WiscWind

University of Wisconsin – Madison

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Executive Summary

WiscWind is a team of undergraduate students at the University of Wisconsin – Madison that has been invited, along with 11 other universities, to the 2017 Collegiate Wind Competition (CWC) Technical Challenge. This is the fourth CWC, and the second that WiscWind will be participating in. Each team has been given the task of designing and manufacturing a small-scale prototype wind turbine to meet the criteria of the competition. The criteria include: creating an efficient power curve, controlling the output power and rotor speed, having a low cut-in wind speed, and being a durable manufactured design. Based on the goals of the competition, WiscWind has been researching and developing advanced and efficient components for their small-scale turbine.

The technical design of WiscWind's turbine uses innovation and engineering knowledge to reach and exceed the goals given by the competition. The team has manufactured a horizontal axis wind turbine (HAWT) that features blades manufactured from carbon fiber, a durable and lightweight material. The final geometry of the blades was selected through software analysis (QBlade and ANSYS), scaled testing, and full-scale testing. The unique features of our various tested blade designs include but are not limited to: blade twist, pitch angle, winglets, and tubercles. The lightweight, optimized blades designed by WiscWind will allow their turbine to achieve a low cut in speed and high power output over a wide range of wind speeds. The blades are mounted on a rotor, which drives an axial flux generator. The generator was custom-designed to allow greater control and variability based on the specific turbine design. The axial flux generator provides low cogging torque and high efficiency allowing the turbine to achieve low cut-in speed and high power output. The turbine must also be capable of handling multidirectional wind, so the team has utilized a passive yaw system to ensure the turbine is at windward position. The passive yaw system does not draw from the power produced by the turbine which will increase the overall efficiency of the system.

Based on scaled testing, the final prototype turbine will produce over 10 W at or before the wind velocity reaches 11m/s with an efficiency of about 20%. The power controls will limit the power output and rotational velocity of the turbine at wind speeds above 11m/s to control the mechanical and electrical loads. The turbine is also expected to begin producing power below 5m/s for optimal performance at slow wind speeds. The durability and safety of our turbine during operation were ensured by calculated material choice and precise manufacturing techniques as well as built-in emergency shut down in the electrical system.

With the aforementioned aspects being in compliance with the CWC Rules and Regulations, the WiscWind team believes their designed and manufactured wind turbine will prove successful during all facets of the competition's testing procedure.

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Technical Design of Prototype Wind Turbine

Design Summary

WiscWind has pursued the design and development of a horizontal axis wind turbine (HAWT) to drive a custom-made axial flux generator. The blade's geometry was designed using various airfoils and analysis software. The turbine's design will handle multi-directional wind by implementing a passive yaw system that will use the wind to rotate the rotor in the windward direction. The rotor, nacelle, and tail wind device will be mounted on a tower made of steel and aluminum for strength and stability. The mounting connection will include a bearing to allow for the yawing of the turbine. The electrical system of the turbine is responsible for controlling the rated power and rotor speed as well as implementing the turbine's emergency brake. The multiple subsystems of the turbine are designed to integrate with each other as well as comply with the competition goals of the 2017 Collegiate Wind Competition.

Mechanical

The main objectives of the mechanical systems were driven by the Rules and Regulations of the Collegiate Wind Competition. Three major criteria were addressed in accordance with these regulations:

1. **Size Constraints:** the turbine must fit within a 45cm x 45cm x 45cm cube. The team decided that with a horizontal axis wind turbine, the diameter of the rotor should be slightly less than the design constraint in order to maximize the wind that the turbine can catch through the wind tunnel. Because of this decision, carbon fiber was chosen for the blade materials because it is lightweight and durable.
2. **Power Production:** to provide the electrical system with enough voltage to produce sufficient power, the mechanical team focused both on producing optimum torque via the shape of the airfoil, and producing the highest possible rotational velocity at a given wind speed. Through experimentation, it became apparent the rotational velocity was actually above 1000rpm (the set constraint of the generator), so a gearing system was implemented.
3. **Durability:** the turbine must withstand 18 m/s wind, including various wind-speed profiles. It must also have the capability to yaw back into windward position. The tower, generator, and interior nacelle were manufactured with aluminum and steel for strength and stability. A passive yaw system was implemented with a tail vane laser cut from acrylic.

The design process of the prototype turbine is described below beginning with blade geometry and ending with manufacturing methods. Testing Data is presented in the **Testing and Results** section.

Designing the Blade Geometry

Blade geometry plays a crucial role in the final performance of the wind turbine. As such, the process of designing a blade for a horizontal wind turbine began by choosing an airfoil based on factors of C_L/C_D data. Once the airfoil was chosen, chord length, twist, pitch, and general shape of the blade were determined by design envelope and QBlade, an analytical program that optimizes these parameters for specific wind speeds and Reynolds numbers. The team began with multiple blade designs, each designed with a different focus. The blade designs were narrowed down to three top performing blades based on experimentation. The three top blades are described below and the final design chosen is **Blade Design 2**, which is an iteration of **Blade Design 1**.

Blade Design 1

Design 1 of the team's wind turbine blades was designed with a focus of twisting the blades for an optimal lift to drag coefficient ratio (C_L/C_D) across the entire length of the blade. The main factors that were chosen while designing this blade include: airfoil, chord length, trailing edge geometry, degree of twist, and degree of pitch.

In choosing the airfoil, the considerations that were significant were its lift to drag coefficient ratio in a 2D analysis as well as manufacturability and application as a HAWT blade. The chosen airfoil, NACA 4415, shown in **Figure 1**, has a maximum C_L/C_D of 27.4 at an angle of attack equal to 8.25° (Re = 100,000 and Ncrit = 5) [2]. This airfoil is a simple asymmetric design that can be manufactured with additive manufacturing as well as composite molding. A HAWT application requires an airfoil that will generate enough lift at its pitch angle to be able to have a low cut-in wind speed for most efficient power output.

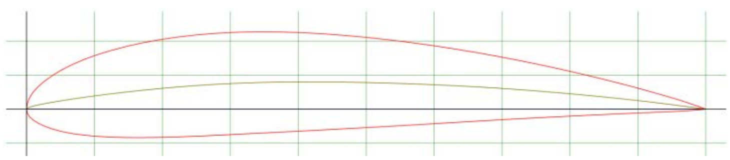

Figure 1. *NACA4415 airfoil outlined in red [2].*

After the airfoil was chosen, the geometry of the blade was designed using the software QBlade that assists in calculating an optimal chord length, twist of blade, and angle of attack. QBlade calculates these factors using the Blade Element Momentum (BEM) Theory, which ultimately computes the torque and final thrust of the entire rotor. The BEM theory is drawn from disk actuator theory which can conclude information about events taking place on each part of the actual blade. The blade is divided into a finite number of blade elements where the relative wind speed for every section can be computed, which allows for the calculation of the angle of attack and the derivation of the lift and drag coefficients, leading to an optimal twist and chord length [3]. Based on QBlade analysis and idealizing the design for manufacturing, the final dimensions are given as:

Table 1*. Design #1 blade geometry dimensions*

Angle of Attack	Twist of Blade	Initial Chord Length	Final Chord Length	Total Blade Length
8°	8°	3.8 cm	1.2 cm	21.0 cm

The angle of attack describes the angle between the plane of the hub and the plane of the blade; the twist of blade describes the angle between the initial chord length plane to the final chord length plane; and the chord length describes the horizontal length of the airfoil cross-section. The final geometry of the designed blade, shown as a front view in **Figure 2**, also features a sharp-cut edge that serves the purpose of decreasing drag near the root of the blades.

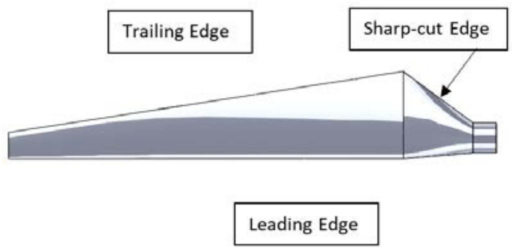

Figure 2. *LEFT. Final geometry of Design 1 blade with an airfoil of NACA 4415*

Figure 3. *RIGHT. Assembly of Blades for Design 1 pictured with a hub and blades pitched at 8-degrees*

The assembly shown in **Figure 3** represents the prototype rotor featuring the blades from **Figure 2** and including an 8-degree pitch at the hub. The designed diameter of the rotor is just below 45cm to maximize the swept area in the competition's design envelope in order to capture the most wind. Because of the maximized swept area, lightweight materials are crucial to keep the turbine from being overweight.

Blade Design 2

Blade Design 2 is an alternate configuration of Blade Design 1. This design features a longer chord length with the same pitch and twist degree angle. It was decided to create additional configurations of design 1 due to high performance in initial wind tunnel testing. **Table 2** states its final dimensions and **Figure 4** represents the SolidWorks model of this design.

Table 2*. Design #2 blade geometry dimensions*

Angle of Attack	Twist of Blade	Initial Chord Length	Final Chord Length	Total Blade Length
8°	8°	5.7 cm	1.8 cm	21.0 cm

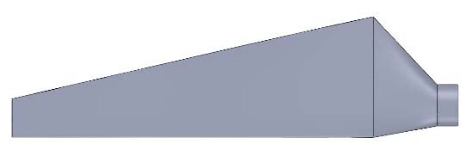

Figure 4. *SolidWorks model of Blade Design 2 that features a longer chord length than Design 1*

Blade Design 3

This blade design focused on the leading edge of the turbine blade featuring tubercles. Tubercles are bumps that are commonly seen on the leading edge of humpback whale flippers. Humpback whales travel thousands of miles in a year and these tubercles are said to optimize the flow of water around the fin making travel easier for a whale [4-5]. WiscWind decided to use these natural features in our designing process.

Applicable claims of the effects of tubercles include: higher resistance to stalling, lower cut-in speed, increased turbulence causing a reduction in drag, increased vorticity on surface of the blade which enhances lift, and quieter operation. Each of these characteristics offering benefits to a conventional wind turbine [4-5].

The airfoil selected was a FX 83-w-108, with a C_L/C_D ratio of 36.8 at an angle of attack at 8 degrees (Re = 50,000 and Ncrit = 9) [6]. A diagram of the airfoil cross-section is shown in **Figure 5** and the blade's final design specifications are stated in **Table 3**.

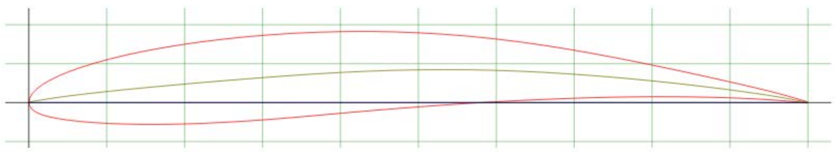

Figure 5*: FX 83-w-108 Airfoil outlined in red [6]*

Table 3. *Design #3 blade geometry dimensions*

Angle of Attack	Twist of Blade	Initial Chord Length	Final Chord Length	Total Blade Length
8°	8°	5.1 cm	2.16 cm	22.5 cm

The blade was then modeled using SolidWorks. A render of this model is shown in **Figure 6**. The blade utilized six 0.25 inch tubercles evenly distributed along the leading edge of the blade. This configuration is strictly experimental and will be compared to a blade without tubercles to conclude if the claims listed above are valid.

Figure 6. *SolidWorks render of tubercle designed blades (Blade Design 3)*

Yaw System

Yaw systems are important components for horizontal axis wind turbines which optimizes the efficiency of the wind turbine. The yaw system allows for the rotor to constantly adjust the rotor axis to be parallel to the direction of the wind. Two main types of yaw systems are utilized for wind turbines; passive and active yaw systems. A passive yaw system includes a tail wind device, while the active yaw system controls the rotation using an electric or hydraulic control system. The yaw system chosen for WiscWind's turbine design is the passive yaw system.

Tail Wind Device Yaw System (Passive Yaw)

A tail wind device is a mechanism attached behind the nacelle that uses a tail vane to rotate the wind turbine at windward position. The tail wind device is usually only seen in small wind applications because of its poor performance at high wind speeds with heavier parts. In these conditions, the tail wind system can become unstable which causes oscillation of the rotor. Although these problems arise with larger wind turbines, the tail wind device can be an effective and efficient design for small-scale turbines. The tail wind device is easy to manufacture and doesn't require power, whereas the active yaw system would require power to function [7].

Based on the reasons previously mentioned, the tail wind device was the chosen design for the team's wind turbine. The design will include a bearing connection between the tower and nacelle. Because of the free-range motion of a bearing, the tail fin needs to be designed in such a way that it is large enough to rotate the rotor, but small enough that the wind does not create a large moment that will cause an overshoot of the target position. The two main factors in designing the tail wind is the area of the tail vane and the length of the tail boom. To determine the tail vane area, it must be compared to the swept area of the wind turbine rotor. The swept area is calculated using equation 1:

$$A_{swept} = \pi R^2 \tag{1}$$

Where R is the radius of the rotor. Based on this calculated swept area, the area of the tail vane should be within 5-10% of the swept area [8]. A larger tail vane will have more influence on the turbine's direction, but making the vane too large can throw the turbine off balance, so it is important so stay within this given range. The optimal tail vane shape is a backwards "arrow shape" due to its symmetry above and below the tail boom [8]. To size the tail boom, the standard equation for its length is given as:

$$L = 120\% * R = 1.2 * R \tag{2}$$

Using these two calculations, the dimensions for the wind turbine tail device of the team's current design will follow the calculated values shown in **Table 4**:

Table 4. *Provides the calculations for the design constraints of the wind turbine tail device*

Rotor Radius	Swept Area	Vane Area (5%)	Vane Area (10%)	Length of Tail Boom
22.5 cm	1590.43 cm^2	79.52 cm^2	159.09 cm^2	27.0 cm

Another significant factor of the yaw system that will affect the turbine's ability to rotate is the aerodynamics of the nacelle casing. Because the designed generator's diameter is just less than a quarter of the blade's swept area, it can potentially cause drag and turbulent airflow by the yaw tail due to flow separation. In order to avoid this, the nacelle casing was designed based on the airfoil NACA 63-018 which was mathematically derived to promote laminar flow at subsonic fluid speeds. The flow will therefore follow the surface of the nacelle casing and not inhibit the yaw system from functioning properly. An

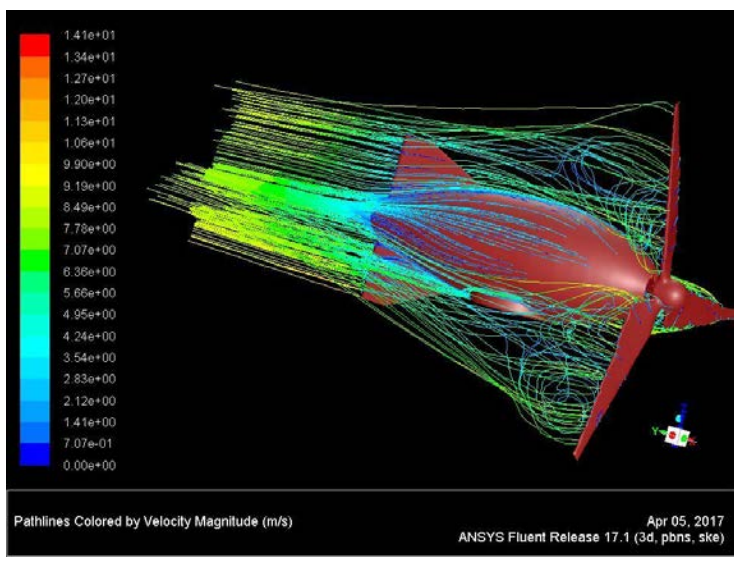

Figure 7. *ANSYS Fluent model representing the air flow around the rotor and nacelle*

ANSYS Fluent model, shown in **Figure 7**, was created in order to verify that the final nacelle design will have a streamlined flow across the surface.

Pitch Design

Wind turbine design often incorporates a blade pitch system. A pitch system allows the wind turbine to control the angle of attack of the blades, which can be used to maximize the lift provided by each blade over a large range of wind speeds. Optimizing the lift generated by the blades ensures the wind turbine is creating the maximum amount of power [9].

Due to the complexity and manufacturing issues of other systems, a fixed pitch system was chosen for the final competition deign. Although pitch control systems in theory increase the efficiency and power output of a turbine, other factors like the simplicity, ease of manufacturing, low cost, and lack of a control system made a fixed pitch system more attractive. Even though a fixed pitch system won't allow for adjustable pitch during competition testing, it can be tested and adjusted for the optimal angle before competition.

An optimal pitch angle maximizes lift, while attempting to minimize drag and boundary layer separation. Many airfoils have been analyzed for lift and drag coefficients at different angles of attack. These graphs can be used to find an approximate optimal pitch angle which provides a high amount of lift and low amount of drag. An example of this analysis is shown in **Figure 8**.

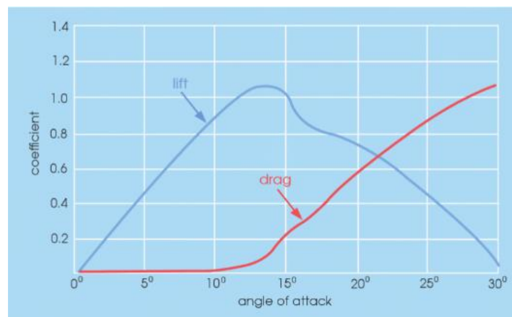

Figure 8*. Lift and Drag Coefficients to angle of attack*

In addition to using coefficient of lift and drag graphs, wind tunnel tests can be used to finely tune the pitch angle. For example, during small-scale testing of the team's blade geometries, pitch was varied on similar designs to find an optimal angle. When testing in the wind tunnel, boundary layer separation can be analyzed. Boundary layer separation occurs when a pitch angle is used which is too high for a given wind speed, causing a loss of lift and increased drag, reducing power output. A diagram of boundary layer separation is shown in **Figure 9**. As the air passes over the airfoil, the boundary detaches from the wing surface, causing turbulence at the trailing edge of the blade [11].

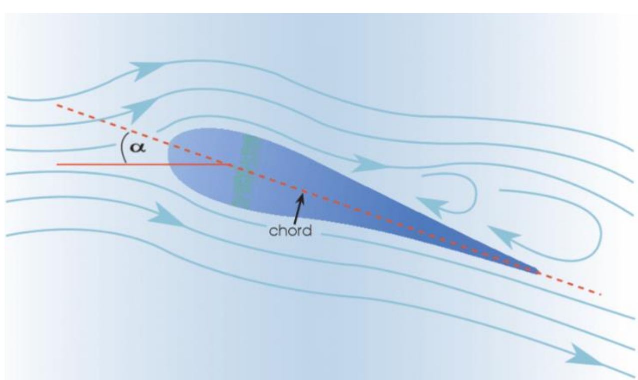

Figure 9. *A diagram of boundary layer separation occurring due to an aggressive pitch angle [11]*

Tower Structure

The tower system is a very important component to a wind turbine. It provides the structure that counteracts the drag forces of the wind on the blades, hub, nacelle, and yaw system. In addition, it gives the wind turbine rigidity from oscillations due to harmonic rotation of the turbine blades. The height of the tower is critical in preventing the blades from being affected by the boundary layer of wind near the earth's surface. To extract the maximum amount of power, the tower structure must be tall enough such that the blades spin where they are unaffected by the turbulent boundary, but not too tall such that there are large deflections of the structure, which increases stress at the base.

The main structure consists of five piece parts. Competition rules dictate that the base of the tower system adheres to the bolt pattern of the wind tunnel. The base plate is 11 gage steel with three holes drilled equidistant from each other at a 0.266-inch diameter. The plate is placed over 0.250-inch diameter threaded studs in the competition tunnel. The tower beam is 1.13-inch diameter steel pipe with 0.188-inch wall thickness, cut to a length of 21.25-inches. A small fillet weld joins the base plate and the tower beam together. A shoulder is machined on the other side of the tower post to house a 1-inch thrust bearing and a snap retaining ring. The thrust bearing is also pressed into an aluminum bearing housing that has the bolt pattern to attach to the nacelle subsystem. **Figure 10** shows the complete tower subsystem assembly.

***Figure 10**. Tower assembly for prototype wind turbine*

The total drag force on a wind turbine can be approximated with the equation:

$$F_D = \frac{1}{2} C_D \, \rho_\infty \, v_\infty^2 \, A_f \tag{3}$$

Where C_D is the drag coefficient, ρ_∞ is the free stream fluid density, v_∞ is the free stream fluid velocity, and A_f is the frontal area perpendicular to the fluid stream [12-14]. The nacelle was assumed to be a cylinder and the drag force was computed on the tower, nacelle and each of the three blades and was found to be approximately 24 N. The steel is strong enough to withstand the drag force, and is being used because of its manufacturability and availability to WiscWind.

Manufacturing & Material Selection

The WiscWind team implemented several methods of manufacturing with our final prototype turbine in order to create a solid product with precise parts. Manufacturing techniques were chosen based on how complex the geometry of the part was, the material we desired to use for the part, and how cost effective the manufacturing process was. During our design process, it was important to think about how each piece could potentially be manufactured to make sure we have a feasible design. The main manufacturing techniques used include:

- Bladder Molding and Carbon Fiber Layups (Turbine Blades)
- SLS and FDM 3D printing (Hub, Nacelle Casing, Scaled Blade Geometry)
- Machining (Generator, Interior Nacelle, and Tower Structure)
- Laser Cutting (Yaw Tail)

Blade Fabrication

The most significant aspect of blade fabrication was choosing the correct material and technique. Due to complex geometry, the blades would either be carbon fiber molded or SLS 3D printed with nylon. In order to make this decision, an ANSYS Fluent model was created to study the deformation of both carbon fiber and 3D printed nylon with the conditions of 18m/s wind speed and a rotation velocity of 1500 rpm. The finite element solution yielded that carbon fiber blades should deform 0.029mm whereas the nylon 3D printed blades yielded a deformation of 2.05mm. Therefore, by using carbon fiber, the blades are 70 times more rigid than nylon 3D printed blades. This finding, along with the blades' reduced mass and thus inertia, supports the decision to fabricate carbon fiber reinforced composite wind turbine blades. The ANSYS results are pictured in **Figure 11** to show the displacement and Von Mises stress contours.

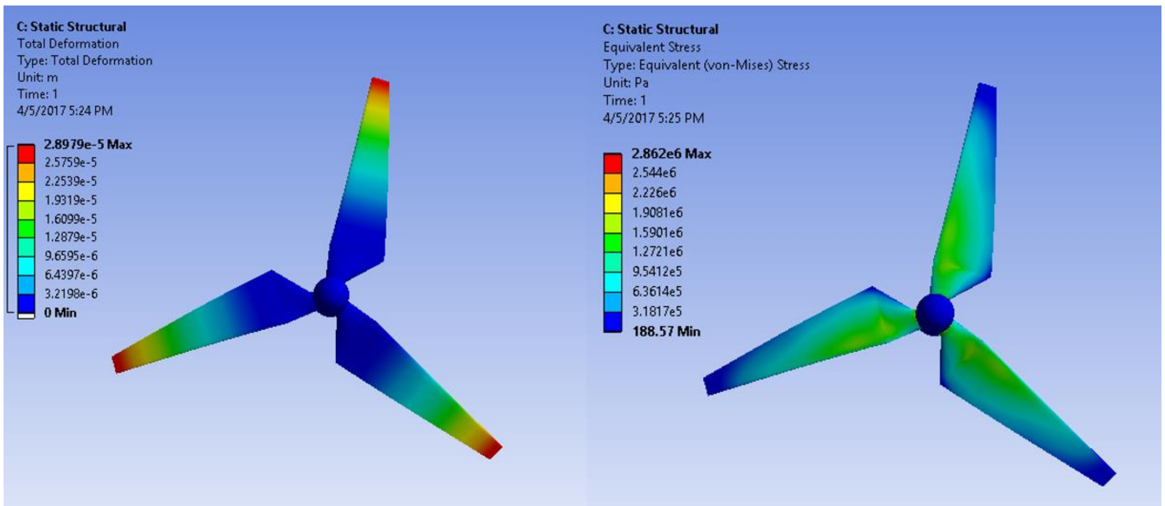

Figure 11. *Displacement and Von Mises stress contours on carbon fiber turbine blades*

Carbon Fiber

The blades were constructed out of a pre-impregnated carbon fiber using a process called bladder molding. Bladder molding is the process of inflating a bladder inside a clam shell mold to produce a laminate. The "pre-preg" pressed inside the mold is then cured via heat from an oven or autoclave. The carbon fiber is placed in the mold as to build a flange on the outside as seen in **Figure 12.** This is the simplest technique and is most consistent in mass and moment of inertia; however, it also has the weakest bond because the flange is trimmed after the curing cycle.

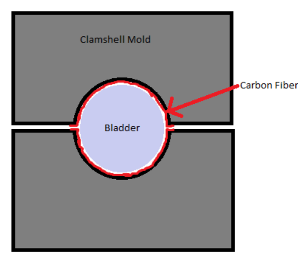

Figure 12*. Carbon fiber bladder molding technique*

Mold/Bladder Construction

The mold was machined out of 6061 aluminum via CAM based CNC milling. The machined molds were then sanded smooth and polished to a mirror finish. Two pins were installed to ensure proper alignment during the carbon fiber layups. The final molds can be seen in **Figure 13.**

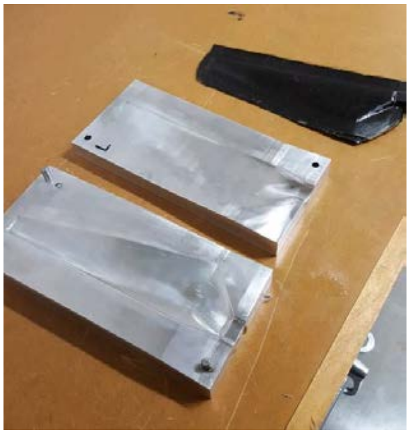

Figure 13. *LEFT. CNC Machined Aluminum Turbine Blade Mold*

Figure 14. *RIGHT. Wax mold coated in silicone to create the bladder*

The bladder was constructed by dip coating a wax plug in tooling grade silicone. Once the silicone fully cured, the wax was melted out, leaving behind a consistent quality bladder capable of withstanding temperatures up to 500 degrees Fahrenheit. **Figure 14** shows a cured wax blade coated in silicone.

Nacelle Fabrication

Generator

The generator was fabricated via standard machining practices. The coils were wound with a winding machine to ensure the correct number of loops and sizing. After assembly, the internal windings and magnets were encased in a cast-able epoxy resin to ensure adequate protection. The final generator assembly can be seen in **Figure 16**.

Housing

The nacelle housing was fabricated via two methods. The structural mounts for the generator, tower, and gear box were machined out of aluminum; whereas, the aerodynamic casing was FDM 3D printed by Subzero - Wolf. The 3D printed casing was then clamped together and mounted around the internal components of the nacelle. **Figure 15** shows the nacelle housing in the process of assembly. Lastly, the yaw tail was laser cut out of acrylic for precise geometry.

Figure 15. *Nacelle housing and casing assembly*

Electrical

The electrical system of the wind turbine is responsible for converting the kinetic energy captured by the mechanical system into electrical energy. Several key components will be used in this energy conversion process. These components will include a generator, an electrical conversion circuit, a control and logic circuit, and an electrical load. There are several requirements these components must adhere to laid out by the Collegiate Wind Competition.

Generator Selection

Several resources were used when determining a generator topology to use. The team considered the previous year's design, which used a 3-phase radial flux topology, as well as the designs other teams submitted for the 2016 competition. Open source small scale wind turbine designs were also taken into consideration, most of which incorporated a custom made axial flux generator. Once the team had considered several options, an ideation chart of important generator characteristics was made. The generator types were then ranked according to these characteristics, with 1 being the worst ranking and 5 being the best.

Table 5. *Ideation chart for generator selection*

Generator Type	Multiplier	DC Brushed	AC Induction Motor	Axial Flux	Radial Flux
Integrates with Controller	2	5	1	5	5
Complexity	1	5	1	2	3
Cost	2	3	1	4	3
Reliability	3	2	5	5	5
Efficiency	3	1	1	4	5
Braking	2	5	1	5	5
Starting/Cogging Torque	3	2	5	3	3
Serviceability	2	5	5	5	5
Accessories Required	2	5	1	2	2
Finding a Supplier	3	5	5	5	1
Total	--	74	60	88	86

After careful consideration, an axial flux generator was selected for the final design. Although the generator must be custom designed and built, the popularity among small scale wind turbine builders made it an enticing choice. Axial flux generators have two main components. The first component is the stator. The stator houses the coils, which convert the rotating magnetic field into electrical current. The second component is the rotor. The rotor contains magnets, which create a rotating magnetic field when connected to the turbine rotor shaft. [15].

Generator Design

As previously mentioned, a custom built, axial flux generator was chosen to allow greater control and variability. The goal was to create a high voltage, low current output at rotational speeds up to 1000rpm. The main components of an axial flux are the two rotating plates (rotors) with axially polarized magnets and one stationary plate (stator) in between with coils of wire to produce a voltage and current from the rotating magnetic field of the rotors. The rotor and stator plates were given a 10cm diameter constraint and a stator width of half an inch to leave plenty of room in the nacelle.

Using these constraints, the electrical team wrote a java code to determine the optimal number of coils, turns per coil, pole-pairs, and the coil area, as well as to get a rough estimate on the balance between voltage and current so the control circuit could be designed.

After experimentation with this code as well as additional constraints due to manufacturing, the team decided on 110 turns of wire per coil for 6 coils total, and 4 pole pairs of .5" diameter, .25 in" thickness neodymium magnets. The following steps were then followed to determine the expected current and voltage:

First, the power was calculated that would be supplied to the generator at 11 m/s wind speed, the levelling off point for the competition:

$$P_{in} = .5 * velocity^3 * \rho * A_{blades} \quad (4)$$

Where *v* is the velocity, ρ is the density of the air, and A_{blades} is the swept area of the blades. Then, using a common coefficient of performance for wind turbines, 40%, the amount of power (P_{out}) that would be utilized and thus transferred to the generator was estimated:

$$P_{out} = P_{in} * C_P \quad (5)$$

Next, the estimated 1000 RPMs given by the mechanical team were translated into rotational angular frequency and then multiplied by half the number of magnetic pole pairs to get the angular frequency of voltage peaks:

$$\omega_{rot} = 2\pi \frac{rpm}{60} \quad (6)$$

$$\omega_e = (.5 polepairs) * \omega_{rot} \quad (7)$$

From there, the maximum Voltage output per phase was calculated from the relation:

$$V_{max} = m * NBA * \omega_e \quad (8)$$

Where m is the number of coils per phase, N is the number of windings per coil, B is the measured magnetic field between two neodymium magnets, and A is the area of the coils. The RMS voltage per phase, because voltage will be a sinusoidal waveform is then:

$$V_{RMS} = \frac{V_{max}}{\sqrt{2}} \quad (9)$$

From there, with an overall efficiency set at 70%, the RMS current was estimated:

$$S = P_{out} * .7 \quad (10)$$

$$I_{RMS} = \frac{S}{3V_{RMS}} \quad (11)$$

Where S is the Apparent Power in the system. Based on this analysis, the final parameters are given in **Table 6**.

***Table 6**. Generator parameters based on analysis*

Velocity [m/s]	ρ [kg/m^2]	A_{blades} [m^2]	P_{in} [W]	C_P	P_{out} [W]	RPM	ω_{rot} [rad/s]	ω_e [rad/s]
11	1.225	.159	130	.4	51.86	1000	104.72	209.44

Polepairs	M [coils/phase]	N [turns]	B [T]	A [m^2]	NBA [Wb]	V_{max} [V]	$V_{\phi RMS}$ [V]	S [VA]	I_{RMS} [A]
4	2	110	.34	.0021	.079	33.11	23.41	41.5	1.8

The parameters chosen based on the java program were then used to create the SolidWorks design shown in **Figure 16**:

***Figure 16.** SolidWorks render of final generator design*

Power Controls

The power electronics of the turbine serve several important purposes:

- Receive the 3-phase AC output of the generator and rectify it to DC.
- Control the amount of power being produced as well as the turbine speed.
- Regulate the voltage for purpose of battery charging.
- Function without storing any power (against competition Rules and Regulations)
- Force the turbine to shut down when the load was disconnected or the manual shutdown button was pushed.

Circuit Layout

The 3-phase input from the generator was first rectified using six Schottky diodes, selected for their low voltage drop. After rectification, a power MOSFET was used to control the power output and speed of the turbine. By adjusting the pulse width modulation (PWM) of the MOSFET, it is possible to alter the associated dump load. This "load dumping" is necessary for leveling off the characteristic curves at 11m/s and above per competition requirements.

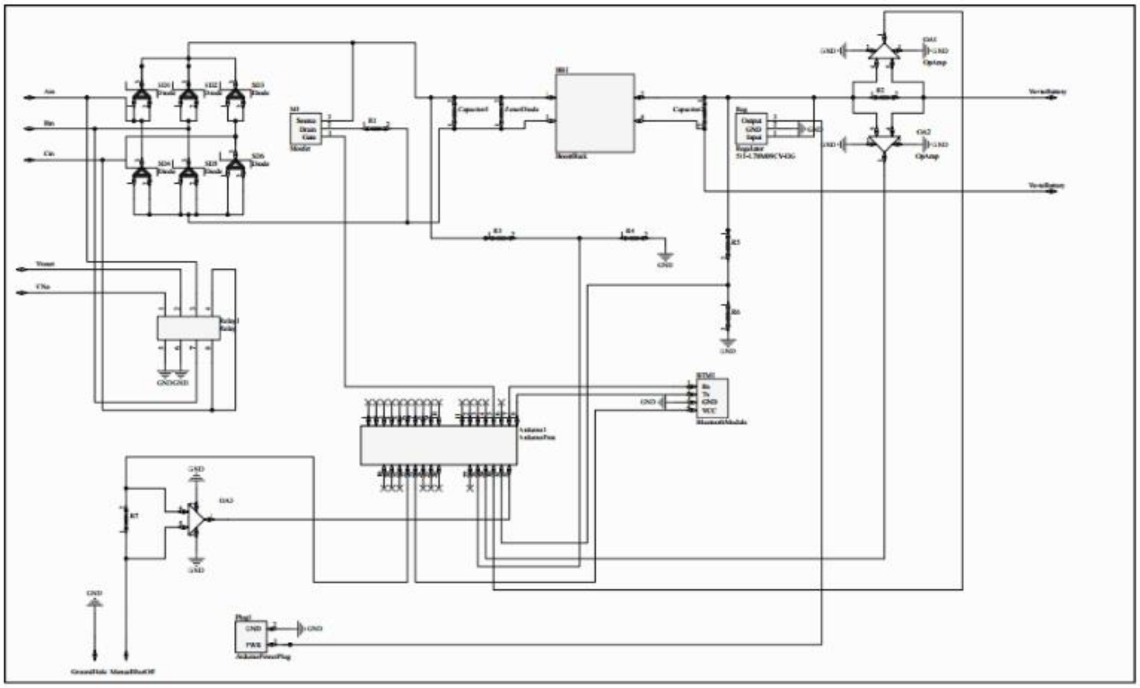

Figure 17. *Circuit layout schematic*

A normally open (NO) latching relay powered by an Arduino Zero microcontroller (MC) is used to control the electrodynamic braking of the turbine. Upon closing the relay, the three phases of the generator are short circuited, resulting in electrodynamic braking that brings the turbine to within 10% of its rotational speed. Additionally, a NO relay allows the turbine to brake and remain stopped even after the MC loses power. Upon restarting, the MC will apply another signal that will unlatch the NO relay.

Control Logic

The control logic of the wind turbine was developed to meet a number of important competition rules. First, the controls had to maintain the power productions and turbine speed between 11m/s and 13m/s. The logic also dictates the means of shutting down the wind turbine when the load is disconnected or when a manual shutdown button is pressed. Lastly, the logic then had to account for the fact that there are no power storage elements allowed on the turbine side of the wind tunnel.

The controls for shutting down the wind turbine went through a number of iterations prior to realizing the final design. Initially, the electrically team hoped to control the shutdown with only passive elements, however, after the testing of a number of designs, it was determined that the circuitry could not be realized without active elements. It was at this stage that the Arduino MC was introduced, with three current and two voltage sensors. A state machine diagram of the turbine behavior is shown in **Figure 18**, illustrating the startup, system ready, run, and shutdown states of the turbine.

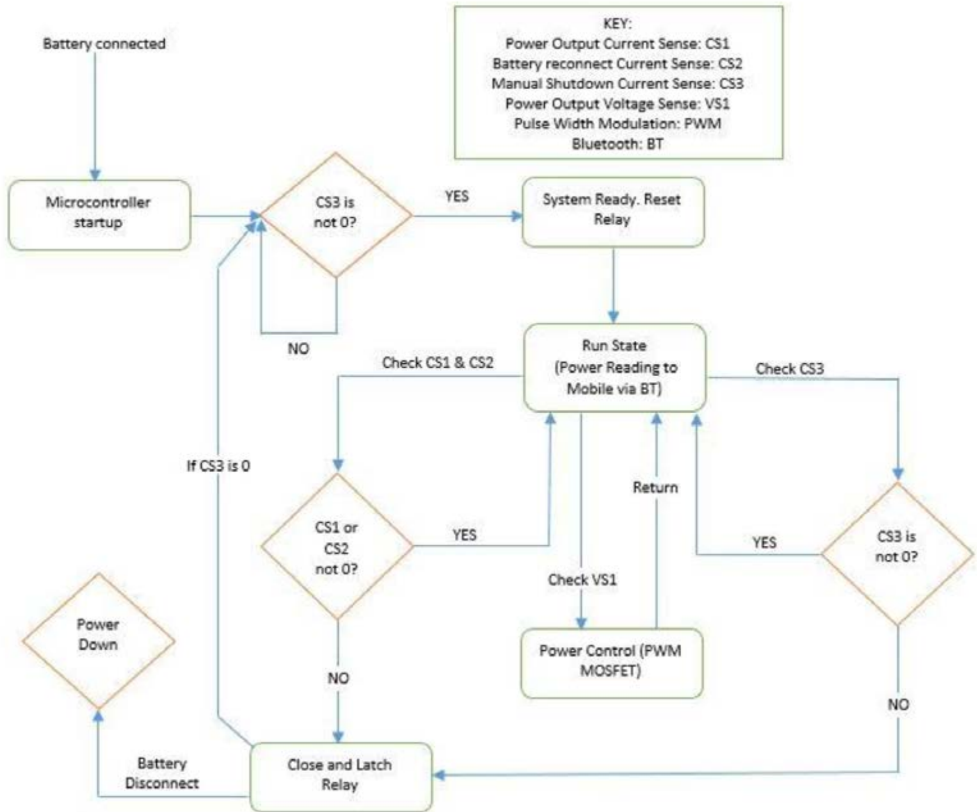

Figure 18. *Control flow diagram*

In order to maintain the power output and rotor rpm at wind speeds from 11-13m/s, the difference in the power outputs at each wind speed with respect to the output at 11m/s is the amount dissipated with a dump load across the generator input terminals. This was done via an Arduino controlled MOSFET.

Safety

Several factors were key to ensuring the safety of the turbine. All power electronics were safely isolated from the tower via an electrically isolated ventilated box. Secondly, all wiring and connection points are insulated or isolated as needed. The isolation of this box involves an additional grounding wire to be dropped from the turbine box to ground. The grounding of the turbine should follow relevant US NEC/FCC standards.

Load

For the load, the team decided to use a cut-out in the shape of the state of Wisconsin with an array of LEDs encircling the city Madison. The Madison LED lights up first and then spreads out to the surrounding areas as the wind turbine gains speed to signify the potential of wind power.

Testing and Results

50% Scale Wind Tunnel Testing & Analysis

In order to increase the efficiency of experimentation, initial blade geometry testing was done at a 50% scale with the use of additive manufacturing techniques. With this, the team was able to save time and finances to decide on the final design of the blade that will be manufactured at the full-scale size.

50% Scale Testing Procedure

Each blade design was made to retrofit to an existing test setup that included a generator and LabQuest software to output data of resistance, voltage, and power. Because these models are at a 50% scale, the numbers will not directly scale with its full-scale design, but rather will be used for performance comparison between the separate blade designs. Each blade was tested at a wind velocity of 10 m/s at the same six resistances varying from 10-250 ohms (chosen based on potentiometer range). During the test, the parameters that were recorded include: rotations per minute, RMS Voltage, electrical power, and cut-in speed. Rotations per minute were recorded using a strobe light, and the RMS Voltage and electrical power were given using the LabQuest. The cut-in speed was recorded based on observation of the wind speed during turbine start up. Calculated values include: frequency, total efficiency, tip speed, and tip-speed ratio.

Eight blade geometries, shown in **Figure 19**, were tested in a wind tunnel and compared based on recorded and calculated data. Blades designs 2 and 4-6 follow the same baseline design as design 1 with varied chord length and pitch angle.

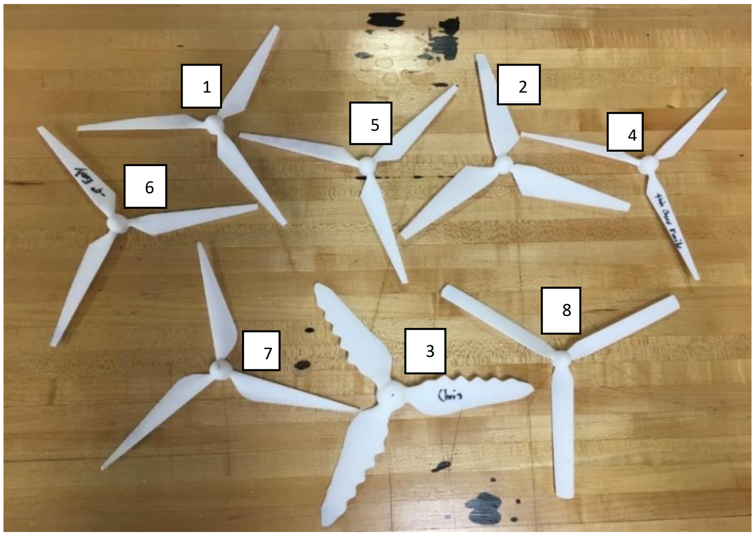

Figure 19. *Eight varying blade designs that were SLS 3D printed by Midwest Prototype*

50% Scale Testing Results

Table 7 shows the significant factors of the testing data that was used to determine which blade should be created as a full-scale prototype. The designs highlighted in red represent the top three preforming blade designs that were then further considered with an ideation chart, shown in **Table 8**.

Table 7. Testing Results of the 50% scaled wind tunnel testing

Blade Design	Maximum Power Output [W]	Maximum Efficiency [%]	Cut-In Speed [m/s]
Design #1 - Baseline	1.0426	4.0341	3.1
Design #2 – Longer Chord Length	1.2075	4.6721	3.0
Design #3 – Tubercles	1.0513	4.0677	1.7
Design #4 – Shorter Chord Length	0.4589	1.9419	3.5
Design #5 - +4 degrees pitch	0.7763	3.0036	2.5
Design #6 - -4 degrees pitch	1.0196	4.1866	4.0
Design #7 – Winglets	0.7630	2.9980	3.7
Design #8 – Large pitch and twist	0.5366	2.0765	2.0

An ideation chart assists in prioritizing the criteria of the team's final blade design. Each criterion has a designated multiplier to represent the weight of the parameter, where a larger multiplier signifies greater importance to that aspect of the design. The final design was chosen by its peak power output, cut-in speed, maximum rotational speed, ease of manufacturing, and aesthetics. Based on the ideation chart, the team was able to conclude that Design #2 was the best performing blade and will be manufactured and optimized at the full-scale dimensions.

Table 8. Ideation Chart for determining final blade design

Criteria	Multiplier	Design #1	Design #2	Design #3
Peak Power Output (1 pt./100mW generated)	4	10	11	10
Cut-In Speed (1 pt./0.5 m/s decrease from 5 m/s)	2	4	4	6
Maximum Rotational Speed (1 pt./ 1000 RPM)	1	6	6	6
Ease of Manufacturing (1-10 scale)	3	5	8	7
Aesthetics (1-5 scale)	1	3	3	3
Total	-	*72*	*85*	*82*

A plot of the efficiency vs. tip speed ratio is shown in **Figure 20** where the maximum efficiency is just below 5% and the optimal tip-speed ratio is approximately 6.9. The plotted efficiency is defined as the power output of the wind to the actual wind power the turbine is being given. The tip-speed ratio represents the blade tip velocity to the wind velocity.

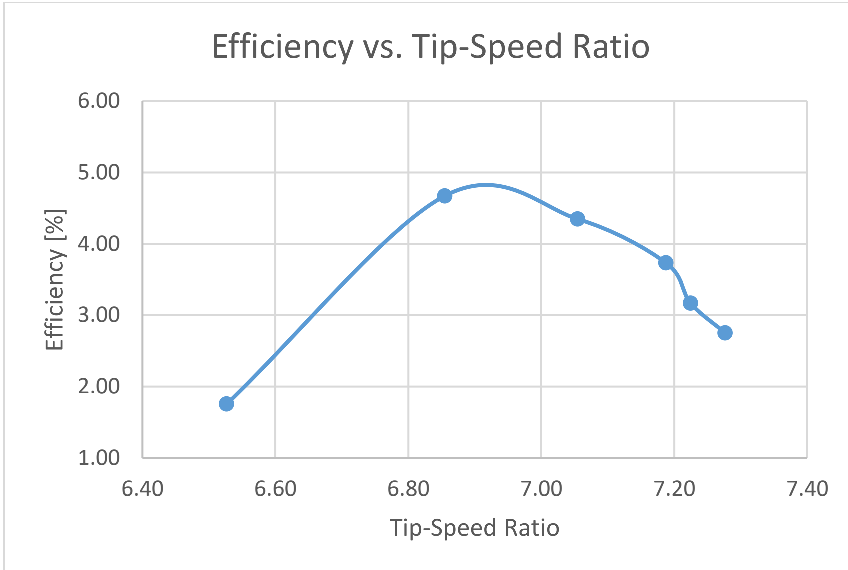

Figure 20. *Efficiency vs. Tip-Speed Ratio plot of the top performing blade design.*

Full-Scale Wind Tunnel Testing & Analysis

Wind Tunnel Testing Procedure

Material testing as well as wind tunnel testing similar to the half scale procedure is done for the full-scale prototype in order to optimize the theoretical designs that were engineered. Because it was decided to manufacture the wind turbine blades with composite material, material testing had to be done in order to choose the strongest, yet lightest material for a durable blade. Based on tensile testing of five various materials, unidirectional recycled carbon fiber was chosen as the best material for the design. This material had the greatest ultimate stress and elastic modulus as well as being a lightweight material (results of material testing are referenced in **Appendix A: Material Testing Data**).

Once the full-scale prototype is fully assembled, testing will begin with choosing incremented values of resistances. Each resistance will be tested at a wind speed of 11m/s in order to ensure the turbine will produce at least 10W at this point. The cut-in wind speed will be determined by observance of the wind speed at the point that the turbine begins to produce power. The turbine will also be tested for its durability and safety. For example, the wind speed in the tunnel will be varied between 5-18m/s in a random manner to ensure it will withstand any wind speed in this range as well as making sure it does not hit a dangerous resonance frequency. In order to test the yaw system, the turbine will be bolted into the tunnel at different angles so the wind will have a chance to produce a moment on the yaw tail to push the turbine back in windward position. The electrical control system will be tested to show that the controls and program will regulate the turbine's power output when necessary as well as incorporating an emergency stop for safety purposes. With these various test procedures, an analysis of the turbine's annual energy production will be done in order to show the performance of the designed wind turbine.

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Appendix

Appendix A: Material Testing Data

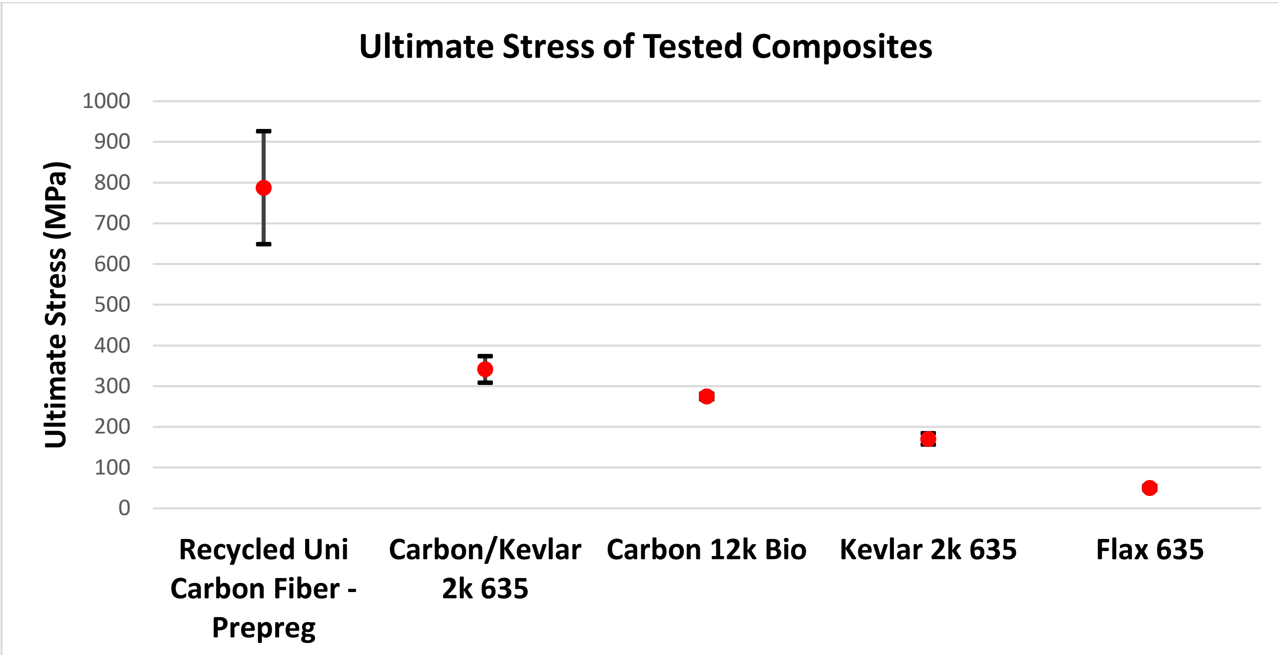


Figure 21. *Ultimate Stress of various composite materials that will be considered for the turbine blades.*

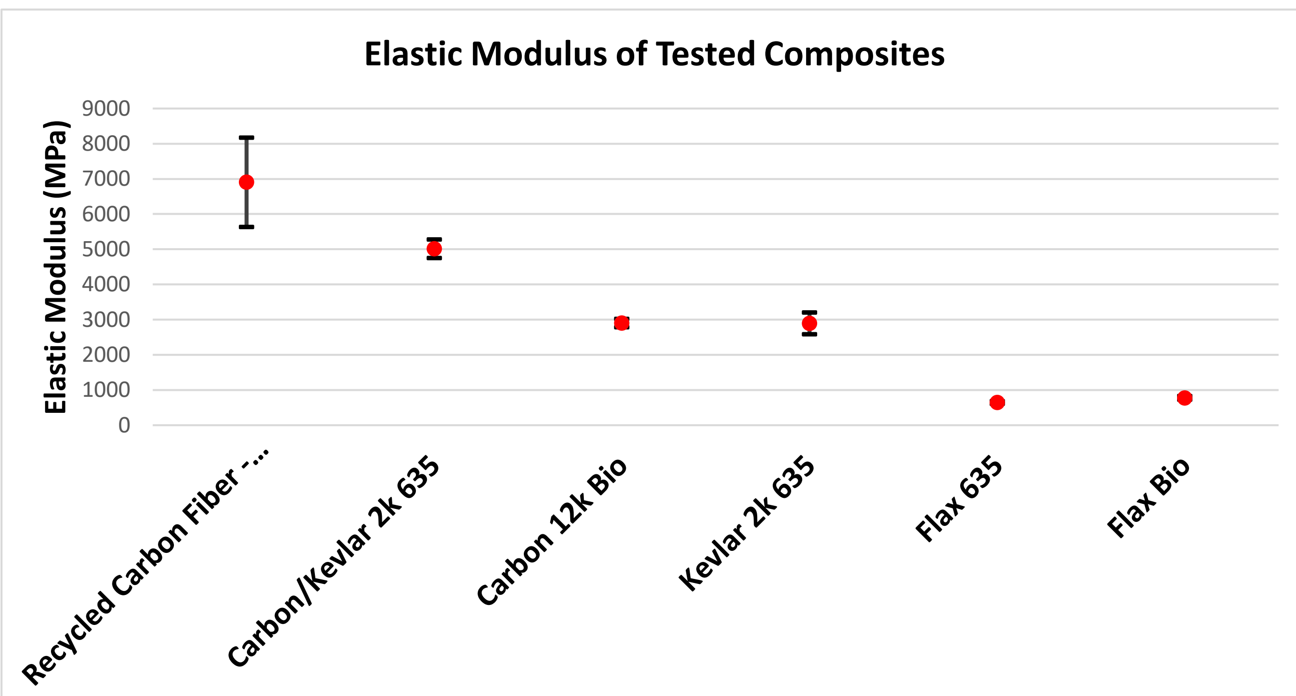
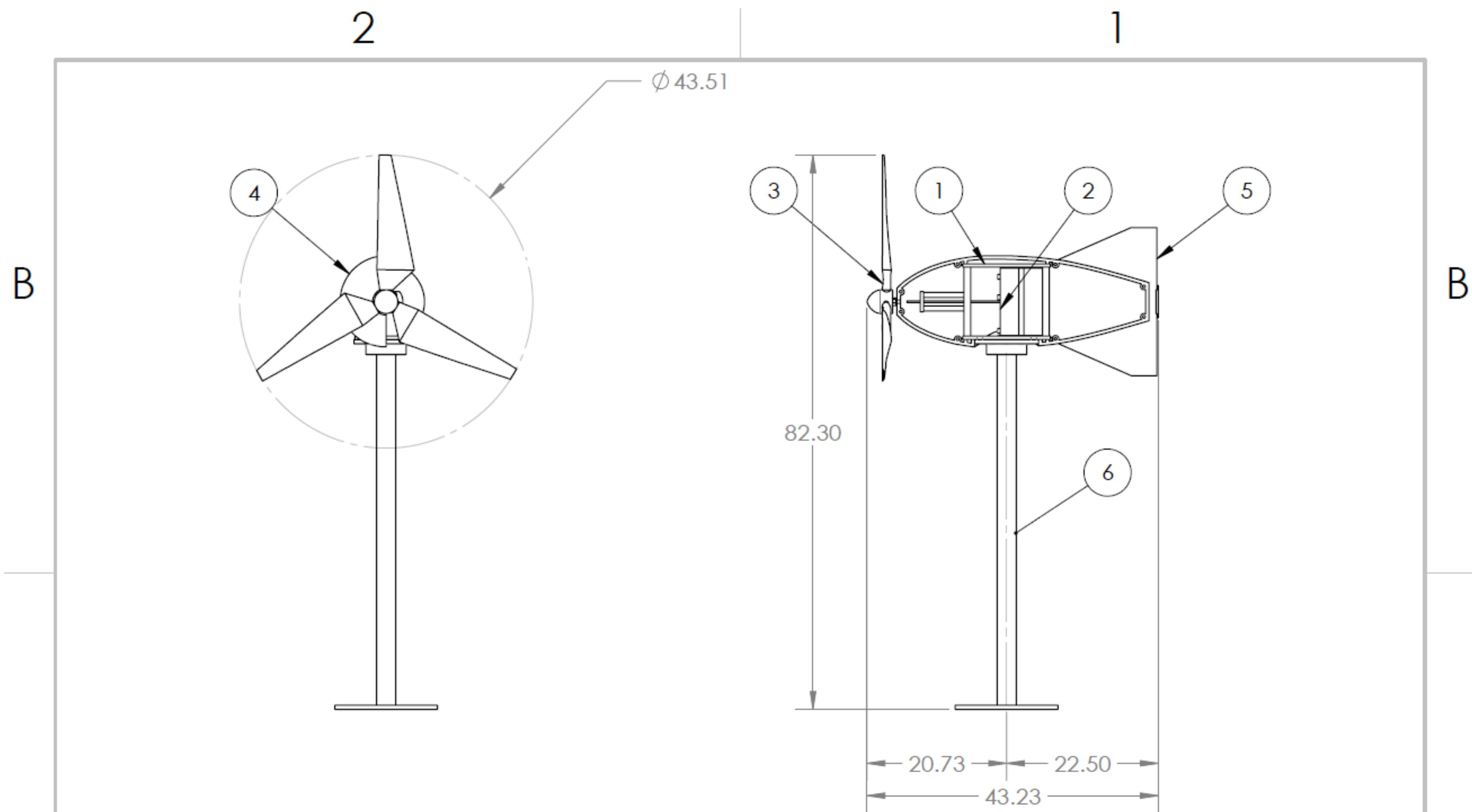


Figure 22. *Elastic Modulus of various composite materials that will be considered for the turbine blades.*

Appendix B: Prototype Drawings



ITEM NO.	PART NUMBER	QTY.
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2	GENERATOR	1
3	BLADE ASSEMBLY	1
4	NACELLE CASING	1
5	TAIL VANE	1
6	TOWER ASSEMBLY	1

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN CM
TOLERANCES:
FRACTIONAL± 0.125
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±0.125
THREE PLACE DECIMAL ±0.125

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL SEE BOM

FINISH SEE BOM

DO NOT SCALE DRAWING

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DRAWN	EEB	04/05/17
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ENG APPR.		
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COMMENTS:

WiscWind

TITLE: WIND TURBINE ASSEMBLY

SIZE A | DWG. NO. 1000 | REV

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A A 2 1

ITEM NO.	MATERIAL	DESCRIPTION	QTY.
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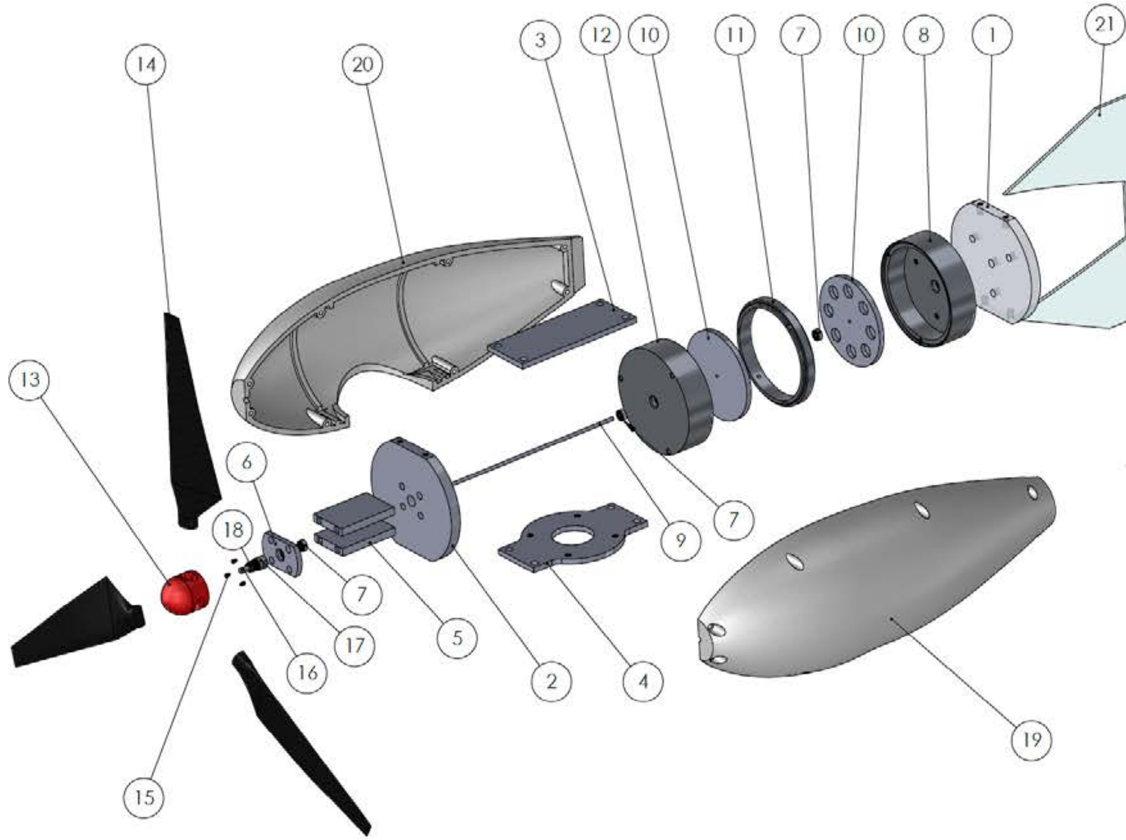
2	6061 ALUMINUM	NACELLE FRONT PLATE	1
3	6061 ALUMINUM	NACELLE TOP PLATE	1
4	6061 ALUMINUM	NACELLE BOTTOM PLATE	1
5	6061 ALUMINUM	NACELLE EXTENSION PLATE	2
6	6061 ALUMINUM	NACELLE FACE PLATE	1
7	HARDENED STEEL	3MM RADIAL BEARING	3
8	6061 ALUMINUM	GENERATOR REAR HOUSING	1
9	BRASS	DRIVE SHAFT	1
10	1018 STEEL	ROTOR PLATE	2
11	6061 ALUMINUM	STATOR PLATE	1
12	6061 ALUMINUM	GENERATOR FRONT HOUSING	1
13	ACRYLIC	HUB	1
14	CARBON FIBER	TURBINE BLADE	3
15	MILD STEEL	SET SCREW	3
16	6061 ALUMINUM	COLLET FASTENER	1
17	6061 ALUMINUM	COLLET	1
18	6061 ALUMINUM	COLLET NUT	1
19	ABS PLASTIC	NACELLE CASE LEFT	1
20	ABS PLASTIC	NACELLE CASE RIGHT	1
21	ACRYLIC	YAW TAIL	1



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WiscWind

TITLE:

TURBINE BODY

DWG. NO. DWG0002

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