Section 407, Group 3 12/10

MAE 4272 Final Report

Summary:

Wind turbine blades are designed to extract maximum power at a certain RPM and wind speed; however, structural limitations also need to be considered since a flow will exert a certain force on the blades. We designed blades that were optimized to extract maximum power in a flow with a velocity of about 4.8 m/s, and we also expected it to withstand the forces that the flow exerts on it during that operating condition. We had some constraints to deal with during the design of the blades in order to be able to properly test them; namely, the blade length had to be less than 6 inches, we needed to design for an RPM less than 2000 to avoid material failure in the blade, and flow velocities could only go up to 15 m/s (in the wind tunnel). The design process of the blades included using data on our chosen airfoil cross section (the NACA 4412) from airfoils.com to calculate how variations in the chord and pitch of the airfoil as a function of the blade length could optimize lift and reduce drag. We also wanted to maintain the structural integrity of the blade so we ran calculations to ensure that the flexural strength of the blade material would not be exceeded in the operating conditions we wanted to test in.

In order to test our blades, we placed blades that we designed into a wind tunnel to find the RPM and flow speed that the blades actually extracted the most power from, and we also wanted to verify that the blades were structurally sound at that flow speed and RPM. To do this, we set the fan frequency to about 7 Hz and then measured the power output as we increased the resistance torque slowly until the RPM of the blades was 0. We repeated this for flows at 6 Hz, 8 Hz, and 9Hz so that we could compare all of our data to see which combination of flow speed and RPM had the greatest power output all while carefully watching the blades to make sure that the material was not failing. We made sure that the RPM did not surpass 2000, which is when we expected failure.

After testing, our results showed that our blades actually extracted more power in higher wind velocities than expected. We had the highest power output when we set the wind tunnel fan frequency to 9 Hz and when the blades were rotating at about 1700 RPM, but we had expected those values to be about 7 Hz and 1900 RPM. We think that this may be because when we were plotting theoretical power curves, we found that peak power output in a flow at 4.8 m/s would occur for our blades somewhere over 2000 RPM, but we didn't want to exceed that value in order to avoid increasing stress in the blades, so we just chose 1900 RPM as the value to optimize our blades for.

Context, Objectives, and Constraints:

The objective of this design project is to design a small-scale wind turbine which can operate in Upson 256 Big Blue wind tunnel and perform with a decent power output.

The constraints of this design include:

- a maximum length of blade of 6 inches,
- blade compatible with standard hub piece of 1 in in radius,
- wind turbine operating at a fixed angular velocity under 2000 rpm,
- Wind in the environment follows a velocity distribution described by a Weibull probability distribution with parameters k=5 and c=5.

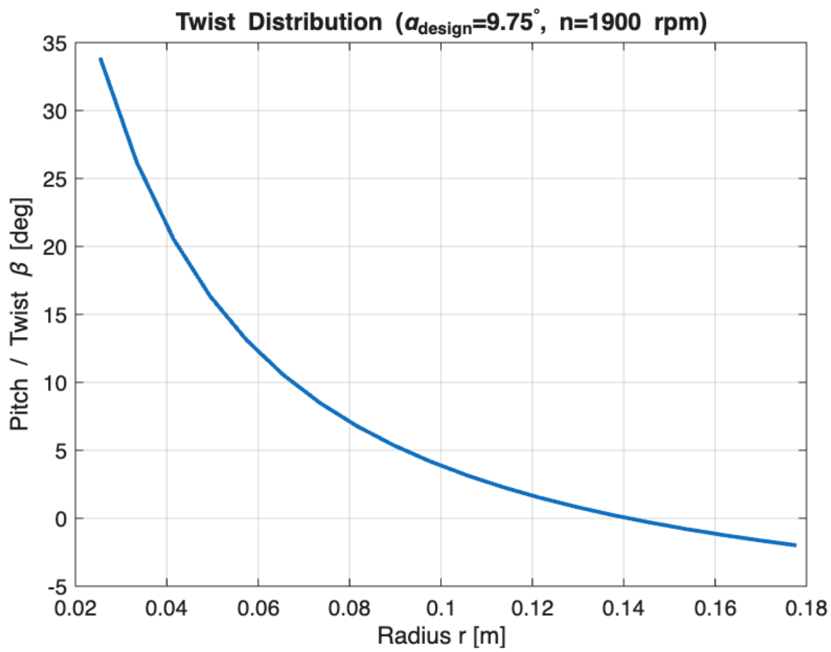
Design Process:

We started by trying to get a representative wind velocity for which we should optimize our blade design. To do this we utilized the equation of total power as the integral of the power at a given velocity multiplied by the probability distribution of wind speeds. The power at a specific wind velocity, P(U), can be written as $P(U) = 1/2 * \rho ACpU^3$. Since air density, rotor area, and power coefficient are constant for a specific turbine geometry, we simplified the equation to be $P(U) = kU^3$, where k combines all constants into one term. We plugged that back into the integral and integrated the expression from 0 m/s to 15 m/s The upper boundary of 15 m/s is determined by a limitation of 25 Hz for fan frequency that was set in previous labs. Doing the integration gave a total power expression of $P_{total} = k * 111.69$. We also know that total power can be written as $P_{total} = 1/2\, \rho AC_p U_{total}^3$ which is also equal to kU_{total}^3. Since both share the same constant k, we set the two equal to solve for the representative velocity corresponding to total power, which ended up being $U_{total} = 4.82\, m/s$

We then used this velocity to do the rest of the design optimization of our turbine. Using it, we calculated a Reynolds number based on the average chord length of 50 mm which came from one of the example turbine blades in the lab and the air viscosity at the room temperature in the lab. The Reynolds number we got was about 16,000.

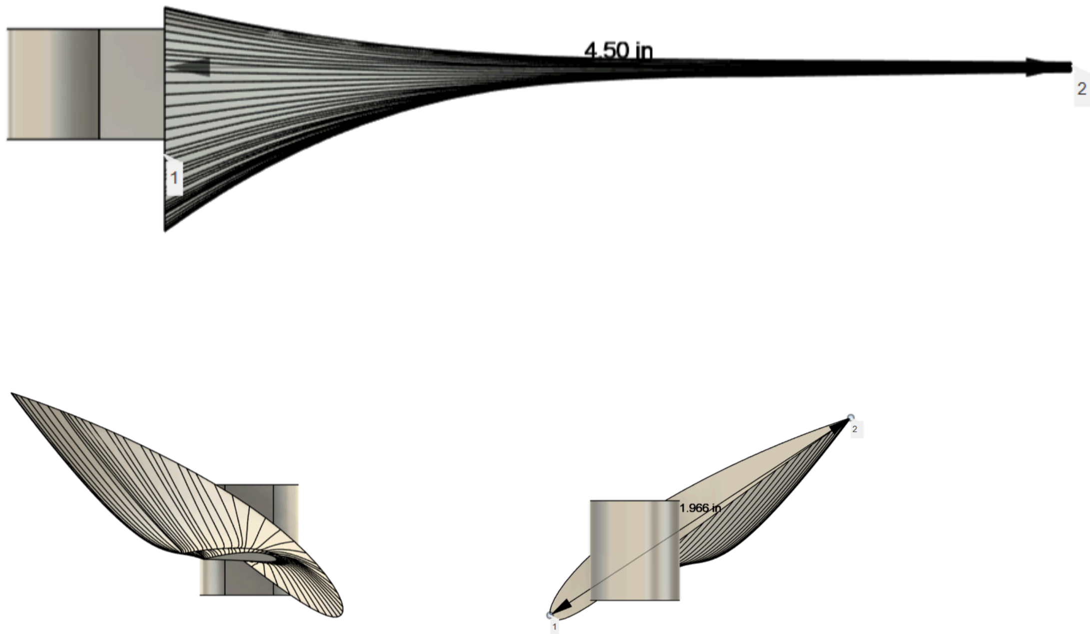
From there, we chose the NACA 4412 to be the airfoil for our blade by looking at the power curves from lecture 13, and seeing that this airfoil had the highest power output at the conditions we were designing for. Using this airfoil and our Reynolds number, we got lift and drag data for different angles of attack from airfoiltools.com and used that to determine the angle of attack that maximizes CL/CD. The *airfoiltools* website only had data for Reynolds numbers beginning at 50,000, so we assumed that the data would be similar to our Reynolds number, and we recognize this difference in Reynolds number may cause discrepancy.

Using the angle of attack, which we found to be 9.75 degrees, we solved for the pitch at all the points along the length of the blade since $\theta = tan^{-1}\left(\frac{U}{\Omega r}\right) - \alpha$



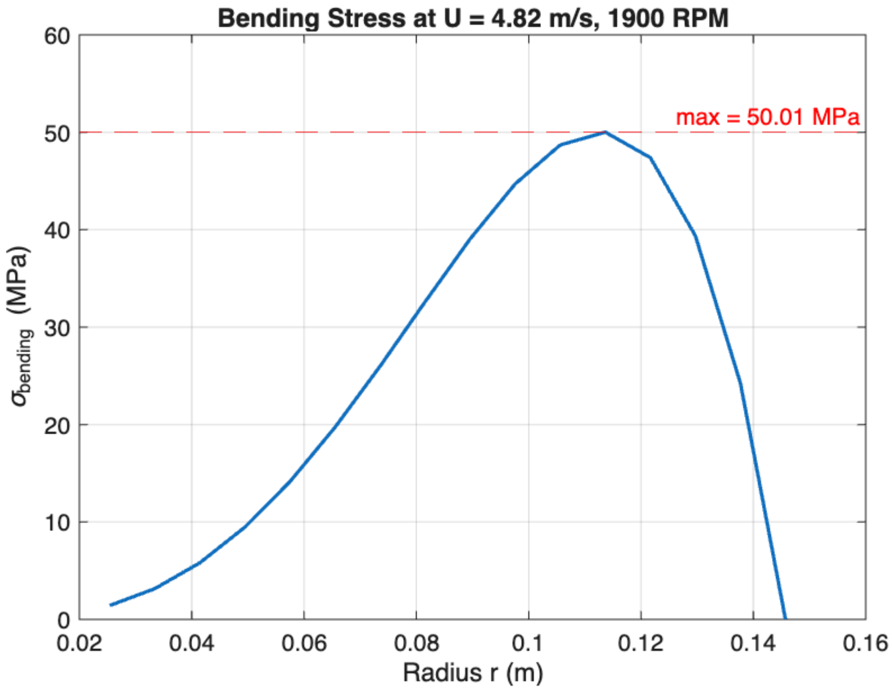
(Figure 1: Blade Pitch Distribution)

Once we had the pitch distribution we worked on getting a chord distribution by testing various taper ratios. We were constrained by the requirement to have a maximum chord length of 2 inches at the hub, so we started with the length and tapered the chord until we found a distribution that gave us the highest power output, which resulted in a taper ratio of 0.142.



(Figure 2: Blade CAD)

Once we had the geometry of the blade, we found the maximum torque on the blades while operating at our design conditions of 4.82 m/s wind speed and rotation rate of 1900 rpm, and found that it did not exceed the rated torque of 3.5 N-cm of the torque brake. We also calculated the bending stress along the length of the blade at the same conditions and found where along the blade there is the maximum bending stress. Initially, we calculated the maximum stress to be over 110 MPa, which exceeds the maximum flexural stress of the material. In order to bring the maximum bending stress down, we decreased the blade length from 6 inches long to 4.5 inches. After decreasing the length, we found the maximum stress to be around 50 MPa about halfway through the span, which is below the flexural strength of Accura25, making our blade safe to test.



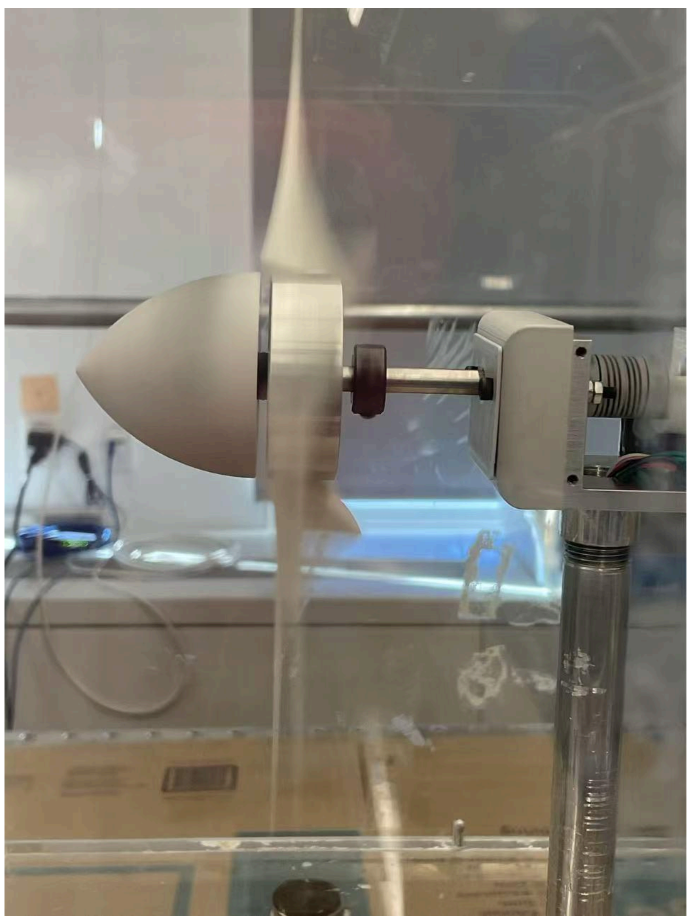
(Figure 3: Bending Stress Along Blade)

Experimental Procedure:

The experiment will be conducted below the structural limits and brake limits (blade rpm <= 2000 and the brake torque <= 3.5N*cm). Below is the procedure we followed and some reasoning behind what we did.

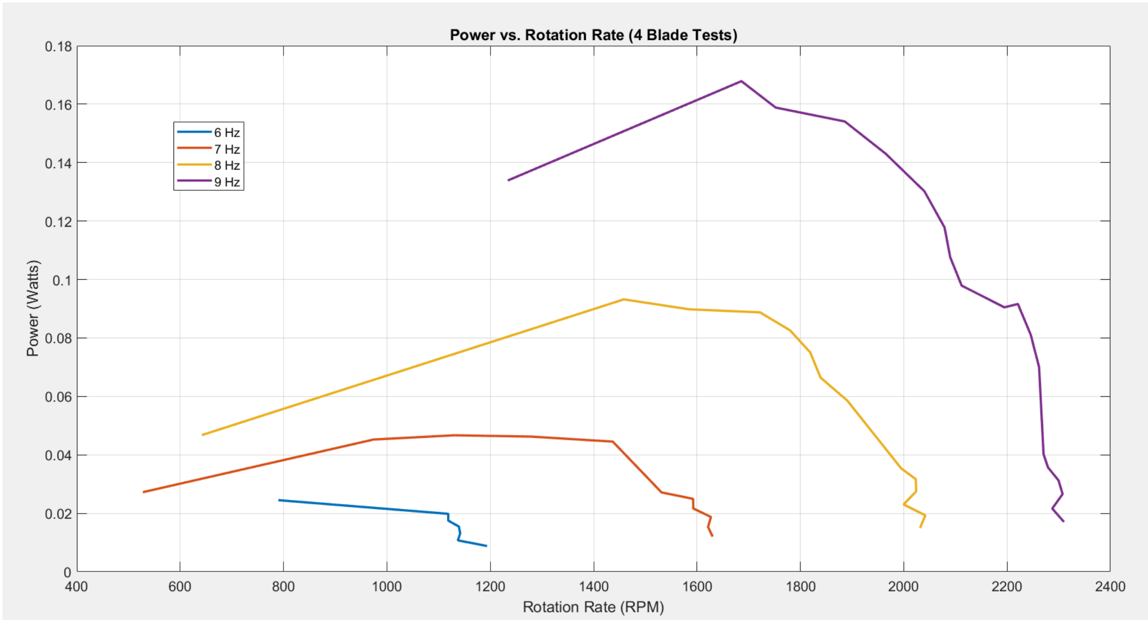
1. Install the designed wind blades to the hub. The ambient temperature and air density will be recorded.
2. Based on the fan rotational rate v.s. flow speed^2 graph we generated from lab 2, we would set the wind tunnel fan at a rotational rate of 7.3 Hz to simulate the wind speed of 4.82m/s. If the designed blade is spinning this time, it means that the primary goal of design is successful.
3. Then we raise the brake voltage gradually (starting with no brake torque) in the VI by small segments until the wind blades stop spinning. Meanwhile, we will have members watch the blade spinning for excess vibration or overspeed. We will immediately lower the fan rotational speed or raise the brake voltage if the RPM reaches 2000.
4. We will export the data sheet from VI which includes rotation rate, brake voltage, and torque applied.
5. We plot the power curve from exported CSV and testify if the rpm corresponding to max power matches with the rpm we found from optimization.

6. Reset the brake voltage and repeat the step 3-5 to verify the data repeatability and get the averaged rpm from multiple trials.
7. Evaluate blades' performance and investigate its relationship with assumptions we made: constant lift force along the cordline.
8. We can also repeat steps 2-6 for different wind speeds. This can help us determine whether the wind speed of 4.82 m/s is actually optimized. We should perform this test for at least one wind speed smaller and one wind speed larger than 4.82 m/s to ensure that we chose an optimal wind speed; if the power curves produced by those trials hit smaller maximums than the 4.82 m/s trial then we know we calculated an optimal wind speed. We could choose an RPM that would put our windspeed in the 3.5 to 4 m/s range, and then for the higher bound we could test at an RPM that puts the speed at the 5.5 m/s to 6 m/s range. This doesn't have to be exact, we just need to know that the wind speed is slightly higher and slightly lower than our calculated optimal one.



(Figure 4: Wind blades during experiment)

Results and Analysis:



(Figure 5: Experimental Power Curves)

The experimental results in the figure above show that the wind turbine's power output increases steadily with rotation rate until reaching a peak, where it would then decline quickly due to stalling. The highest measured power was approximately 0.17W at a flow speed of 9Hz, which is more than double of our predicted peak power output of 0.08W at 7.4Hz. This is most likely because our initial RPM wasn't chosen at a peak since our initial power curve calculations showed us a graph that increased past 2000 RPM, which exceeds structural limitations.

We also thought that more stalling would occur at higher wind velocities, but since the turbine kept extracting power and maintained strong performance, this meant we experienced stalling much later than our initial predictions. We believe that this happened because the actual operating Reynolds number was lower than the value that we used during design. On airfoil tools, the only options were 50,000 and 100,000 for our chosen airfoil, both of which were higher than our calculated value of 16,000. Therefore, the optimal wind velocity may compromise from our choice of higher Reynolds number.

Overall, our blade design met all of our constraints that were established at the beginning of the project. We had a maximum RPM of 1700, which is under 2000 RPM. There was also a maximum wind speed of 5.23 m/s, which is well under the maximum constraint of 15 m/s. Our blade had a length of 4.5 inches, which was under the 6 inch length constraint.

We achieved all of our initial objectives, as the aerodynamic performance of our blade design exceeded initial expectations by generating more power than initially calculated, even though it was at a different wind speed. During testing, our blade also remained structurally sound the entire time, without any excess vibrations, which was one of our initial goals. Since the blade remained intact, this means the blade never experienced a stress higher than our calculated flexural stress of 50 MPa.

Looking back, we would have changed a few things that we did during the design process in order to be more accurate with how we optimized our blades. For example, we made a lot of assumptions, which is likely what led to our results being different from what we expected or calculated. One of the biggest assumptions we made was that it was okay to use the NACA 4412 airfoil data for a larger Reynolds number than what we had calculated our blade to be operating under since airfoiltools.com only had data for Re = 50,000 or Re = 100,000. If we had optimized our chord to reach a set Reynolds number instead of vice versa (which is what some other groups talked about doing during their presentations), we would not have had to make such an approximation. Additionally, we would have liked to be able to take more trials for each flow speed in the wind tunnel in order to verify the accuracy of our data with larger sample sizes. Looking at the experimental results, we also could have designed for a higher power output, since we saw that some groups got around 10x more power from their blades.

Conclusion:

Other than the things we wanted to change, we think that this project went well. We were able to find a peak power output at a fan frequency of 9Hz, and the RPM that the power output was maximized at (1900 RPM) was pretty close to our experimental value of ~1700 RPM. We also verified that our blade was structurally sound enough to withstand the operating conditions it was designed for, which was something that we tried to be really careful about accounting for. As for our group dynamic, we think that things went pretty well. Communication worked out well; we would set aside specific times to get work done, such as when we would work on progress reports, the final presentation, or when we were free to actually go into the lab for CAD work sessions or blade testing. Finally, we made sure to split work evenly across each section of this design project, from the design phase to this final report.