Wind Turbine Blade Design Report
12/18/2024
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Executive Summary:

The purpose of this report is to outline design, testing, and analysis of the performance of the blades of a small wind turbine, which were designed for the MAE 4272 class by Group 452-2. The goal is then to select the rotational frequency at which the wind turbine would generate the highest average power given probabilistic wind speed distribution.

The geometric parameters that were varied are airfoil shape, chord length distribution, and pitch angle. The airfoil shape was selected to be MH32: it is a slick airfoil with decently high Cl to Cd ratio in low Reynolds number regime of 50000. Due to lower Cl and Cd values than those of more conventional NACA4412 and Selig 1223 airfoils, the airfoil does not generate as much torque. This is critical to ensure the adherence to the torque limit of the torque brake - one of the design constraints. The slicker shape allowed us to run the wind turbine at a higher rotational rate to generate higher power and compensate for the lower torque therefore satisfying the constraint. The pitch angle was selected to be the one that maximizes the ratio of coefficient of lift to coefficient of drag, since it is the main metric that maximizes torque, and reducing it would only hurt performance. The chord length distribution along the length of the blade was first based on the Betz model, but was later modified to account for the data learned from previous labs: blades with longer chords performed better than the one switch a Betz model chord length distribution, a good example being Blade #3. Therefore, the chord length of our blade was adjusted to match the length of the chord of Blade #3 at about halfway point to the tip. Additional features for improving the blade geometry were also introduced. To simulate the performance of the blade, the MATLAB script provided by the class was utilized. The average power of 2.95W and average coefficient of power of 0.366 were calculated from the simulations of the blade performance.

During the experimental testing stage, the blades were tested at a range of velocities between 2.7m/s and 6m/s at varying rotational frequencies between ~1000 RPM and ~2000 RPM, which were adjusted by increasing the torque applied to the wind turbine. The Cp values mostly lie in the range of 0.5-0.59 in the optimal frequency range, which is a very good indicator. The data was processed to determine the optimal rotational frequency of 1350 RPM with average power of 4.18W across the range of farfield wind velocities. The main issue faced during the experiment was potentially incorrect measurement of farfield wind velocities, which produced theoretically impossible Cp`s of up to 0.69. Therefore, the farfield velocity data at each wind tunnel frequency from previous labs were used to calculate coefficients of power.

Context:
This report covers the design of a small wind turbine blade for Cornell`s MAE 4272 class, Group 452–2.

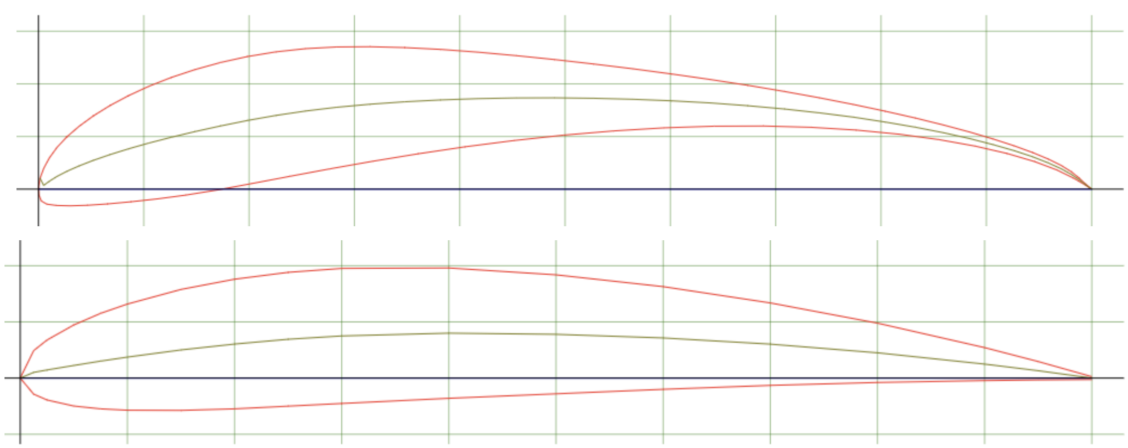
Objective:
The objective of the project is to design a small wind turbine blade that would generate maximum average power given the provided Weibull distribution of wind speeds.

Constraints:

1) Max Length of the blade: 6in/0.154m
2) The blade is to be compatible with a standard hub piece
3) The wind turbine must operate at a fixed rotational frequency Ω that does not exceed 2000 RPM.
4) Torque exerted by B5Z torque-brake must be below 0.034Nm (adjusted during real test to 0.282Nm for the B2)

Design Process:
Hypothesis: A wind turbine blade with airfoil of high Cl/Cd and chord length that is hybrid of Betz Model and constant chord length will generate the highest average power.

The first step of the design process was to determine the key characteristics of the wind turbine and the blade that affect the performance. The initial assumption was that a high coefficient of lift to coefficient of drag ratio (Cl/Cd) will allow the blades to generate optimal torque and therefore maximum power. Therefore, airfoils Selig 1223, NACA 4412, and NACA 0012 were selected as initial candidates (See Figure 1). Their Cl and Cd distributions at different pitch angles were selected for Reynolds number of 50000, which is close to the scale of our experiment - falling within several tens of thousands, depending on the distance from the center of rotation.
The other parameters that directly affect the power output of the wind turbine are rotational frequency, air speed, chord length distribution along the blade, and the pitch angle. The pitch angle was selected to be such that Cl/Cd is maximized. The rotational rate and the wind speeds are the variables through which we iterated in the simulation step. The chord length distribution along the length of the blade (that is chord length as a function of the radius) was initially based on the Betz model, though it was later modified according to the previous lab data.



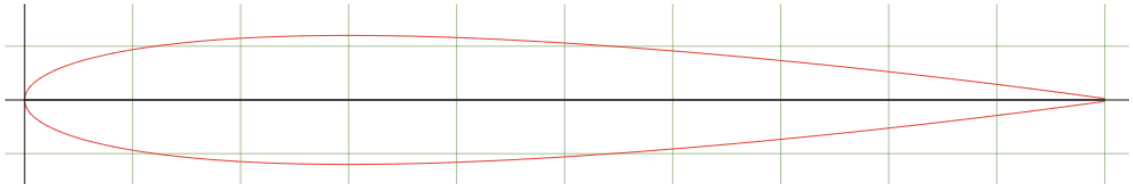


Figure 1: Selig 1223 (top), NACA 4412 (middle), and NACA 0012 (bottom) Airfoil Shapes

To obtain information about the theoretical performance of our blades, we used a MATLAB script provided by the class, which uses XFoil and BEM. We simulated the three blades over a range of wind speeds between 4m/s and 6m/s and a range of rotational frequencies between 1000 RPM and 1500 RPM. When two values with high performance were determined, the points between them were probed to find a peak in the power distribution curve. All blades had their power peak within these ranges, so we know that the performance was optimal.

After analysing the power and torques generated by the blades, we noticed that the torques exceeded the wind turbine brake limit of 0.034Nm. To tackle this issue, we decided that decreasing the torque generated by the blade while increasing the rotational rate of the wind turbine would allow us to satisfy the maximum torque requirement while still generating high power. Therefore, we looked into airfoil shapes with low coefficients of lift and drag. Such an airfoil was MH32 - a slicker airfoil with high Cl/Cd values at Reynolds numbers around 50000, but Cl and Cd values are individually lower than their counterparts like Selig 1223 and NACA4412. Therefore, MH32 was selected as our primary candidate for further simulations.

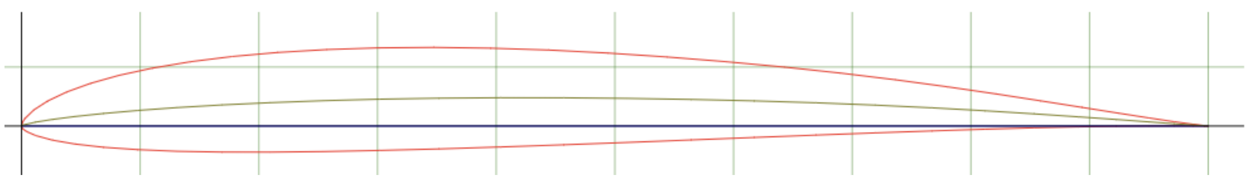


Figure 2: MH32 Airfoil Shape

The simulation approach was the same as previously, and the airfoil showed good performance. However, at that point we determined - with the help of TAs - that the Betz model does not account for the tangential induction factor, α' and is therefore not particularly accurate. We also knew from previous laboratories that Blade #3 - the blade with a constant wide chord - performed exceptionally well. Therefore, we modified that chord length of our blade to be approximately constant halfway through our blade, as in Figure 3. We also cut a bit of chord length at the base of the blade to make sure that the blades fit in the hub and cut the corner of the blade to remove the sharp edge that can generate air vortices and drag. This was done to mimic the airplane wing. The exact shape of the blade is presented in Figure 2. The exact value of the constant chord length was selected to be similar to the chord length of Blade #3.

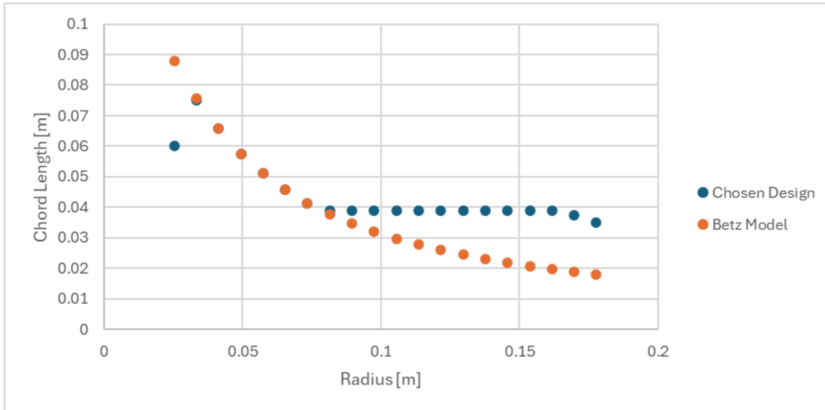


Figure 3: Chord Length Distribution Along the Blade

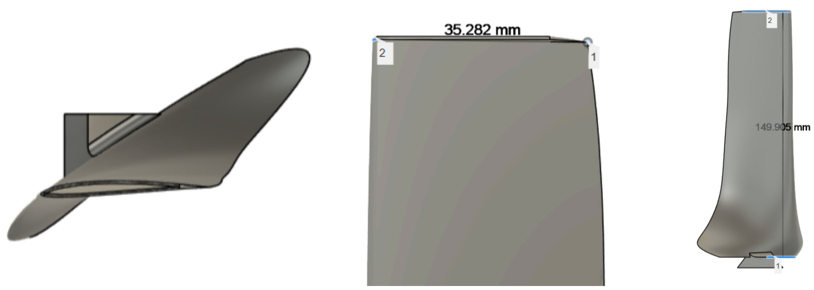


Figure 4: Blade Geometry

With this step done, the final simulation showed a bit worse values for the performance of the blade, but the belief that this approach will work based on previous lab experience made us commit to our decision. The final distribution of power as a function of wind speed is presented in the Figure 5 below, with an average Cp of 0.3663 and average power of 2.95W when operated in the provided wind distribution.

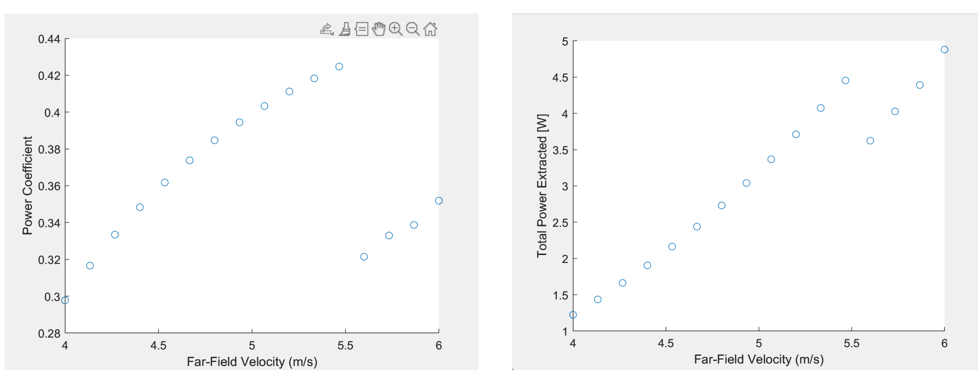


Figure 5: Theoretical Blade Performance

The maximum power at 5m/s wind speed was generated with the following conditions:

P = 3.8 W

ω = 1250 rpm = 131 rad/s

P/ω = 0.029 Nm

Free Stream Velocity: 5 m/s

In order to ensure our blade would not be at risk of failing due to structural constraints, we evaluated the maximum theoretical torque and maximum bending stress that our blade might undertake. For the analysis of the bending stress, we modeled our blade as a cantilever rectangular beam only using the thinnest width in order to ensure we stayed within the constraints.
For our Maximum torque, we used our matlab simulation to predict the following values:
P = 3.8 W | ω = 1250 rpm = 131 rad/s | P/ω = 0.029 Nm | Free Stream Velocity: 5 m/s
From these values, and a cantilever beam approximation, we determined the structural feasibility of our design using the following values and equations. Our expected print material was PLA with the corresponding ultimate strength being 40 MPa.

M = $\frac{2}{3} * 6in(16N/m * \frac{1}{2} * 6in) = 0.12Nm$
Bending Stress at base = $\frac{My}{I} = \frac{0.12Nm * 0.00125m}{\frac{1}{12} * 0.04m * (0.0025m)^3} = 2.88MPa$
which gives a safety factor of ~14 with the ultimate strength of PLA (40Mpa).

The centripetal force for rotating rectangle on average =
$M \cdot \omega^2 / R = \rho \cdot R \cdot c \cdot t \cdot (\omega^2) \cdot (R / 2) \approx 3427 * (\rho = 1240\ kg/m^3) \cdot (0.15 \cdot 40\ mm \cdot 2.5\ mm) \approx 64\ N$
=> tensile stress from centripetal force = 64N/ (c*t) = 0.64 Mpa
Bending Stress at base + tensile stress ~ 3.52MPa

We therefore calculate a maximum theoretical stress of 3.52 MPa, which is well within ultimate tensile strength for PLA. This value gave us a safety factor over 11 which gave us confidence in the structural stability of our blades during testing.

Performance assessment:
Our approach to assessing the performance of the blade involved the following steps:
Experimental Testing:
1. Find far-field velocities as a function of big blue frequency.
2. Test blade over variety of far field velocities (~3.5-5.5m/s) and rotation rates.

During the experiment, the approach was changed a bit to find optimal performance at wind tunnel frequencies between the ones with high performance to determine the peak power and coefficient of power. Example of such is 9.5Hz frequency selected for testing after testing the blades at 9Hz and 10Hz. The exact wind wind tunnel frequencies and corresponding farfield velocities are:

Wind tunnel frequency [Hz]	Farfield velocity [m/s]
7	3.97
7.5	4.28
8	4.59
9	5.215
9.5	5.53
10	5.83

Note: these are not the farfield velocity values that were collected during the first stage of the experimental process, as using those values for data processing resulted in unrealistic coefficients of power (i.e. above 0.593). Therefore, these values will be used instead. More discussion on this topic below.

The wind turbine rotational rate was controlled the following way: the blade started at high rotational rate close to 2000 RPM and relatively low torque such that the rotational rate does not significantly exceed the rotational rate limit and such that the torque brake limit is not exceeded and there is a wide range of torques left to test. After that, the torque was increased up to 0.033Nm and to values that are higher than 0.034Nm until the generated power started falling. This was done with the approval of TAs and understanding that the new torque brake can provide higher torques. This also allowed us to get a more comprehensive picture of the performance of the blade at a wide range of rotational rates at each given wind speed.

Analysis:
To get a comprehensive understanding of the performance of the blade, the following performance indicators were derived from the raw experimental data:

- Power distribution across wind speeds and frequencies
- Coefficient of power distribution across wind speeds and frequencies
- Average and maximum Power and Coefficient of Power
- Range of operating rotational frequencies
- Coefficient of Power vs Non-dimensional velocity
- Adherence to the design constraints, such as torque limit

Data Processing and results:

As presented in Figure 6a, the coefficient of power exceeds the value of 0.593 in more than half data points, which is not realistic as explained by theory behind Betz's limit. Therefore, we decided to use farfield velocity values from previous labs and obtained Figure 6b. In that case, the coefficients of power stay below 0.593 at maximum value of 0.563. For each wind speed, a bell-like curve is clearly visible with the peaks around 1100-1600 RPM with the majority around 1400 RPM. In Figure 7a, the power generated at different frequencies is presented for the same wind speed conditions. The peaks of the curves shift in the direction of increasing rotational frequency and increasing power. This shows that the frequency at which the maximum power is generated increases with the wind speed. Indeed, nondimensionalizing the speed to be the ratio of far field velocity to the speed of the tip of the blade to obtain Figure 6b shows that the maximum coefficient of power for all speed modes lies at about the same non-dimensional speed value with the main difference being that the coefficient of power is slightly higher for some wind speeds than for other.

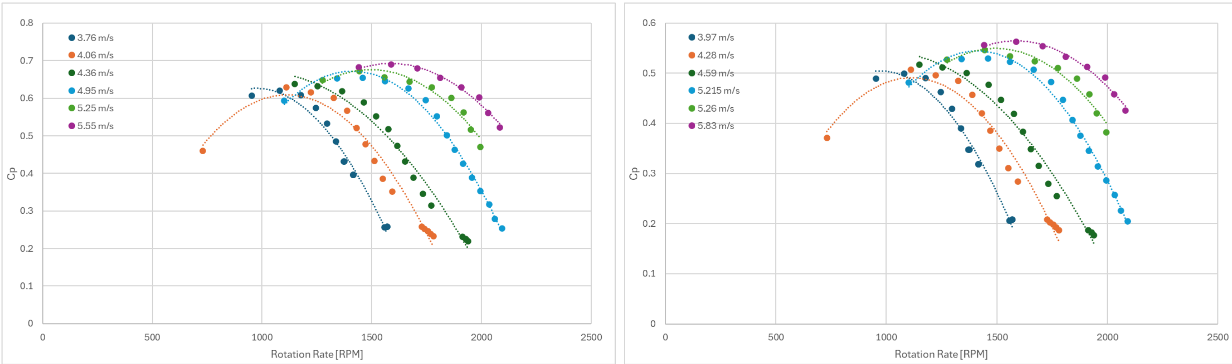


Fig 6 a) Cp vs. Rotation Rate b) Cp vs. Rotation Rate with Adjusted Far-Field Velocities

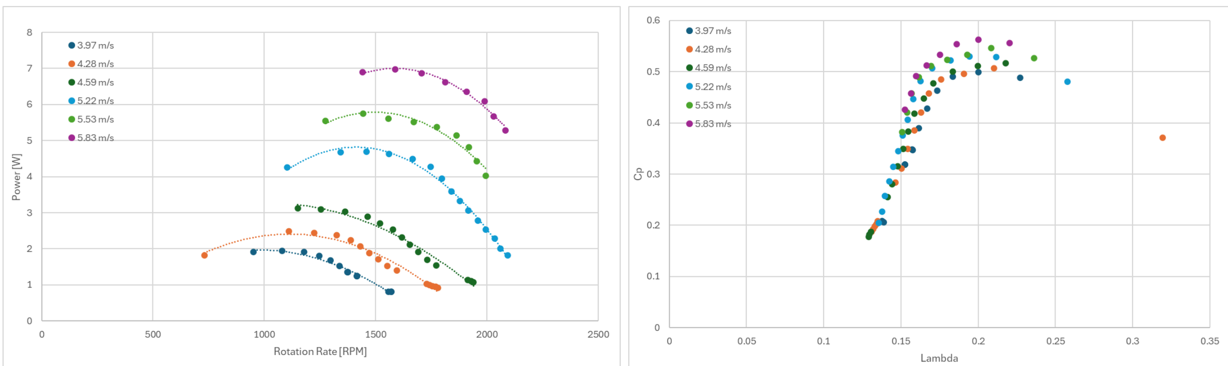


Fig 7 a) Power vs. Rotation Rate at Varying Far-Field Velocities b) Average Power vs. Non-dimensional Velocity

The Figures 8a and 8b below present the average coefficient of power and average power across the range of frequencies that we tested. The blade performed best in the narrow corridor between ~1250RPM and ~1570RPM, because blades could not reach higher frequencies at low wind speeds and were stalling at low frequencies (and high torques) at high wind speeds. The average coefficients of power were calculated using the Weibull probability distribution and probabilities of wind speeds falling within the ranges of each wind speed tested. This resulted in Cp being the highest at frequencies around 1250 RPM and decaying onward. The average power also seems to peak at around 1250 RPM and fall to smaller values at higher frequencies. It is interesting to note that although the Matlab code did not predict the correct Cp values, it did successfully identify the optimal rotation rate for the blade.

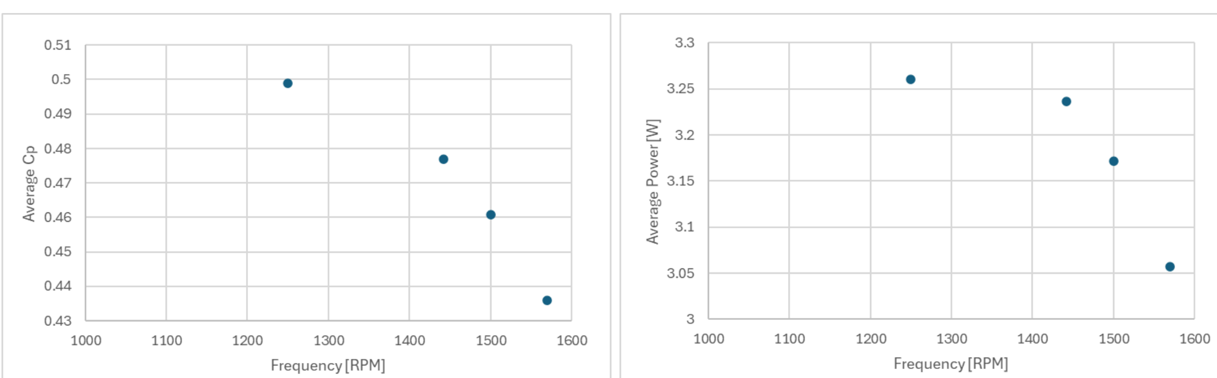


Fig 8 a) Average Cp vs Frequency, b) Average Power vs. Frequency

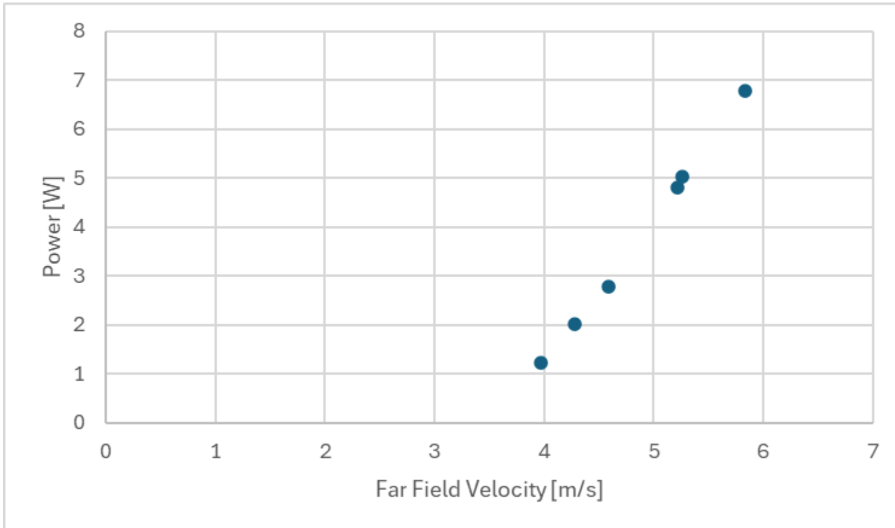


Fig 9 Power vs. Far field velocity

Discussion:

During data processing, we noticed that the calculated power coefficients were often above 0.593, the theoretical limit. The maximum calculated Cp was 0.69. This is certainly not an order of magnitude difference, which made us think that there could be an error related to the calibration of the equipment and values of constants and gain coefficients. We noticed that the farfield velocities from previous labs are consistently higher than the values collected on the day of the experiment, and when using past velocity data, the new coefficients of power are reduced to maximum values approaching 0.563, which makes theoretical sense. We therefore decided to use the velocity data from previous experiments to perform the rest of our analysis.

The blade was designed to have the highest coefficient of power at rotational frequency of 1250 RPM, and this is the case for the experimental data: the peak power is obtained at around 1250 RPM with a value of about 3.27W on average. We noticed that the maximum power (i.e. power peak) might be obtained between 1250 RPM and 1450 RPM based on Figure 8b. Specifically, we went with 1350 RPM. To confirm this, we used our raw data from experimental trials and extrapolated it using best-fit line equations to predict the blade performance at 1350 RPM for each wind speed. After averaging the speeds based on the weights obtained from Weibull distribution, we obtained a predicted average power value of 4.18W. The exact power values for each farfield velocity are presented in Figure 9.

The shapes of the plots obtained from experimental data make significant sense: they are similar to the ones we saw in previous labs in shapes, they lack any sharp peaks or significant groups of outliers, making them sufficiently smooth. It is surprising how the power vs farfield velocity plot (Figure 9) is very linear: the reason for that is the increasing power coefficient at 1350 RPM towards higher wind velocities, as in Figure 6.

There is a significant discrepancy between the MATLAB simulation results and the experimental data. We believe that the difference might be coming from the fact that the wind tunnel is not a true open space, and the walls of the tunnel might have an effect on the performance of the wind turbine.

Overall, it looks like the design decision to increase chord length paid off, as the blade performed particularly well compared to a lot of skinnier blades from the previous labs.

Within our initial design, all of the constraints were met. Closer to the testing date however, we were notified that the new B2 torque break we would be using had a range of 8 times as large as the initial B5Z torque break. Instead of a torque break limit of 0.035Nm, it was extended to 0.28Nm for testing. During the testing of our blade, the max torque experienced was 0.0497Nm which was well within the bounds (F.S. = 5.6).

Our chord length distribution was a hybrid of the Betz model and blade #3 from previous labs. After seeing how well blade #3 performed, we noted that the parameter of blade #3 that was most different from the other blades tested was its thick, consistent chord length. Because of this we decided that we would follow the Betz Model until we hit the chord length from blade #3. From there, we simply kept chord length consistent nearly until the tip. We did not derive a distribution of chord length from theory from this, but rather we essentially just copy and pasted from Blade #3. If we were to move toward a second iteration, we would simulate and iterate with many potential chord length distributions and create a parametric equation for the chord length distribution that is most optimal for Power Output. For this, it would be very helpful to have all other lab groups data from their performance. This could help us find what worked for others and potentially come up with other ideas to change our blade design.

One of the difficulties we faced was related to determining the optimal distribution of chord lengths along the blade. The Betz model does not account for wake and drag and assumes that the angular induction factor is zero. Therefore, the Matlab simulations should overestimate the performance of a Betz blade. However, the Matlab model results also indicate that the Betz blade is the best performing blade and thus the MATLAB model underestimates the performance of our blade. Therefore, the optimal chord length is different from the blade geometry calculated in the Matlab simulation and had to be accounted for. This was confirmed by the performance of our blade.

Conclusion:

Our blade design performed particularly well at high velocities bringing in high coefficients of power, which allowed us to obtain high average power. The optimal rotational frequency was determined to be close to the design rotational frequency, which confirms the quality of design, and the idea to mimic geometry of well-performing blade #3 for the reasons of tangential induction. The blade generated an average power of 4.18W across the probabilistic distribution of wind speeds at a rotational frequency of 1350RPM. The group dynamics was good throughout the project with timely communication over Slack and good organization to complete each stage of the project on time.