TECHSAN WIND

Turbine Design Report

Texas Tech University, TTU & South Plains College, SPC

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Executive Summary

To meet the tasks assigned for the 2023 Collegiate Wind Competition (CWC), the Techsan Wind Team (TWT) designed, built, and tested a wind turbine model capable of functioning in emulated offshore conditions. Many of the components from last year are similar but have been enhanced, details of which will be specified in their respective sections. The design of the turbine components evolved after careful analysis of how each subsystem assembly would interact, with revisions and alterations made subsequent to their construction and testing. Performance testing for the foundation, blades, yaw, pitch, and power generation was extensive. Numerous minor adjustments to foundation installation methods and the Arduino code were made consistently up until the competition. The overarching goal of TWT was to improve the controls of the turbine from last year, as neither the emergency stop nor the pitch system performed as expected. As TWT had the best power curve among all the competing teams last year, that was not the focus. Instead, efforts were concentrated on a functioning pitch, yaw, and emergency stop system, so that the turbine could complete more of the required challenges presented by the competition organizers.

Design Objective

The turbine's design objective is to prototype and manufacture an autonomous small-scale offshore turbine for the Gulf of Mexico. The turbine's components include active pitching and yawing systems, as well as emergency stop capabilities. The turbine's blades will be manufactured in conjunction with South Plains Community College to test different materials and manufacturing processes, facilitating the selection of the best procedure and choice.

The foundation requirements necessitate a design capable of withstanding both thrust loads and the force of the wind on the turbine tower. This year's prototype was designed to withstand omnidirectional loads and be as lightweight as possible. Extra time was invested in testing the foundation assembly process to ensure consistency, and as many TWT members as possible were trained in this process. This ensures that in the event of a scheduling conflict or emergency, anyone could step in to install the foundation.

Individual assembly components were tested for their efficiency and ease of use. They were then modified to perform optimally before being tested as a whole. This approach ensured the subassemblies would function as effectively as possible as a collective unit.

The design components are designed to withstand the set restrictions mentioned in the design overview. The materials and the electrical load for the turbine are designed to withstand wind speeds of up to 22 m/s without system failure. Components used include Blades, an MN5008 Antigravity T-Motor drone motor, servos, relays, an Arduino Uno, power smoothing filters, optocouplers, a full-bridge rectifier, and an electrical load model. For the foundation, the set restrictions were addressed with an installation plan designed to prevent any contact with the water, using an auguring anchoring system installed with battery-operated drills and extension attachments. The foundation is composed of steel ground augers, steel sheet metal, and nominal OD steel pipe.

Continuity from Last Year

The turbine's foundation, improved upon from the previous competition, follows a similar design methodology. This iteration of the foundation was designed to be more lightweight, yet still capable of maintaining stability during load testing. The foundation assembly process mirrors the previous design, but with more team members involved to expedite the installation process, facilitated by the use of battery-powered impact drills.

Static Performance Analysis

For the Rotor Performance Analysis, an analysis was conducted using the Davis airfoil from last year and a locally developed Blade Element Momentum (BEM) Code, written in Excel for instructional purposes. The code is based on standard BEM Theory as presented by Hansen[1] and adapted for MS-Excel, as described by Swift[2]. The Excel Code employs standard BEM algorithms and the Excel "Solver" for axial induced velocity calculations over each blade segment. Tip losses and other secondary effects are disregarded for simplicity. **Figure 1** displays the Power Coefficient - Tip Speed Ratio (TSR) for a pitch angle of +8°, with a maximum power coefficient (C_p) of 0.29 at a TSR of 4.28.

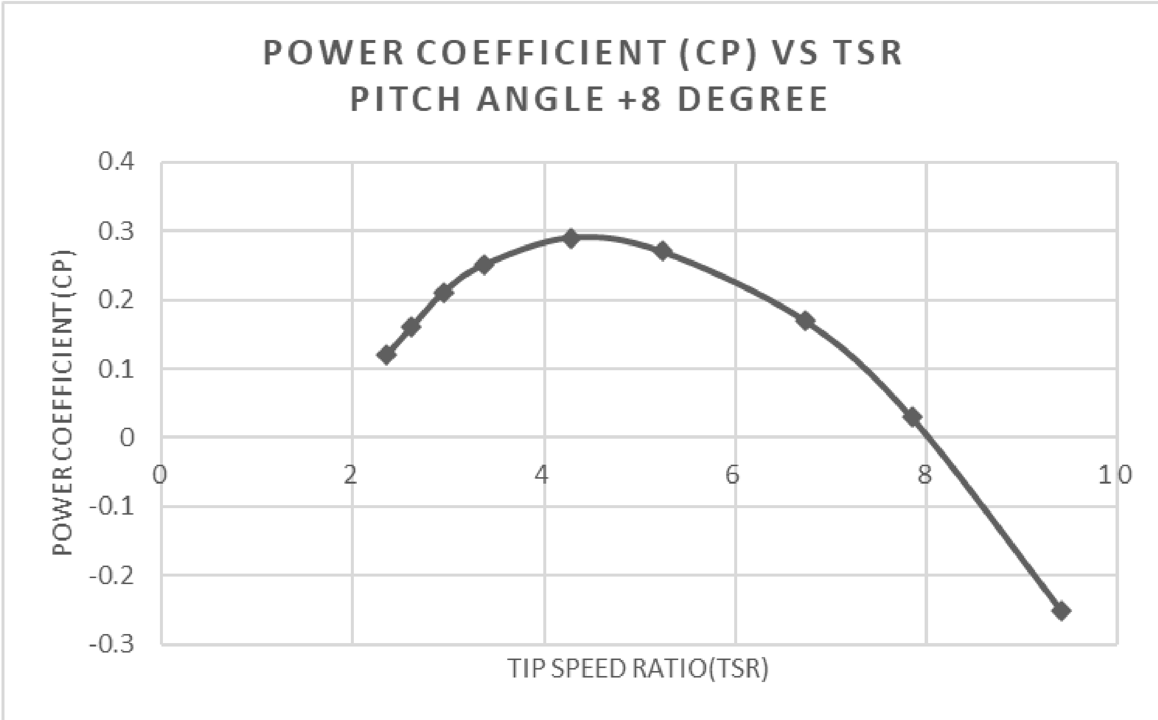

Figure 1: Power Coefficient vs Tip Speed Ratio results using In-House Excel BEM Code.

Experimental Set Up

Experimental data was taken using the 1.2m x 1.2m wind tunnel as shown in **Figure 2**.

Figure 2: 1.2 m x 1.2 m wind tunnel at Reese Technology Center.

The wind tunnel has a door on the back and a clear plexiglass viewing side. The wind tunnel has a 4 x 4 ft. (1.2 x 1.2 m) cross section and an approximately 10-foot (3 m) long test section with a venturi inlet. Flow is driven by a 4 ft. (1.2 m) diameter fan that uses a belt-driven 230/240 V, 15 hp, frequency-controlled variable speed motor. Additionally, the lower frame has a 2 ft. (0.6 m) cut-out to attach to an offshore foundation model that embeds in a tank filled with sand and water, emulating offshore subsurface conditions.

Instrumentation includes a pitot-static wind speed measuring system and atmospheric measurements to include temperature, pressure, and relative humidity. Additionally, the instrumentation includes a laser-based rotor RPM measuring system, electrical measuring equipment that includes an adjustable resistive load, voltage and current measurements, and an external power supply, as shown in **Figures 2** and **3**.

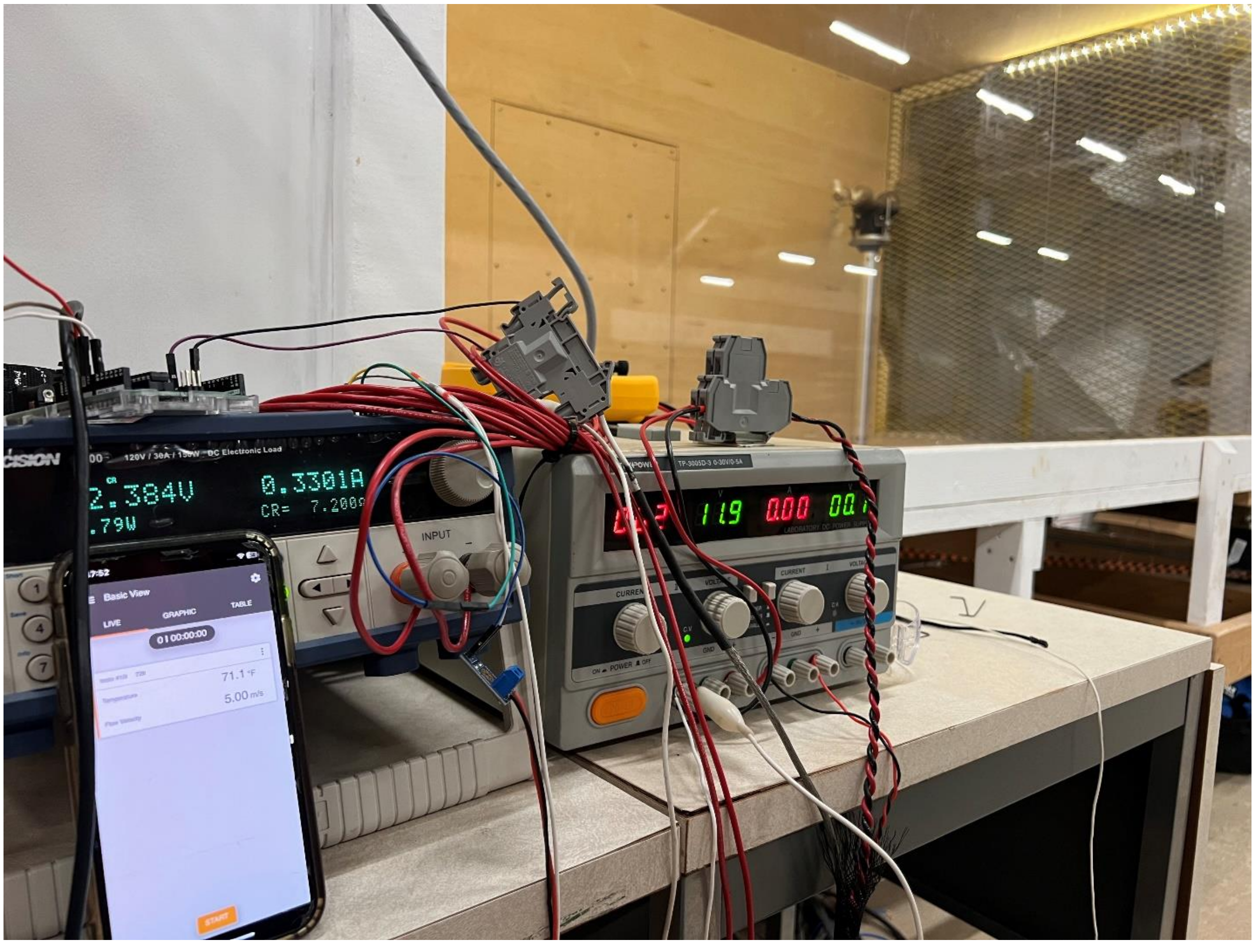

Figure 3: Wind tunnel electrical instrumentation setup.

Wind speed measurement was verified by comparing pitot tube measurements with a portable Testo anemometer shown on the tunnel floor upstream of the wind turbine in **Figure 2**. Blade pitch was calibrated using a blade-mounted laser system that traces the laser path on one of the wind tunnel walls upon changes in blade pitch, as shown in **Figure 4**. Rotor speed was measured using the Monarch Corporation laser-electronic measuring system.

Figure 4: Rotor pitch laser calibration.

Table 1 shows the Excel data sheet for the prototype power curve test. Atmospheric variables were entered first, and air density was calculated. The wind tunnel was operated from startup to 11 m/s, and the turbine data were recorded, as shown in the table.

Table 1: Copy of Excel Data Sheet for Prototype Turbine Power Curve Test.

		4/26/2023		1.2 x 1.2 m Wind Tunnel;					
Prototype Turbine Test; Reese Technology Center, Lubbock, TX									
	Atmo. Data Inputs			calculated values					
temp	deg F>	74.9	deg C>	24					
Bar Press	inches Hg>	29.9	mb>	1013					
Humidity	%>	49							
Gen. Load	Ohms>	7.2							
Yaw Angle	degrees>	0							
		Station	Pressure>	inches Hg>	26.50	mb>	897		
		Dry	ir density>	kg/m^3>	1.06				
		Moist	ir density>	kg/m^3>	1.04	Click here	...calc moist air density;		
						Using Omnicalculator/physics/airdensity			
	Operational Data inputs								
Red Oil									
Pitot Tube	Calculated		Blade						
meas.	wind speed		pitch angle	RPM	Gen	Gen	Gen		
Inches H2O	m/s		deg	rev/min	volts	amps	watts		
0.075	6.0		8	1096	5.03	0.69	3.5		
0.105	7.1		8	1395	6.61	0.90	5.9		
0.135	8.1		8	1691	8.33	1.14	9.5		
0.172	9.1		8	1944	9.64	1.34	12.9		
0.21	10.0		8	2225	11.4	1.59	18.1		
0.2505	11.0		8	2479	12.73	1.77	22.5		
0.22	10.3		13	2229	11.18	1.57	17.6		
0.25	11.0		16	2220	11.23	1.57	17.6		
0.19	9.6		-15	0	0	0	0	Note 1	
0.037	4.2		8	0	0	0	0	Note 2	
		Note 1: High wind turbine shutdown test							
		Note 2: Minimum wind speed operation test							

The test data above were then used to generate the prototype power curve and compared with the BEM code predictions. **Figure 5** shows the comparison with a Variable Data Chart, which includes pitch angle, output power in Watts (Electric), and RPM×100. The solid lines show the BEM code predictions for each variable, while the dots show experimental results from wind tunnel tests. Discussion of results follows in the In Situ Test Results section.

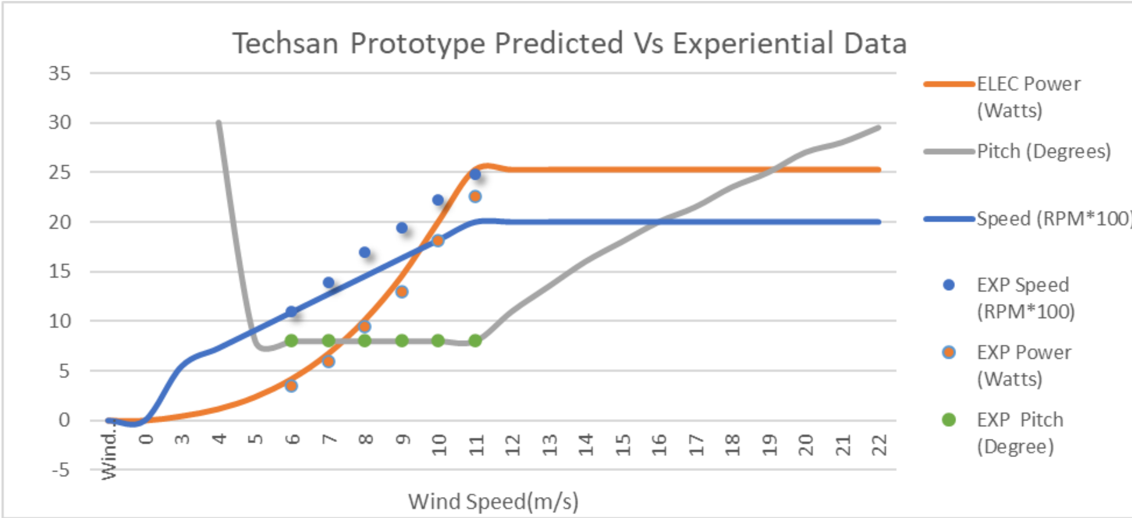

Figure 5: Prototype Excel BEM Code and Experimental Wind Tunnel Data.

Figure 6 shows the BEM predicted rotor thrust (N) with a maximum thrust of 3.97 N at a wind speed of 11 m/s.

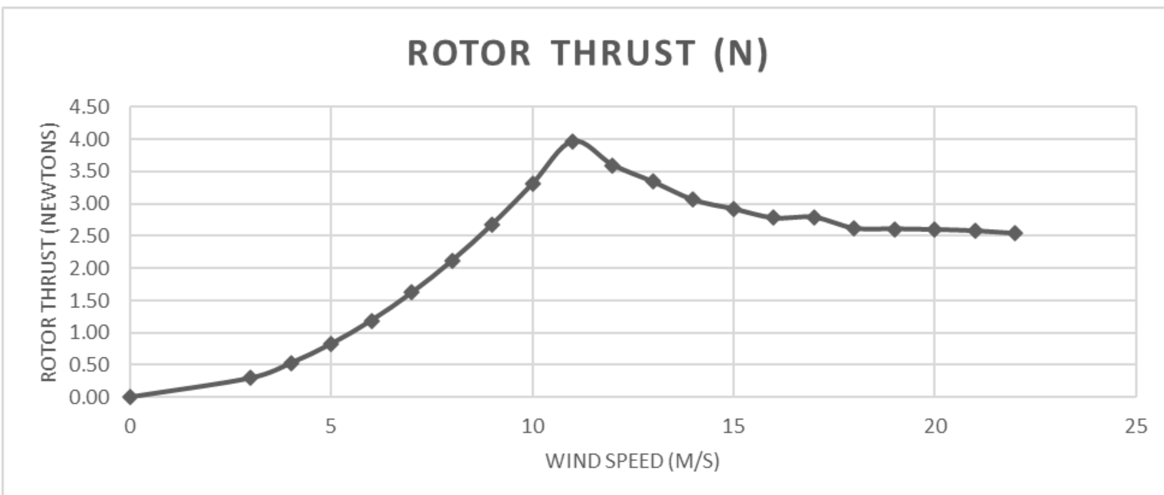

Figure 6: Prototype Excel BEM Code Predicted Operational Thrust Data.

Figure 7 shows expected power curves set at different air densities including sea level (1.23 kg/m^3) with a rated power of 31.5 Watts, Lubbock, Texas (1.04 kg/m^3) at 26.7 Watts, and Boulder, Colorado (1.0 kg/m^3) at 25.7 Watts.

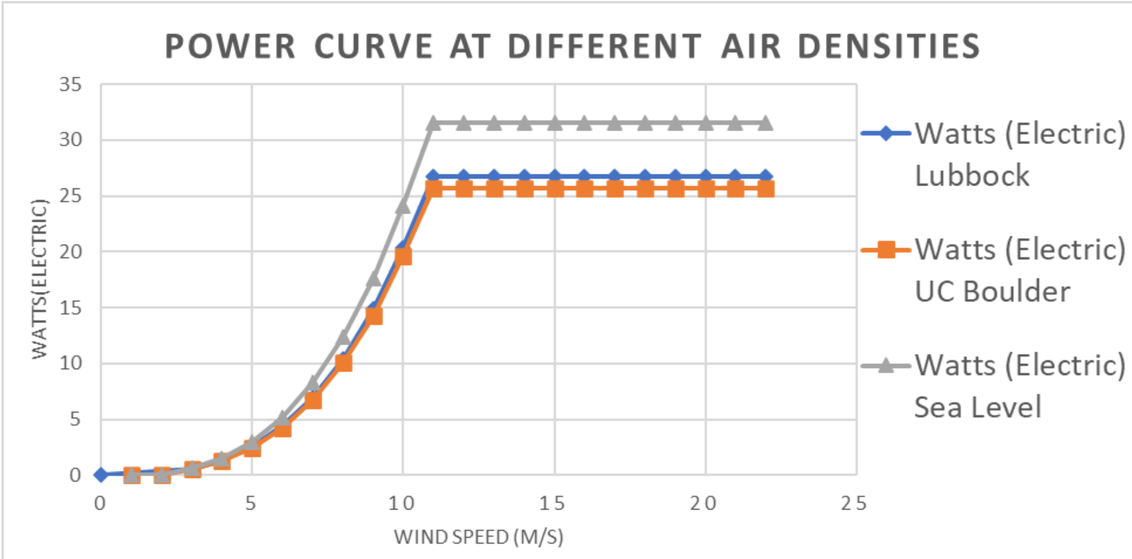

Figure 7: Expected Prototype Power Curves for various locations.

Mechanical Load Analysis

The purpose of the following calculations is to obtain an estimation of the tipping moment to be compared to the actual tipping moment of the foundation, in order to obtain a factor of safety (FOS). It should be noted that some interactions have an insignificant effect on the overall structure. Because of this, gyroscopic properties, such as spin, precession, and nutation, may be discounted to allow for simpler calculations. Since axial loads increase moment capacity, gravitational loads may be taken as zero for a more conservative approach. Additionally, the stub and foundation are not subject to wind loads since they reside outside of the wind tunnel.

The remaining loads are wind forces on the blades, nacelle, and tower, each with a respective moment that must be endured by the foundation. TWT will be considering two cases: rated wind speed (11 m/s) during operational conditions, and maximum testing wind speeds (22 m/s) while parked. To find the thrust, in newtons, that wind applies to a given surface, use the following equation:

$$T = C_T \frac{1}{2} \rho A V^2$$

For the chosen blade, the coefficient of thrust (C_T) for rated wind speed was found to be 0.4 in BEM, and air density (ρ) in Boulder, CO is 1.04 kg/m^3.

Thrust from spinning blades at rated wind speed:

$$T = (0.4)\frac{1}{2}(1.04\, kg/m^3)(\pi[0.225m]^2)(11\, m/s)^2 = 4.00N$$

Thrust from parked blades at max testing wind speed:

$$T = (1.0)\frac{1}{2}(1.04\, kg/m^3)(3 \cdot 0.00413m^2)(22\, m/s)^2 = 3.12N$$

The nacelle may be assumed to be a square prism. The height to depth ratio (1:3 for common practice[3]) yields a C_D of about 1.3[4]. TWT's nacelle has a 2.7 in. diameter (5.73 in^2), but will assume a 2.7 in (0.06858m) square (7.29in^2) to be conservative.

Thrust from nacelle at rated wind speed:
$T = (1.3)\frac{1}{2}(1.04\,kg/m^3)(0.0047m^2)(11\,m/s)^2 = 0.38N$
Thrust nacelle at max testing wind speed:
$T = (1.3)\frac{1}{2}(1.04\,kg/m^3)(0.0047m^2)(22\,m/s)^2 = 1.54N$

The tower may be assumed to be a cylindrical rod perpendicular to flow. The height to diameter (L/D) ratio ($60cm/3.81cm = 15.7$) provides a C_D of 0.91 using a L/D of 20[5].

Thrust from tower at rated wind speed:
$T = (0.91)\frac{1}{2}(1.04\,kg/m^3)(0.6m \times 0.0381m)(11\,m/s)^2 = 1.31N$
Thrust from tower at max testing wind speed:
$T = (0.91)\frac{1}{2}(1.04\,kg/m^3)(0.6m \times 0.0381m)(22\,m/s)^2 = 5.24N$

The moment experienced by the foundation at the surface of the soil can be found by using the following equation:

$$M = F \cdot d$$

where the force (*F*) is the thrust calculated prior, and distance (*d*) is the location of the superimposed load above the soil. The heights of all structural components are as follows:

Nominal 1.5" OD pipe: 0.2296*m*
Stub: 0.19685*m*
Rotor measured from flange: 0.6*m*

The blades thrust into the rotor at hub height.
Moment for blades at rated wind speed:
$M = 4.00(0.6m + 0.19685m + .2286m) = \ 4.10N \cdot m$
Moment at max testing wind speed, parked:
$M = 3.12N(0.6m + 0.19865m + .2286m) = 3.21N \cdot m$

The nacelle causes a bending moment at hub height.
Moment at rated wind speed:
$M = 0.38N(0.6m + 0.19685m + .2286m) = 0.39N \cdot m$
Moment at max testing wind speed:
$M = 1.54N(0.6m + 0.19685m + .2286m) = 1.58N \cdot m$

The wind applies a distributed load, so a virtual load at the midpoint of the tower height can be used.
Moment at rated wind speed:
$M = 1.31N(0.3m + 0.19685m + .2286m) = \ 0.95N \cdot m$
Moment at max testing wind speed:
$M = 5.24N(0.3m + 0.19685m + .2286m) = \ 3.80N \cdot m$

The total moment enacted on the foundation is obtained by adding all the individual moments together.
Total moment at rated wind speed:
$M = 4.10N \cdot m + 0.39N \cdot m + 0.95N \cdot m = 5.44N \cdot m$
Total moment at max testing wind speed, parked:
$M = 3.21\,N \cdot m + 1.58N \cdot m + 3.80N \cdot m = 8.59N \cdot m$

Underwater Structure and Anchoring System

Initial designs were to include multiple auguring discs mounted to each anchor shaft with the ideology that more discs would provide more resistive force. Multiple anchor prototypes, shown in **Figure 8**, were constructed to confirm this theory. The vertical pull test rig constructed can slide underneath a collar, and the instantaneous tension is displayed on the digital load cell. The load cell hook was inserted in the wire loop, and tension was increased slowly by hand. Once the displayed force began to drop or stay constant, the maximum tension was noted. It was found that two discs mounted to the shaft were significantly weaker compared to the single disc variant, which was able to withstand 15 lbs.

Figure 8: Foundation testing setup.

Once the strongest anchor was established, nuts on the threaded shafts were replaced with welds, as shown in **Figure 9**.

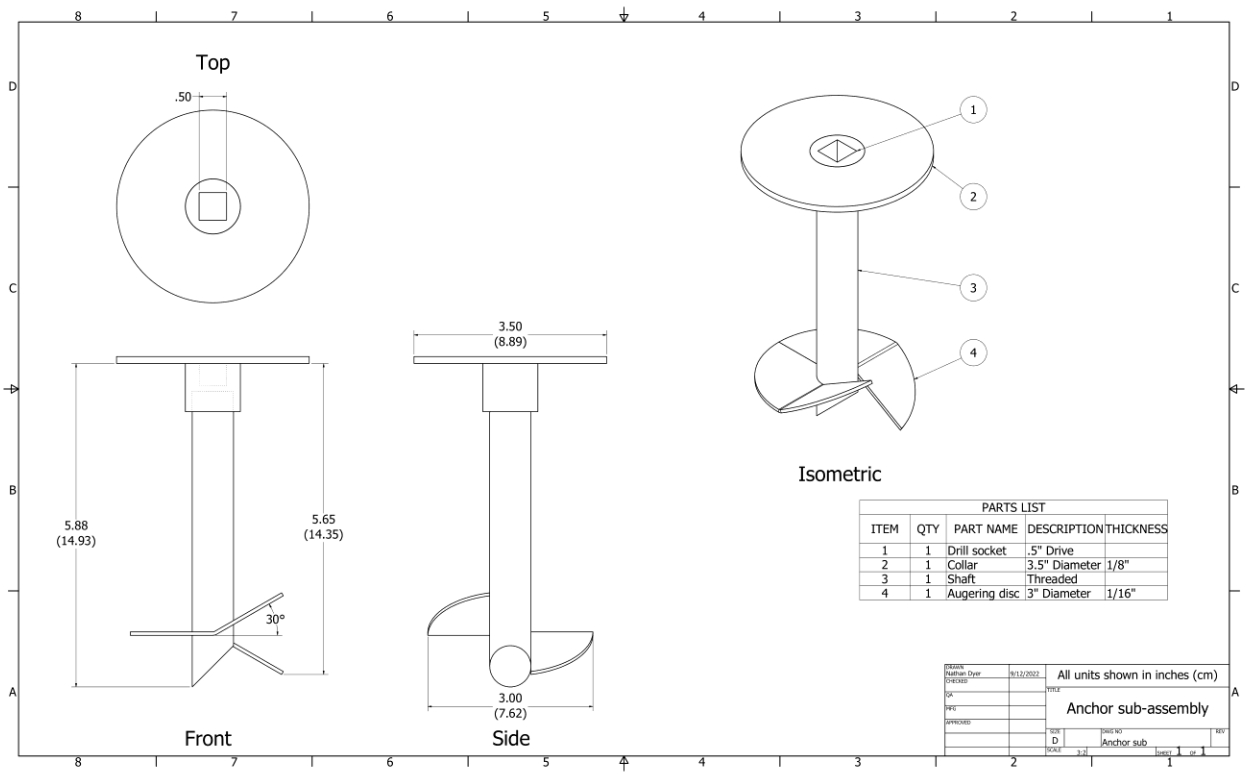

Figure 9: Auguring anchor sub-assembly

The multi-directionality of the foundation, indicated by trigonometry shown in **Figure 10**, was verified using the digital load cell. Two predominant wind cases were tested: two anchors windward, and one anchor windward. The tipping moment is calculated by multiplying the tension force found at failure (F) by the distance from the center of the foundation aligned with the wind direction. After full assembly of the foundation, the ultimate tipping moment was tested with the digital load scale and a rod of known length. A resistive moment of 9.6 N·m was confirmed in all directions, thus allowing for the FOS calculation:

$$FOS = \frac{\sigma_{ult}}{\sigma_{req}} = \frac{9.6N \cdot m}{8.6N \cdot m} = 1.12$$

suggesting that the foundation will not deflect.

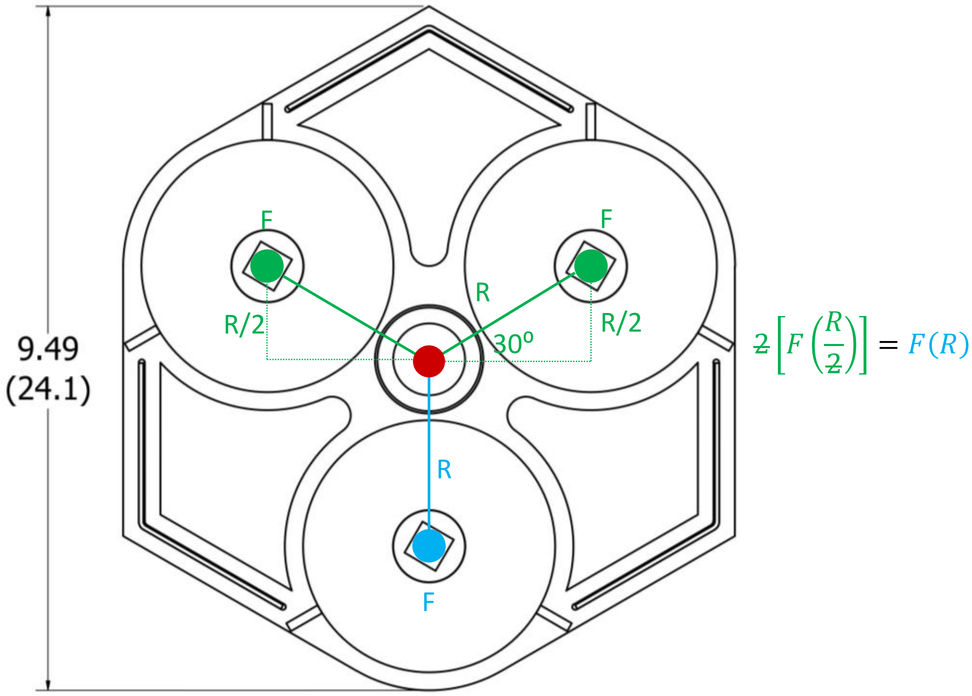

Figure 10: Trigonometric analysis of foundation.

Electrical Analysis

The generator is a T-Motor antigravity MN5008 drone motor. This generator is a 3-phase permanent magnet motor operated as a generator. The motor has low cogging torque for smooth operation and is ultralight with high efficiency. The stator is an imported silicone steel sheet, with antirust treatment rated for up to 180 C operation. The shaft diameter is 6 mm with imported 696ZZ bearings. The coil insulation is rated for 500 V with a centrifugal cooling design. The motor size is 55.6 mm diameter by 32 mm thick and weighs 128 grams. The motor/generator is rated for 47 V, 11.5 A, and 6300 RPM.

Controls Analysis

The control system consists of three major components (see **Figures 11** and **12**).

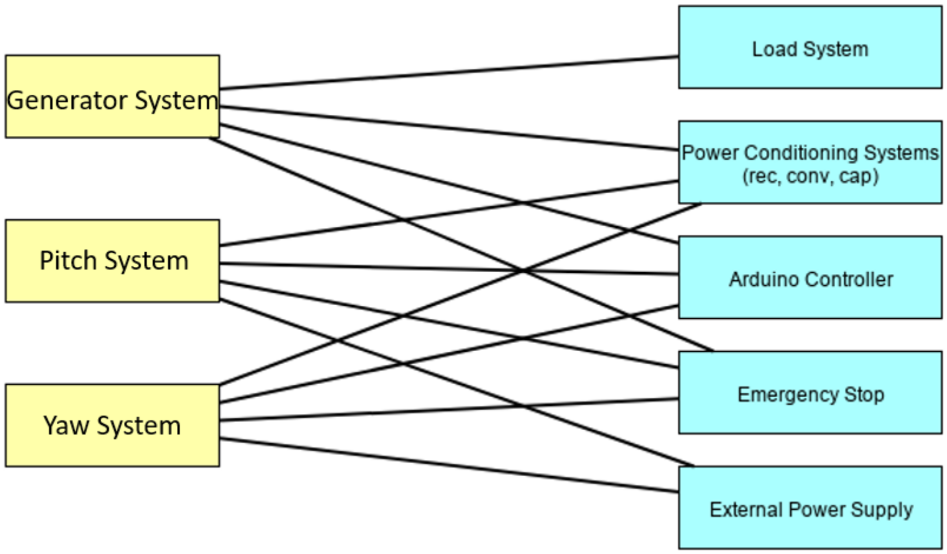

Figure 11: Canonical Model.

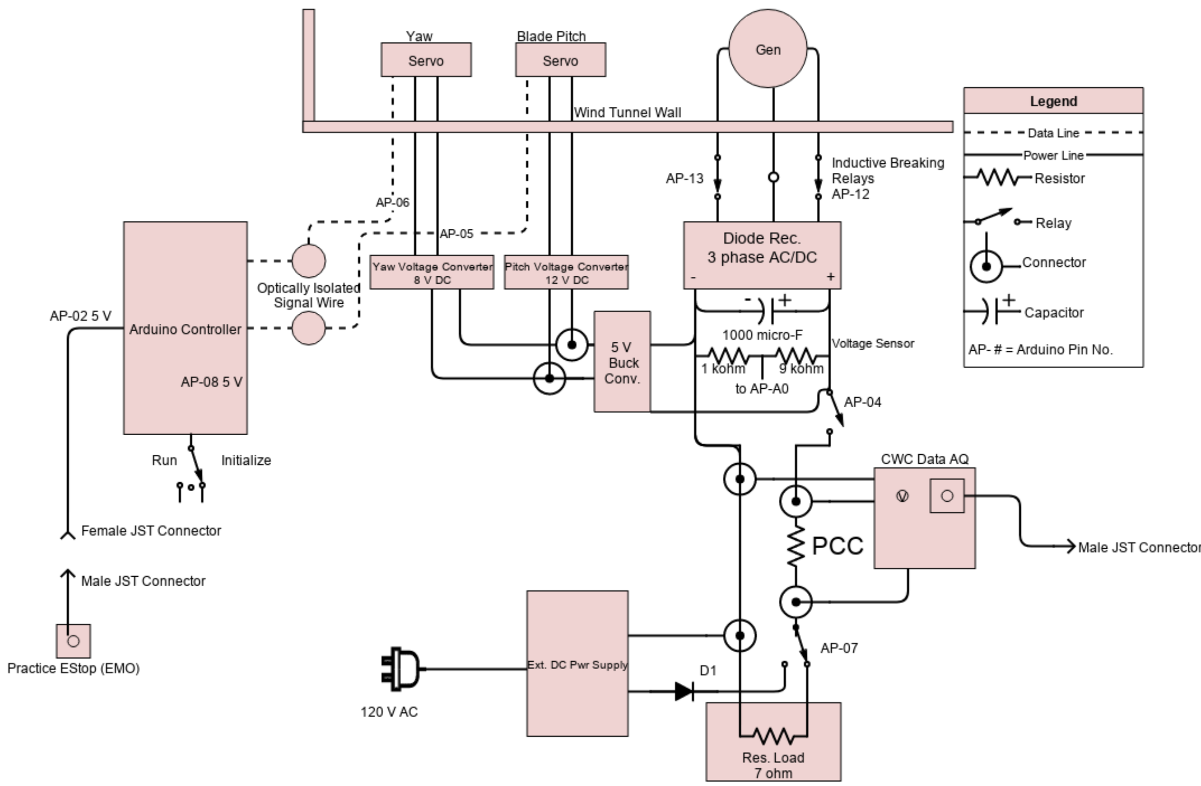

Figure 12: Control System One-Line Diagram

The control box contains the Emergency Stop System, Arduino micro-controller, AC/DC rectifier, voltage converters, and surge capacitor. Next, the load box contains control relays and a 7.2 Ohm load rated for 150 Watts. The third major component is an independent DC power supply and control relay. These components are shown in the system wiring diagram. After connections are complete between the wind turbine and control system the turbine can be initialized for testing. After final wind turbine adjustments are completed, the control system is switched into the automatic run mode. The turbine auto-sets the rotor blade pitch angle at 56° for startup. When the wind speed increases to start-up speed, the blades begin to spin, and voltage is generated. When the generator output exceeds 5 volts the controller adjusts the pitch to 8° for maximum efficiency and at the same time disconnects the load-connected power supply and connects the resistive load - transmitting power from the generator to the load. When Emergency Stop is activated, the machine goes into an emergency shutdown procedure. The load is immediately disconnected while inductive braking is applied by short-circuiting the generator output and providing inductive braking. While the blades are pitching to the stop position at approximately -10° of pitch angle, the nacelle is yawed 90° from the wind direction to assist in a full rotor stop. Before the auto restart sequence is engaged, the turbine stays in this state for 30 seconds. During auto restart the blades are adjusted to approximately 16° and the nacelle is slowly turned back into the wind. Once sufficient rotation is detected by adequate generator voltage levels, rotor efficiency is maximized by again setting the blade pitch to 8°.

Turbine Control Sequence

Pre-Start

1. Power supply (off)/ load (on-closed)
2. Power supply (on) (Remote control switch closed)
3. Blades pitch and turbine yaw move to start position
4. Power switch (off)/ load (off)

Start Test

5. Read voltage on generator power lines
6. Wind speed increases
7. At start voltage, power supply (on), load (on)
8. Pitch blades to run position (power supply needed to supply voltage to operate the pitch servo)
9. Voltage and generator power increases to rated value at rated wind speed. Pitch held constant in “run”
10. At rated wind speed, pitch blades to hold generator power constant at rated value
11. At activation of the EStop button, signal sent to Arduino and power control relays switched (off)
12. Pitch blades to start and yaw to 90 °
13. Power supply (off), load (off)
14. Read EStop position
15. Go to step 2 and restart

Software Architecture

Data acquisition uses an Arduino microcontroller shown in the one-line diagram in **Figure 12**. A two-position switch is provided to initialize and run the system. The initialize position includes setting the yaw to zero, the pitch to start position and turns off the inductive braking. In the run position, the turbine is controlled by continuously reading generator voltage output and then by varying blade pitch appropriately to maintain rated voltage. Upon Estop command, relays are engaged to inductively-brake the 3-phase generator, blades are pitched to the start position, and the turbine is yawed 90 ° to the wind. The load is disconnected using the same procedure as Estop. The turbine operating states are emergency stop, initialization, and operation in the 4 power curve Regions. Turbine actuators are low-voltage DC servos controlled by the Arduino micro-controller. The actuator input voltage is conditioned by a voltage and buck converter. The signal lines to the servos are optically isolated. Data archival capability is not built in the Arduino, however, the experimental performance was measured using an external power supply, load controller, pitot tube for wind speed, laser rpm system, atmospheric conditions in the TTU 1.2 m x 1.2 m wind tunnel and manually noted in an Excel sheet, as described above.

Assembly of subsystems

The steel tower base has a short tube welded to it that has threaded holes on the shaft. The tower base fits inside the aluminum tower with bolts to secure the aluminum tower to the flange. The top of the aluminum tower tube has a flange bearing that is held in place by a screw that passes through the journal and sets the height on the tower. The flange bearing bracket clamps onto the bearing outer casing with two threaded posts that allow L-brackets to be held in place by nuts that pinch the horizontal surface. Screws, in the vertical surface of the L-brackets, screw into the nacelle and help to ensure contact between the nacelle and the bearing track casing.

The foundation was designed in Inventor as sheet metal and CNC plasma cut at the McDermott Prototyping Facility at Texas Tech. The auger discs and interface fins, shown in **Figure 13**, require bends and were constructed of the thickest gauge, 1/16 in., allowable for the bending brake at McDermott. The rest of the interface & augers were cut from 1/8 in. sheet metal or manufactured with off the shelf parts.

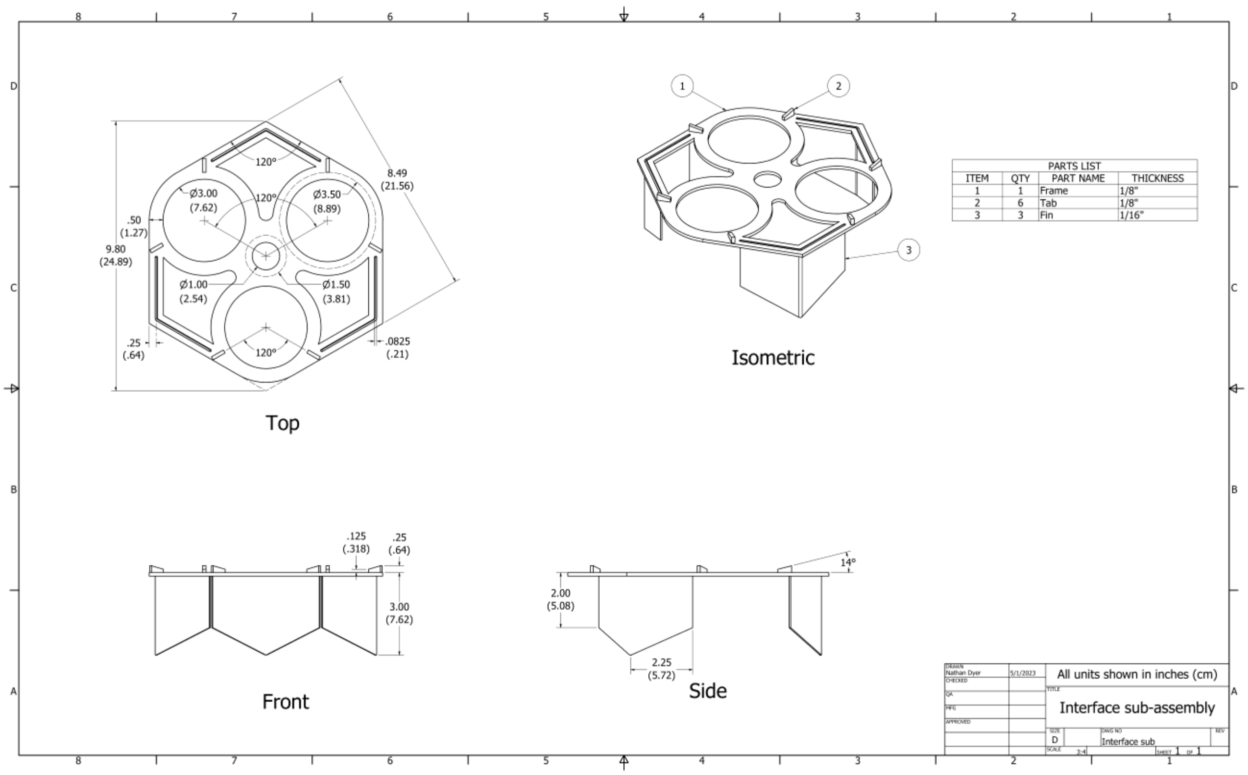

Figure 13: Foundation interface sub-assembly

Once all sub-assemblies for the foundation were constructed, the nominal OD tube was welded on the interface, and auguring anchors could be inserted as shown in foundation full assembly (**Figure 13**).

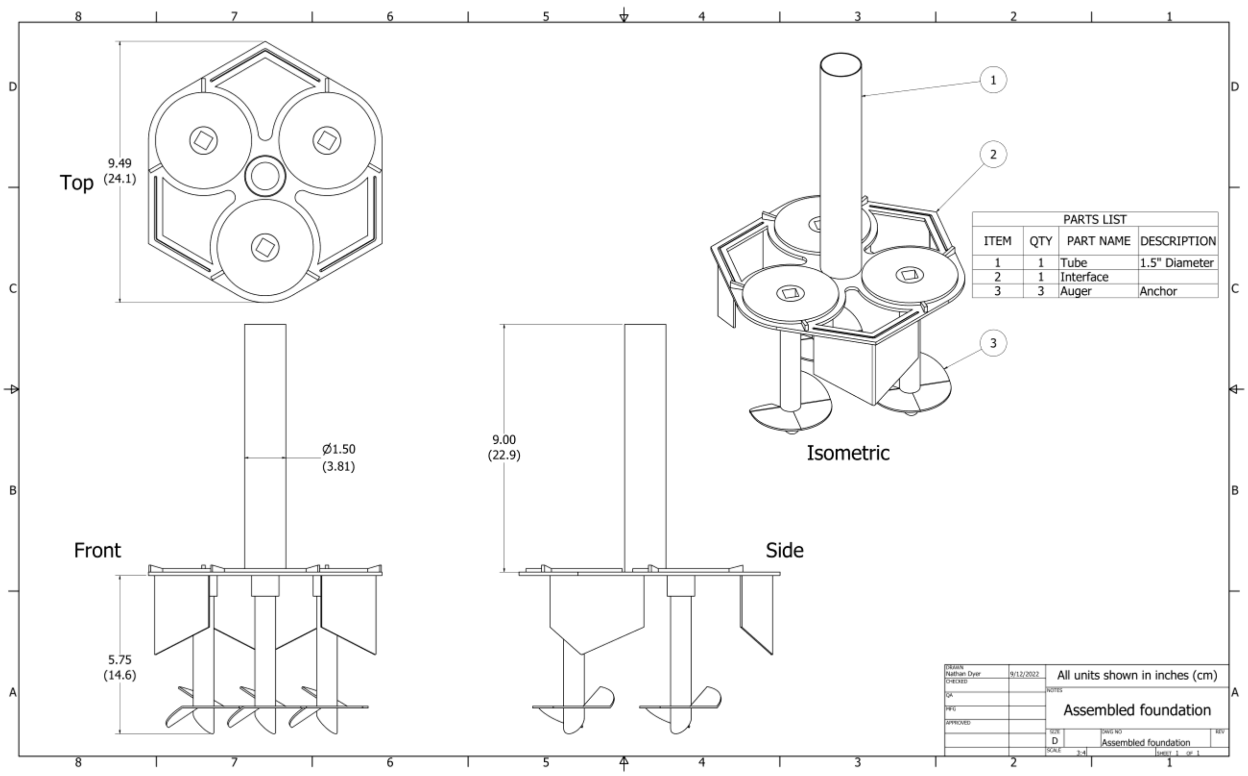

Figure 14: Foundation full-assembly

Commissioning Checklist

Ensure Controls Functionality:
1. Open up control box
2. Check rectifier continuity on DC side.
3. Check that initialize-run switch has continuity
4. On relay board check:
5. Check relay board for normally closed continuity
6. Buck converter no continuity
7. Boost converters continuity positive and positive, neg and neg
8. When set to initialize, relay 1, 2 and 8 light on along with boost converter and buck converter light on when once plugged in make sure there's clicking
9. Light on aux RELAY ON PS turns on when E-stopped is pressed
10. Make sure pitch and yaw are connected to the correct inputs
11. On program make sure it it's the right board and check for bugs

Pre-assemble Turbine:
1. Attach yaw bearing and secure set screw
2. Insert square-drive adapter in tower and secure set screw
3. Feed wires from generator, pitch, and yaw through tower
4. Place yaw motor in slot
5. Attach square-drive adapter to yaw rotor and secure set screw
6. Insert Yaw bearing posts into nacelle L-brackets
7. Couple square-drive adapters
8. Secure nacelle to yaw bearing by clamping L-brackets with nuts on threaded posts
9. Insert pitch arm through front of nacelle, place in slot, and secure with set screw

10. Attach generator to back of nacelle with washers and screws
11. Attach rotor coupler to generator and secure with set screws
12. Insert blades into hub and secure with screws and nuts
13. Pass shaft through nacelle bearing, insert in rotor coupler, and secure with set screws
14. Close nacelle
15. Secure hub swash plate to pitch arm with screw

Feed wires through foundation

Install foundation into box:

1. Attach extensions to drills
2. Attach augers to extensions
3. Insert augers into foundation interface
4. Screw augers into sand to provide a partial-anchor that can still be manipulated
5. Align partially-anchored augers with interface concentric centering tabs
6. Maintain vertical tension though tube to keep augers aligned
7. Slowly and simultaneously install augers such that the interface is flush to the soil surface
8. Remove extensions from augers

Feed wires though Stub

Attach Stub to Foundation

Insert pre-assembled turbine tower into tunnel

Connect wires from tower to stub wires

Stow wire connections in stub

Couple tower & stub flanges and secure bolts

Align nacelle with predominant wind direction

In Situ Testing Results

The prototype turbine performance was measured using the wind tunnel as shown in **Figure 2** and described above. The turbine pitch, yaw, and load were manually controlled during the test, unlike the autonomous operation requirements prescribed by the CWC R&R. Regardless, a reasonable agreement was observed between experimental and analytical data. The solid orange line in **Figure 5** shows the BEM code-generated power curve for the model turbine. The power increases proportionally to the wind speed cubed (Region 2) and is constant beyond the rated wind speed (Region 3). The experimental measurements align closely with the BEM code-generated power curve. The minor differences can likely be attributed to the limitations of the generator, which is a drone motor. This can be clearly observed in the differences between the predicted and the measured rotor speed at higher wind speeds. Further, the pitching schedule for the maximum possible Cp at different wind speeds is shown in **Figure 5** as well. Since the experiments were conducted in Region 2, the operating pitch was held constant at 8 degrees. Furthermore, **Figure 15** below shows the measured Cp versus TSR, compared to the BEM code predictions. The model TSR was around 4.28 for various inflow wind speeds as tabulated in Table 1 shown earlier. The measured Cp ranged from 0.23 to 0.28 for turbine operation in Region 2. This measurement accounted for the 85% generator efficiency. This performance data again demonstrates the agreement between experimental values and BEM Code predicted values.

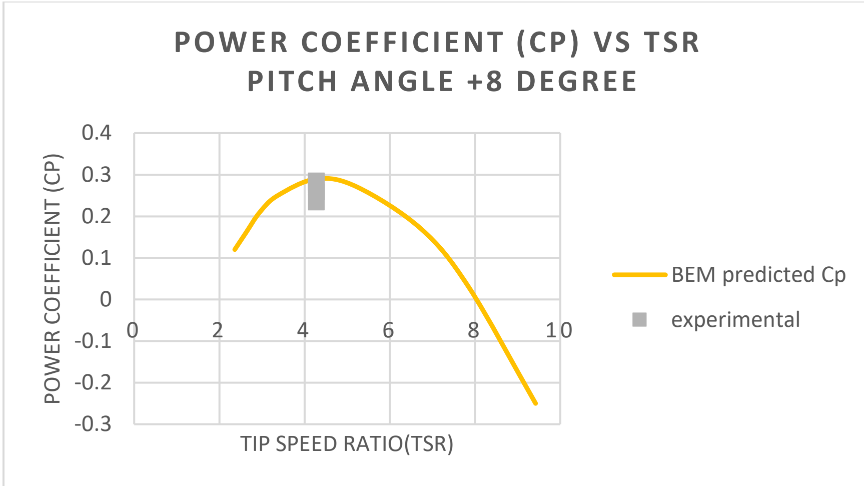

Figure 15: Measured vs. BEM Code predicted C_p vs. TSR.

Conclusion

This year's design took into account the improvement recommendations made by the judges from CWC 2022. The team also addressed areas they knew could be improved, but couldn't implement previously due to factors like time constraints. The foundation was made lighter this year, and the team practiced the installation process to ensure greater consistency. In partnership with South Plains Community College, we tested the blades and explored a wider range of manufacturing processes. The turbine’s controls were developed to include a functioning pitch and yaw system along with emergency stop capabilities. This year's design represents a holistic improvement over last year's.

References:

[1]Hansen, Martin O.L. "Aerodynamics of Wind Turbines", Routledge, ISBN 9781138775077, 113877507X, 2015

[2]Swift, A., "Rotor Aerodynamic Modeling using Blade Element Momentum (BEM) Methods", Texas Tech University, National Wind Institute, Internal Document, 2011

[3]https://www3.nd.edu/~nathaz/journals/(1998)Parametric_study_of_flow_around_rectangular_prisms_using_LES.pdf

[4]https://iopscience.iop.org/article/10.1088/1742-6596/753/9/092013/pdf

[5]https://deepwaterbuoyancy.com/wp-content/uploads/DeepWater-Buoyancy-DSA-Mooring-Matters-Drag-Coefficient-Uncertainty-Image-2.png