Compact Wind Turbine Blade Design and Testing

Curtis C. Miller[1] and Saakib A. Chowdhury[2]
The University of North Carolina at Charlotte, Charlotte, NC, 28223, United States

The task presented to the UNC Charlotte Collegiate Wind Competition (CWC) team was to build a small-scale floating wind turbine that could withstand winds up to 13m/s. Given this directive and a set limit of 45 cm cubed box to fit the nacelle and blades, the blade designers had to get creative with their designs and testing. The prototype blades were designed in an open-source software, Qblade, and were 3D printed using Elegoo PLA. To advance to the next round of the competition, the team focused heavily on performing both structural and aerodynamic testing. Through various methods such as rooftop car aerodynamic testing and fatigue RPM tests the team has narrowed down blade profiles that will be optimized moving towards the end of the competition. This paper will provide an overview of the research, design, and testing of UNC Charlotte's CWC prototype blades.

I. Introduction

Renewable energy is a growing and prolific sector of America's energy grid, with wind energy maintaining a key role. Wind turbine electricity generation produces 10.2% of the United States energy according to the U.S. Energy Information Administration [1]. The Department of Energy (DOE) and the National Renewable Energy Laboratory (NREL) wanted to help further the development of college students around the nation in this quarter of energy production. Through this the CWC was created with the goal of advancing careers, knowledge, and excitement for the renewable energy sector. UNC Charlotte was accepted to be part of this competition and a small senior design team of two mechanical engineers, two mechanical engineering technologists, and a computer engineer were designated to participate in the contest.

With the limited manpower, a mechanical engineer and mechanical engineering technologist took on the role of researching, designing, and testing the blades for the small-scale wind turbine. Rule requirements which limited the blade size coerced the designers to get creative in every step of the process [2]. This paper will follow the route the blade designers took and give the audience some perspective in the design choices made as well as walk through the testing methodology. Plans for future optimization of the prototype blades will also be outlined.

II. Research

This year's CWC team is only the third iteration of UNC Charlotte's attempt at this competition. As such the team had limited information to reference when starting the long design process. The main knowledge from the previous team was their airfoil research, which they had extensive details on but ended up being utilized incorrectly. A preliminary goal of the blade designers was to create an effective blade design that could be optimized in the 6-8m/s range, as that was the heaviest weighted category to be judged in the power curve performance task.

The first steps taken were using a blade design process delineated by the paper, *Wind Turbine Blade Analysis using the Blade Element Momentum Method* [3]. Through a series of calculations with TSR and RPM equations used from *Renewable and Efficient Electric Power Systems* [4] as well as the TSR selection table in Grant Ingram's report the

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[1] UNC Charlotte Undergraduate Student, Mechanical Engineering Technology, University Student Member.

[2] UNC Charlotte Undergraduate Student, Mechanical Engineering, University Student Member.

team selected a Tip Speed Ratio (TSR) of 3 because at low wind speeds this would produce the most amount of torque. With a small number of known variables such as TSR, expected wind velocity, number of blades, and a theoretical turbine efficiency of 40% due to the industry standard, the designers were able to select a few promising airfoils that would suit the turbine's needs. This information gave the team both a coefficient of power curve and a coefficient of drag curve to look for when optimizing blade profiles.

The next step in the team's research was material selection and production methods for small scale blades. The materials available to the team were either resin or polylactic acid (PLA). The team had considered using resin since it would produce the best-looking blade, which would not have print lines and visible layers like PLA, but resin had its own sets of challenges. The team had access to a resin printer through one of the engineers, but the prints would take much longer and had a post-printing process that was not the case with other forms of printing, such as PLA. Resin would also prove to provide a heavier blade than PLA, which was not ideal since it did not improve its strength in combating heavier weights. PLA printing proved to be the optimal choice for the team for both material properties and production speed. The production method was chosen to be 3D printed using Elegoo PLA inside a P1S Bambu Labs printer.

The last step for the designer's research was coordinating the blade design with the selected turbine motor to produce the most power at 5-8m/s wind speeds. This proved challenging as the previous year's team selected a geared BLDC motor that required a large amount of torque input to generate power. However, with the computer engineer's research, the team used a brushless drone motor, which lowered the input torque requirements significantly. This allowed the design team to create blades with a smaller swept area and gave a greater scope regarding chord length selection.

III. Design

The wind turbine blades were designed through Qblade; the software was chosen because of its ease of use and the amount of data it provides throughout designing blades and airfoils. There were many distinct aspects to take into account whilst designing the blades, with the main one being the size constraints of the CWC competition guidelines. The wind turbine must be able to fit within a 45 by 45 by 45-centimeter box, which limits the length of the blades. The previous year's competition team had done extensive research for the blades but lacked physical testing. With that taken into account, there was a sizable amount of focus on testing for blade design this year. The previous year's team had various airfoils within the blade, but as a result of the blade being limited in length, the 3D printer was not able to correctly generate all the different airfoils, and it turned out to be one large NACA 2414 airfoil. Considering there was already a great deal of research done by the team on the 2414 airfoil, the team decided to include the airfoil for testing purposes alongside other blades, such as the NACA 0013 airfoil and a custom foil developed by the blade team through Qblade with the specifications determined by Qblade. Qblade, in return, generated graphs and established the optimum drag coefficient.

The blade configuration was another problem that needed to be solved through research and testing. The two-blade configuration was considered as well as the three-blade configuration. The two-blade configuration seemed to perform well, but research showed that it tended to produce a lot of vibration and noise within the blade, which was not favorable for the structural integrity of the blade. The three-blade configuration is by far the most widely used configuration for commercial use since it is the most balanced and provides a steady torque output compared to two-bladed wind turbines.

As mentioned before, the wind turbine must be able to fit within a 45 by 45 by 45-centimeter cube, so the blades can only have a 21cm length from the middle of the pitch system to the tip of the blade to account for human error whilst placing the wind turbine within the testing cube. Since the length of the blade is only 21 cm, including the root of the blade, the team had to make sure that the blade still had a sizeable amount of swept area to still be able to generate as much power as possible given the area of the blade and the amount of wind energy available and at any of the given speeds.

Two different shapes of blades were created to evaluate which blade produced the most power at the desired wind speeds. Fig. 1 and Fig. 2 pictured below, along with their respective Power vs TSR and Cp vs TSR graphs. Both blades were built to be optimized at a TSR of 3, which was done through a function in Qblade. With the data provided through these graphs, it is apparent that the constant chord length blade produces more power, but it also suffers from a drastic decrease in power through higher tip speed ratios, whilst the blade that was created through Qblade by the blade design team member had a more gradual decline in power even though it produced slightly less power.

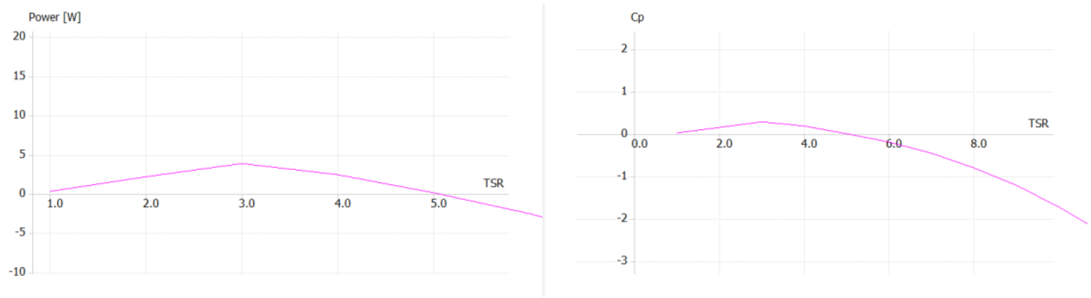

Fig. 1 NACA 2414 Power vs TSR and Cp vs TSR Qblade Data

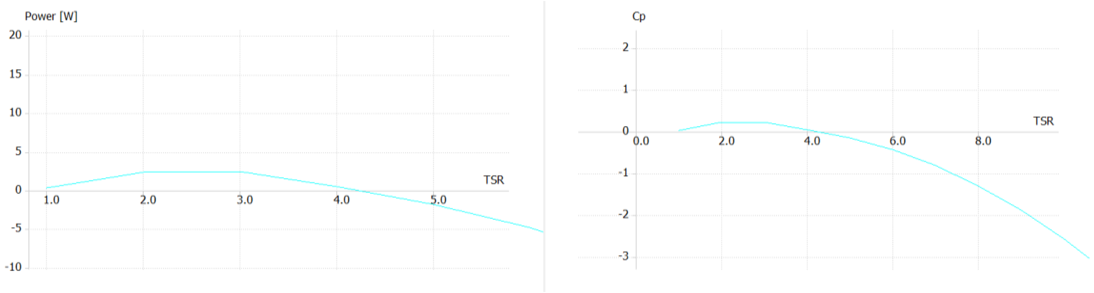

Fig. 2 NACA 0013 Power vs TSR and Cp vs TSR Qblade Data

With those parameters considered, physical testing had to be done to gather more data and decide on which blades would be used. In order to also test out different airfoils with the different blade configurations, both of these blades were printed in 2 sets, one set with 2414 airfoil and the other with 0013 airfoil, as shown in Fig. 3 and Fig. 4. One of the reasons why the blade was not chosen based on research alone was because of the information that was provided in the graphs and how similarly these two blades performed within the given parameters.

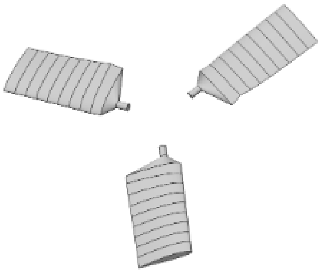

Fig. 3 NACA 2414 Airfoil Model

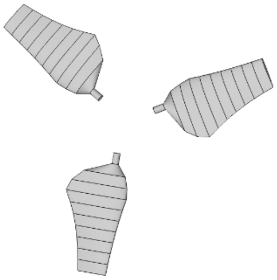

Fig. 4 NACA 0013 Airfoil Model

IV. Testing

With preliminary blade designs created, a principal aspect of the 2nd phase of the CWC competition was physical testing of teams' design work. Because of this the team started structural testing on the prototype blades quickly. The team decided to approach the structural testing as if it were empirical evidence. Various root infill percentages were tested to determine the optimal 3D printing method moving forward. RPM and bending structural tests were performed on the prototype blades to confirm if they would perform under the specified wind loads. Fatigue tests proved that the blades could perform up to 1700 RPM which was the expected maximum RPM at 13 m/s. This test was accomplished through the reuse of a previous team's BLDC motor and a simple Arduino circuit created by the team's electrical engineer. The team had to machine a Delrin adapter to house the 3D-printed blades first. The final piece of RPM test was the pitching mechanism taken from a KidWind wind turbine set. This allowed the team to clamp the blades securely in a timely manner with no extensive machining needed. The bending tests, shown in Fig. 5, demonstrated that the 85% root infill blade can withstand the most force, at 12.2 Newtons, while deflecting the least, at 5.5 degrees.

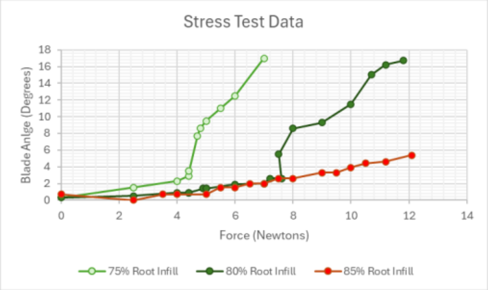

Fig. 5 Structural Testing Data

With these preliminary tests it proved the team's prototype blades could withstand the forces needed to create the most amount of power at various wind speeds. Assessing the blades' aerodynamic properties was slightly more time-consuming and required the use of Qblade. Aerodynamic testing was performed by fabricating a tower mounted turbine sitting on the rooftop of a car. The rooftop mounted turbine allowed for the team to have an environment with a semi-consistent airflow to test which blade profile created the greatest power within competition wind specifications. There are complications with the rooftop turbine testing setup, however.

As a result of it not being a controlled environment such as a wind tunnel, there were wind gusts that altered the team's aerodynamic testing data. Even with a pitot tube reading out the wind speeds the variation of the data can sometimes be problematic. As shown in Fig. 6, where the maximum power generated is above 60 W at 9 m/s, breaking the Betz limit. Even with the occasional aerodynamic testing run influenced by outside factors, the test was a resounding success. The next step was to improve the results through optimizing the blade pitch angle.

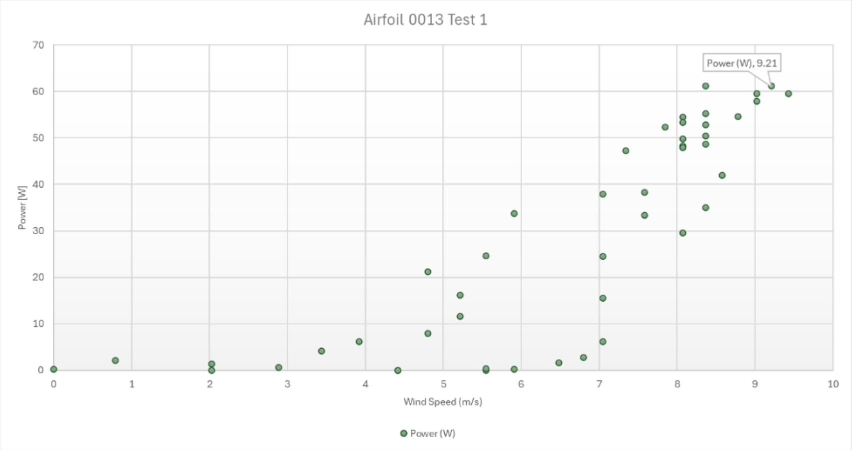

Fig. 6 Airfoil 0013 Test 1 Power Curve

The turbine’s motor was a low cogging torque drone motor, which had minimal power losses. This motor combined with the pitch system as previously stated permitted the team to evaluate various airfoils at the optimal pitch angles as found through the Qblade software. The team tested three different airfoils that being the NACA 2414, 0013, and a custom blade designed through Qblade. A blade with a constant chord length was also tested to see if maximizing swept area would result in the most power generation.

Utilizing Qblade, the optimal pitch for these blades to be rotated varies depending on the wind speed; however, at the maximum wind speed at which power generation will occur, 11 m/s, the pitch angle is 10 degrees. This pitch angle was determined through Qblade to maintain a consistent TSR during aerodynamic testing. The blades are mounted to the pitch system by using heat-set inserts in the root of the blade and using M3 bolts to go through the root of the blade. This pitch system is connected to the motor through a machined motor mount that is threaded. The shaft that holds the pitch system is a threaded M6 rod which both acts as a connector to the mount and a simplified way to hold the pitch system at a certain degree of pitch.

V. Results

Structural and Aerodynamic testing ended up being a success with both forms of testing giving the team invaluable information for the future. Structural testing demonstrated that the prototype blades could withstand the forces of the wind and extended periods of time at high RPM’s. Aerodynamic testing helped further the team's electrical design goals as well as proved the design benefited the team. Treating both the structural and aerodynamic tests as if they were empirical tests enabled the team to better grasp the information gained. These tests also better enabled the team to move forward with certain designs. For example, figure – provided the team with the statistics to justify moving forward with the 85% infill root percentage. The constant chord length aerodynamic tests granted promising results but showed that the blade could not withstand the increased stress on the blade root. The custom airfoil mixed with NACA 2414, as shown in Fig. 7, realistically shows the best result of 24.7 W at 7.75 m/s. With a percentage of error of about 20% considering small inaccuracies in both the pitot tube and power curve generation code, this result is the closest to the calculated power in the wind according to the equation.

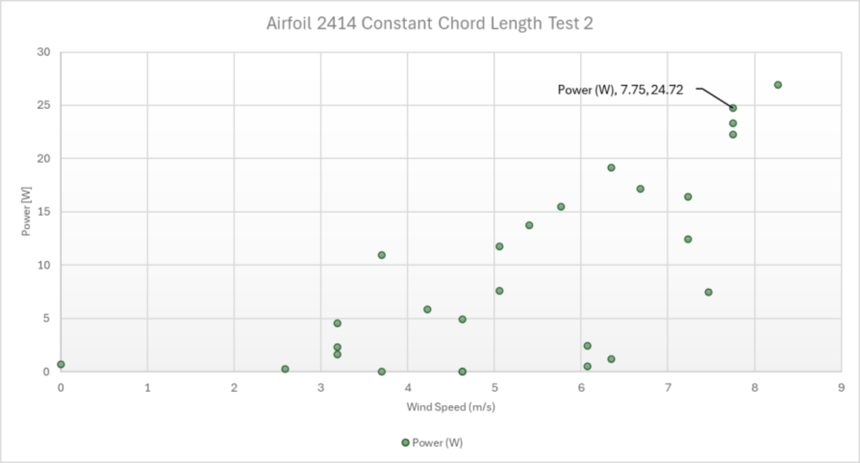

Fig. 7 2414 Constant Chord Length Test 2 Power Curve

VI. Conclusion

Through the analysis of the research, design, and testing discussed it proved the design of the UNC Charlotte's CWC blades is suitable for optimization. With design size requirements being limited to 45x45x45 cube the team was able to maximize power generation to the highest weighted category for the power curve generation competition section. Comprehensive structural analysis and aerodynamic tests were conducted through scientific methodologies to prove the designs' worth. Environmental factors which added variability to the testing methodologies did not limit the team yet provided a firm foundation for future improvement. UNC Charlotte’s CWC team will continue to optimize these blade profiles and gain more information through hands-on engineering experience thus meeting the Collegiate Wind Competitions original objectives.

Acknowledgments

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