or no oscillation. A successful tail design will keep the turbine facing the direction of the wind, with turbulent wind speeds up to 20m/s.

Two different designs were considered for this year's yaw control system. The first is a cylindrical tail design motivated by the turbine shroud concept. The cylinder is supported by 3 supports extruded radially from the detachable tail core, which slides into an insert in the back side of the nacelle. The supports are located 120 degrees apart and have an airfoil shaped cross-section to support the cylinder and reduce the effect of the wind shadow. Figures 10 and 11 show the cylindrical tail and testing assembly.
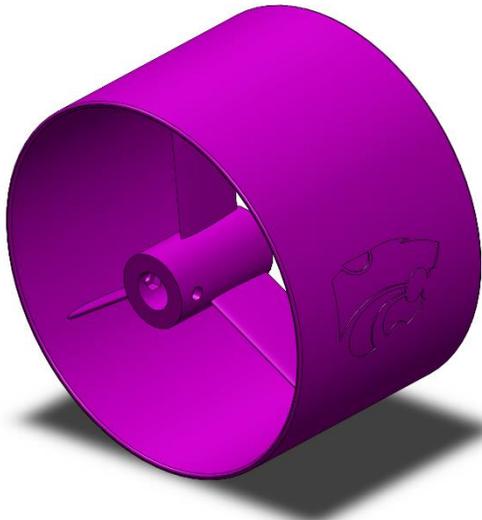

Cylindrical tail concept

Figure 10
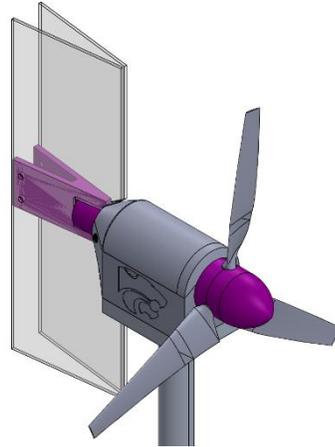

Shroud tail mounted to nacelle for testing

Figure 11

The second tail design is a twin wing tail. Two acrylic sheets with and angle of 14 degrees are mounted to a detachable tail core. Both tail cores are interchangeable and are mounted into a slot at the back of the nacelle. The twin wing tail experiences yaw at the same rate as a flat tail but shows less oscillation due to the damping produced by the wedge shape (Ebert & Wood, 1995). Figures 12 and 13 illustrate the twin tail.
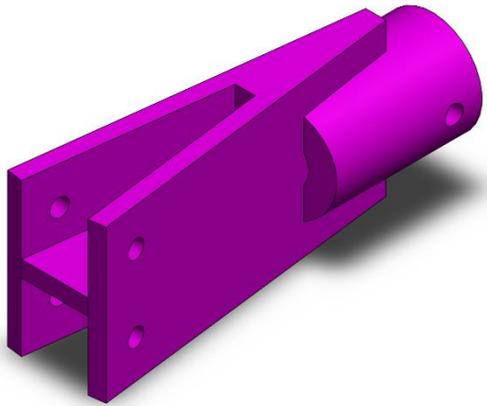
Twin-wing tail adapter.
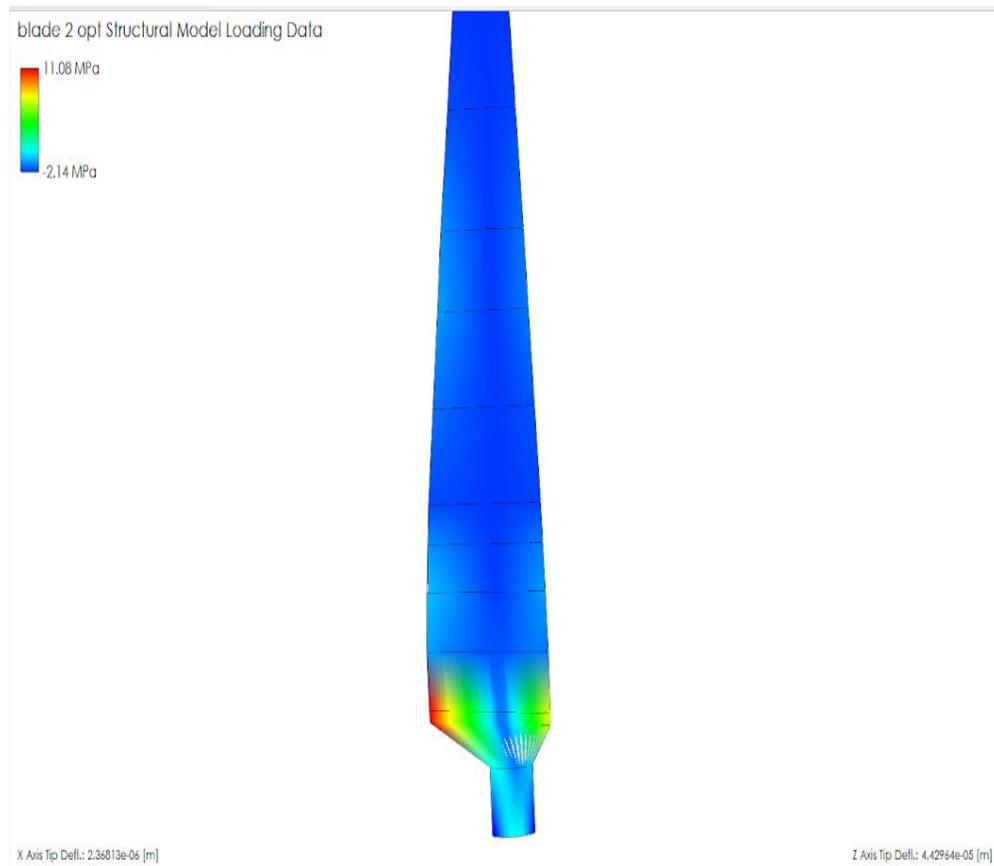
Figure 12

Tail mounted to nacelle.

Figure 13

We brought the two different tail designs to the wind tunnel for empirical testing. Both tails stabilized the turbine throughout the test, although the damping of the twin wing tail allowed it to settle to equilibrium quicker than the cylindrical design. We believe this damping will be an important factor in yaw control, especially in the 16m/s to 20m/s range we expect see at competition but cannot test in our wind tunnel.

The controls and power wires that feed out of the nacelle through the tower are given enough slack to allow for 2 full rotations in either direction. All wires in the nacelle are secured to a single screw terminal board win tin the nacelle, to allow ease of access and to secure continuity as the tower rotates during the yaw tests.

Blades

Blade analysis has been a large focus for the Wildcat Wind Power Team in previous years of competition. The blades design we used for this year's turbine are based on the previous year's design, with little modification. This design was developed using an in-house python program to compare thousands of airfoils and find the ones with the highest lift and lowest drag for each section of the blade. As a result of this process, the airfoils in our blade are comprised of the thin, high lift, low drag airfoils: BE50sm and SA7024. Using Q-Blade, further optimization was introduced by adding a twist of approximately 30 degrees.

The blades have a theoretical power coefficient of 0.52 according to QBlade. After losses, we are going to assume the coefficient of power will be closer to 0.42. Figure 14 shows FEA analysis performed in QBlade on our twisted blades based on a tip speed ratio of 4. According to these calculations, the maximum stress that the blade will see is roughly 11 MPa. The breaking point would be located near the root of the blade, with a factor of safety of roughly 3.4, given that the ultimate tensile strength of PLA plastic is 37 MPa.

QBlade FEA analysis on twisted blades.

Figure 14

This year, further optimization has been added to the manufacturing of the blades. The slicer settings for the 3D printer were optimized to allow for more accurate printing of thin features along the edge of the blade. Additionally, blades with different print materials and blade orientation were compared in order to maximize durability and print quality. The different materials tested are PLA and Polycarbonate (PC). Although the PC has more strength, the PLA blades were chosen because the print quality of the PC blades suffered.

To experimentally determine which RPM was optimal for our turbine, we ran the turbine through 3 different wind speeds each at 10 different resistances. All the tunnel data was measured and logged using our new LabVIEW control system. Although the Q-blade analysis suggest a tip speed ratio of 4, our results shown in Figure 15 supports a tip speed ratio closer to 5. We are not satisfied with a maximum power coefficient of 0.16, which is well below our 0.42 prediction. We suspect additional losses within our new nacelle design. With the time we have before competition, the mechanical team will work to reduce these losses and maximize the power coefficient.
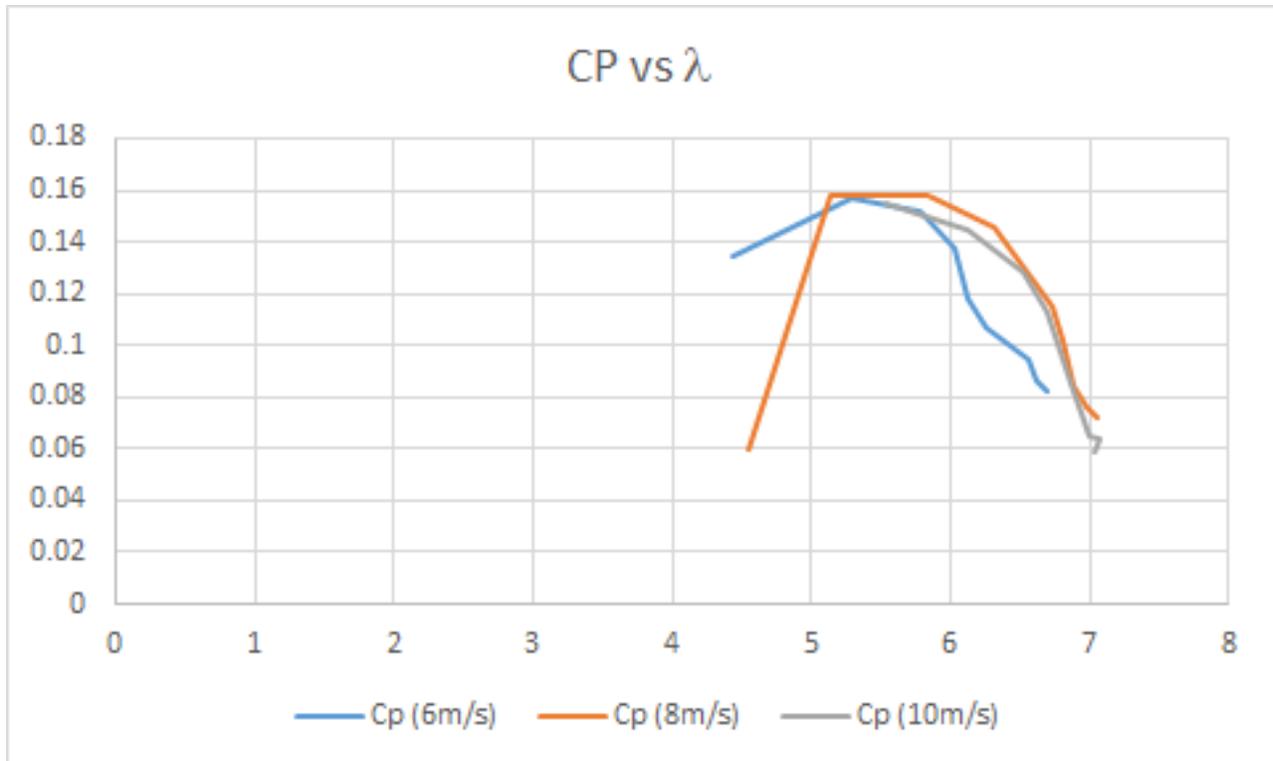
Power Coefficient as a Function of Tip Speed Ratio

Figure 15

Nacelle

Being the centerpiece of the wind turbine that connects all of the other parts together, the nacelle is a crucial part of the wind turbine design. The main body of the nacelle is based around a large rectangular vessel in the center, this was necessary to house our braking system, rpm sensor, generator, and other electrical components. It was made to be as small as possible while maintain space for all of our components. This design had to be made entirely from scratch, since this was the first year Wildcat Wind Power used mechanical braking, and an RPM sensor, both residing inside the nacelle.

To make the design more streamlined, while having enough space for all of our components, loft profiles were added at the front and back of the rectangular vessel. This was done to delete unused space and make the design more aerodynamic overall. The back of the nacelle is hollowed out behind the generator mounting holes, to accommodate the tail adapter. Once the generator is installed, the tail can be inserted into the hollow portion and attached with a screw on either side of the rear loft profile. Figure 16 shows the nacelle.
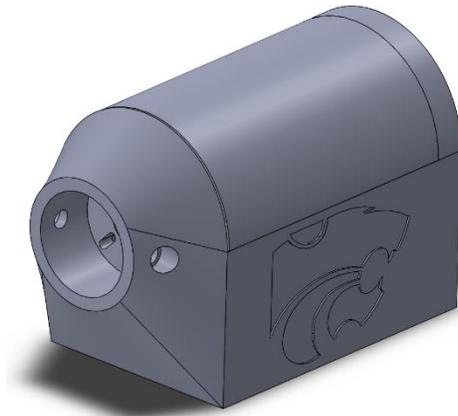
Loft Profile at the Rear of the Nacelle.
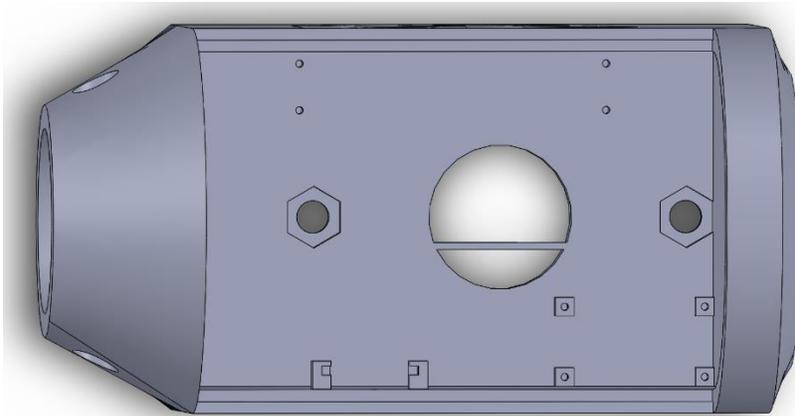
Figure 16

The front of the nacelle also features a loft profile, and a cutout for the hub to maintain smooth lines all around the nacelle and make it more streamlined. In addition to this, there is a cutout to house a single bearing held in place by an interference fit. The shaft is passed through the bearing and attached to the generator using a shaft coupler. The machined shaft also features M10 threads in the section that extend out of the front of the nacelle for easy installation of the hub/blades assembly, and the nose cone. Figure 17 shows the front of the nacelle.
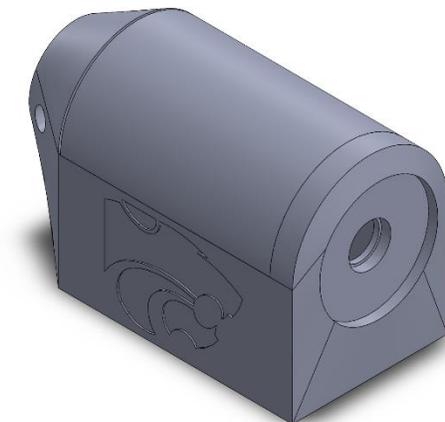
Loft profile at front of nacelle and bearing hole.

Figure 17

With additional equipment being housed within the nacelle, the layout had to be optimized to minimize the time it takes to assemble or modify or troubleshoot within the nacelle. The wiring for the RPM sensor, and breaking servo are routed through a screw terminal board located in an accessible location. From these terminals, removable wires are threaded through the tower and to the circuit. The configuration maximizes the electrical or mechanical team's ability to quickly make changes within the nacelle without compromising the other assemblies. Figure 18 shows the bottom of the nacelle.

Mounting points for RPM sensor, braking servo, and extra circuit.

Figure 18

Hub

While simultaneously researching and prototyping passive and active pitch systems for our turbine, we primarily used a fixed pitch system in our turbine for testing. This allowed us to easily switch the blades out and constantly try new designs and pitch angle to find the best performance for our turbine. Using the fixed pitch system with our twisted blades, we observed low cut-in speeds, and sufficient power production, giving a confidence that the fixed pitch hub would suffice.

The hub is made up of two halves; the screw side and the nut side. The screw side has a cut-out for the head of the screw to be recessed and the nut side has cut-outs the same size as the nuts to hold them in place and keep them recessed. Both side have holes that go all the way through for the screw shank. These screws serve two purposes; to hold the two halves of the hub together, and to keep the blades at the same pitch. The screws pass through holes in the root of the blades to ensure the pitch of them does not change. In addition to this, the blade roots have flanged ends that fit into slots in the hub, this takes some of the stress off the holes the screw passes through. Figure 19 shows the fixed pitch hub.

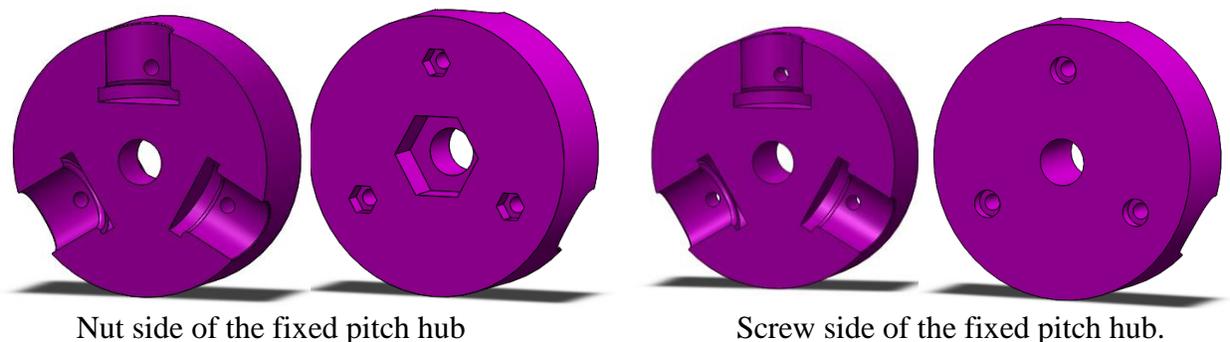Nut side of the fixed pitch hub   Screw side of the fixed pitch hub.

Figure 19

The team experimented with using five blades instead of three with fixed and passive pitch as well. In the end, the five blade concepts only performed slightly better, and not enough to justify the extra manufacturing time and materials. The team decided to use three blades, because of the simplicity and ease of testing multiple blade profiles, and pitch angles.

A nut that fits into one side of the hub is ultimately what translates rotation of the hub to rotation of the shaft. The nose-cone is then screwed on from the outside, also using a nut with an interference fit. During testing, the team noticed on several occasions that this nut could come loose from the hub and result in a loss of produced power. To solve this problem, the team replaced the basic nut in the nose cone with a nylon locking nut of the same size. This provided a very tight fit around the threads and prevented any of the rotational parts from coming loose.

Baseplate, Tower and Bearing Holder

The base plate and tower designs were very tightly constrained by CWC rules, leading to few design decisions to be made by our team. The base plate, tower, and bearing holder are all made out of aluminum to reduce weight. To attach the nacelle to the tower, a rectangular piece of aluminum was machined to be the exact same size as the base of the nacelle. A bearing was pressed into the aluminum piece, to provide easy installation to the rest of the tower and allow seamless yaw of the turbine. The bearing inner diameter is the same size as our tower allowing the bearing to easily slide around the top of the tower. To attach the nacelle to the bearing holder, both the nacelle and bearing holder have two bolt holes in the same location, so they can be simply bolted together. It also features a cutout for a large bearing that will provide seamless yaw ability of our turbine. The bearing inner diameter is the same size as our tower allowing the bearing to easily slide around the top of the tower.

Our team used finite element analysis to determine that the tower and base structure would be strong enough to withstand the maximum 20 m/s wind speed. The force on an area based on wind speed was calculated from:

$$F = \frac{1}{2} * \rho * As * 2$$

where F is the force on the nacelle, ρ is the density of air, As is the swept area of the blades, and is the wind speed. This equation was used to determine the force applied to the tower by the area being swept by the blades, and the frontal area of the tower itself. This force applied to the entire up-wind side of the tower is be:

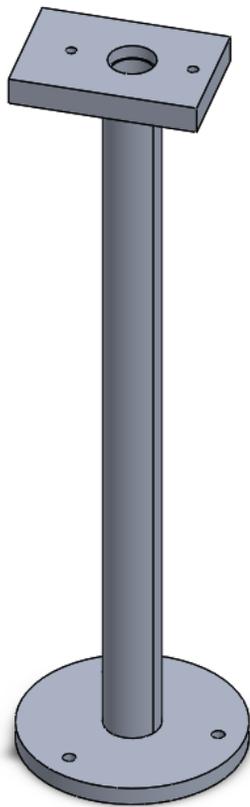$$F = \frac{1}{2} * 1.225 \text{ kg/m3} * /4*(0.02m)2*(20m/s)2$$

or

$$F = 4.9 \text{ N.}$$

Additionally, for the area being swept by the blades, applied to the top face of the tower, where the nacelle would be attached is

$$F = ½ * 1.225 \text{ kg/m3} * /4*(0.220m)2*(20m/s)2$$
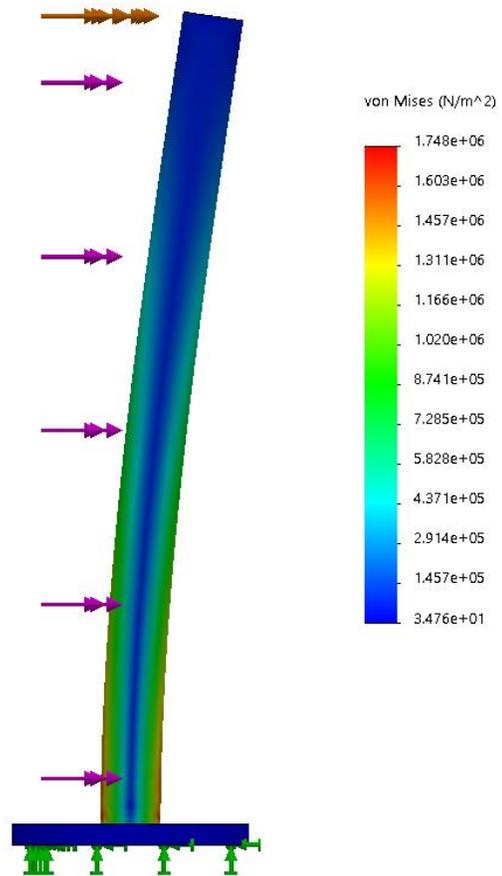
or

$$F = 9.32 \text{ N.}$$

As a result of these forces combined, the maximum stress was located at the bottom of the tower, where it connects to the base. This maximum stress is still not large enough to break our material or connection. It also yields a factor of safety of 31.5, which is more than enough. Figures 20 and 21 show the tower and the finite element analysis, respectively

von Mises (N/m^2)

1.748e+06
1.603e+06
1.457e+06
1.311e+06
1.166e+06
1.020e+06
8.741e+05
7.285e+05
5.828e+05
4.371e+05
2.914e+05
1.457e+05
3.476e+01

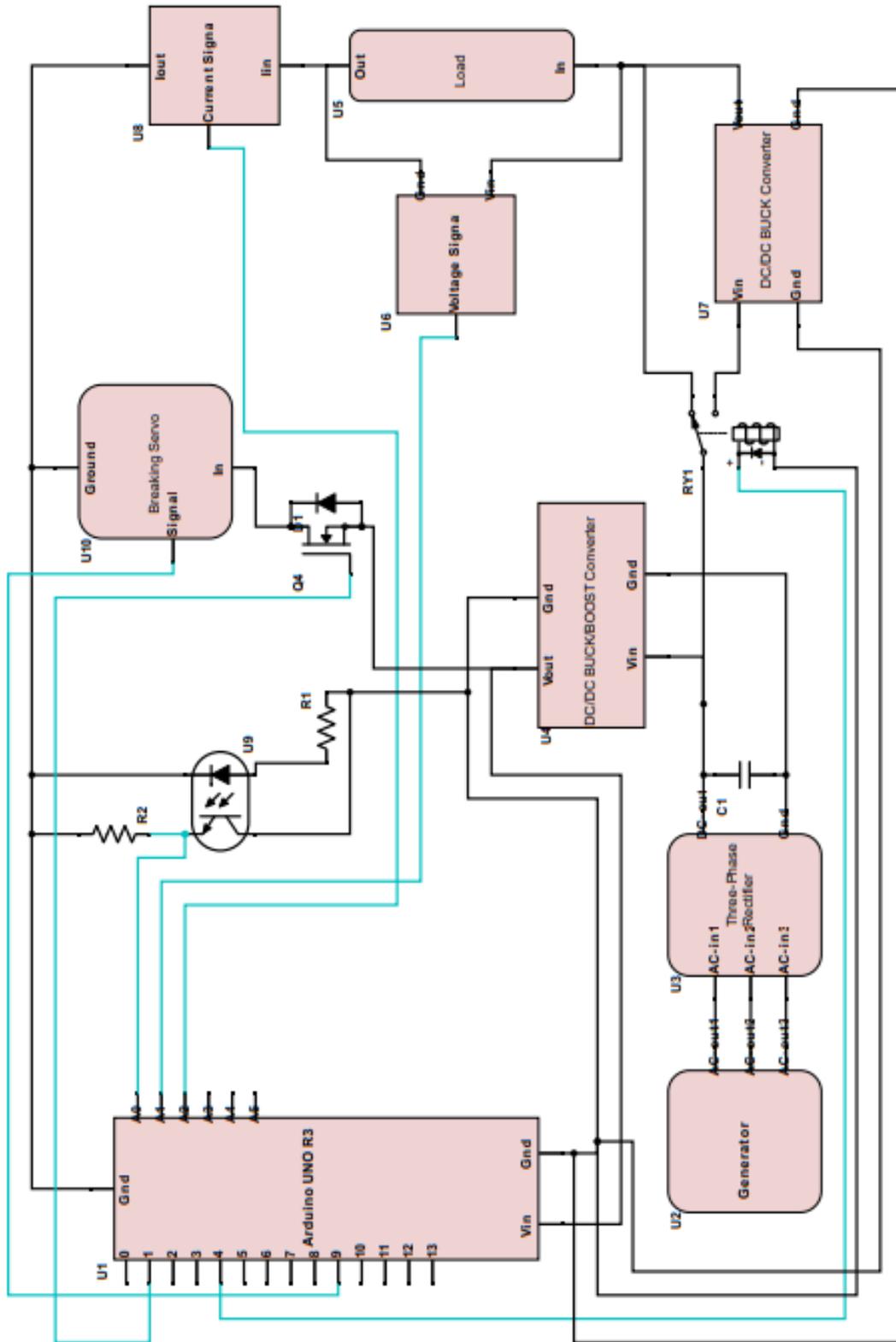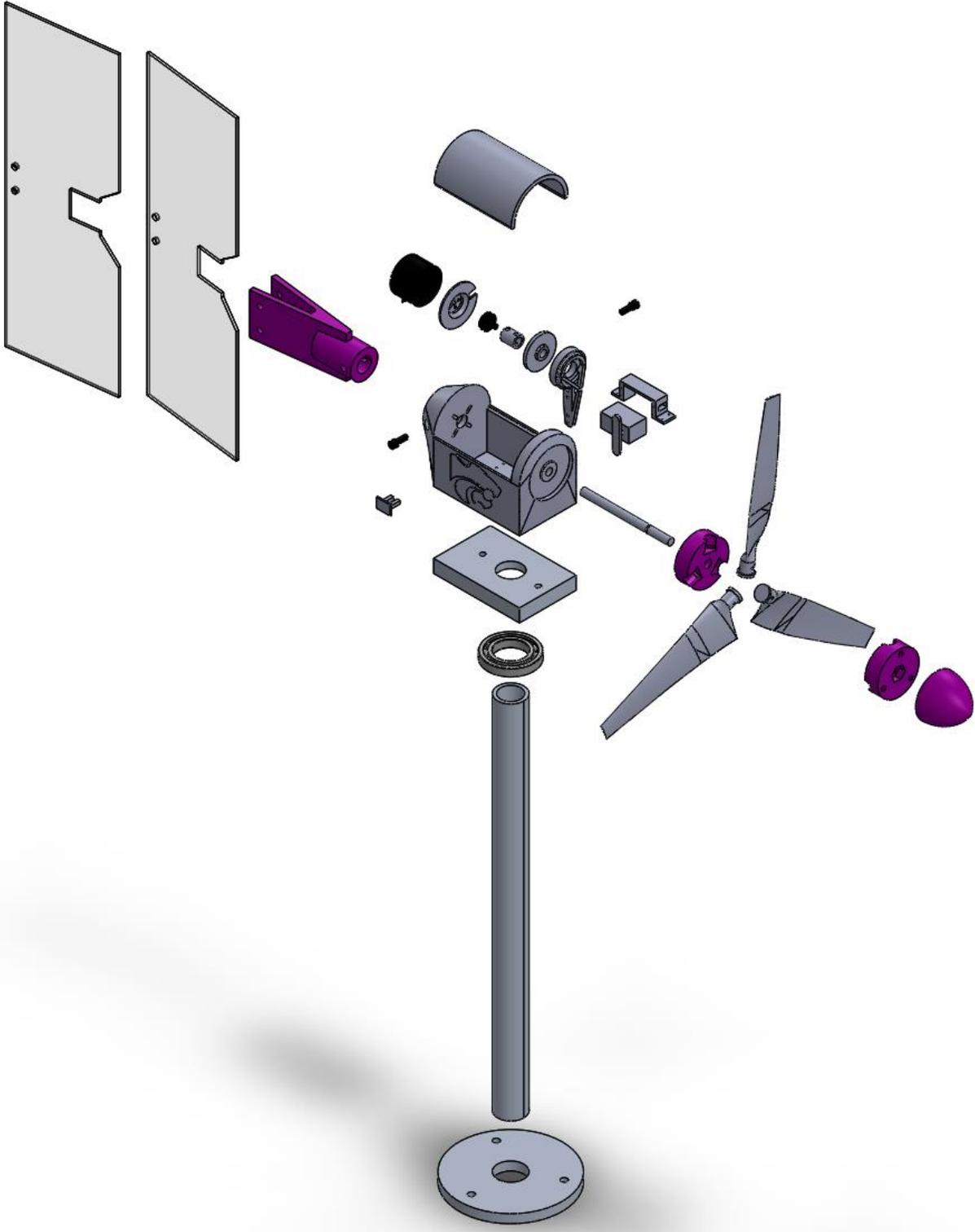Tower and bearing holder assembly.

Figure 20

Tower FEA analysis

Figure 21

Appendix A. Circuit Diagram

Appendix B: Mechanical Drawing

References:

Servo Picture: https://www.savoxusa.com/collections/low-profile/products/savsb2263mg-be-black-edition-low-profile

Ebert, P.R., Wood, D.H. (1995). On the dynamics of tail fins and wind vanes. Journal of Wind Engineering and Industrial Aerodynamics, 56(2-3), 137-158.