Design and Development of Wind Turbine Blades using Additive Manufacturing of Continuous Fiber Reinforced Polymer Composite

IUPUC OFFICE OF STUDENT RESEARCH

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Introduction

This research project involved developing and testing wind turbine blades, manufactured using continuous fiber reinforced (CFR) polymer composite. A primary goal in the development was to reduce the blade weight, while maintaining comparable strength to conventional turbine blade materials.

The most common type of wind turbine in use today is a horizontal axis wind turbine and the blades are made using a lamination of fiberglass sheets, balsa wood, and resin. Turbine blades can weigh more than 10 tons and that can add up to a total turbine weight of more than 36 tons [2]. Due to the large mass, the process of starting a wind turbine is an inefficiency in power generation. Power must be used to start the turbines rotation and energy from wind must be used to accelerate the rotation to usable speed before electricity can be generated.

To increase the efficiency of a wind turbine, the starting process needs to use less energy. One way to increase efficiency is to decreases the mass of the turbine blades. To do this, the blades could be constructed using additive manufacturing of CFR polymer composite. Using continuous fiber allows the material to be printed with optimal fiber design and layout which saves weight while maintaining strength.

Methodology

The first step of the project was to design and then model a wind turbine blade in ANSYS CAD modeling software. The blade design included determining the airfoils to be used along the length of the blade and the blade dimensions. The root, mid span, and tip of the blade all have different airfoils to optimize lift at each section. Additionally, the angle of attack of each airfoil or twist along the length of the blade was calculated for each section.

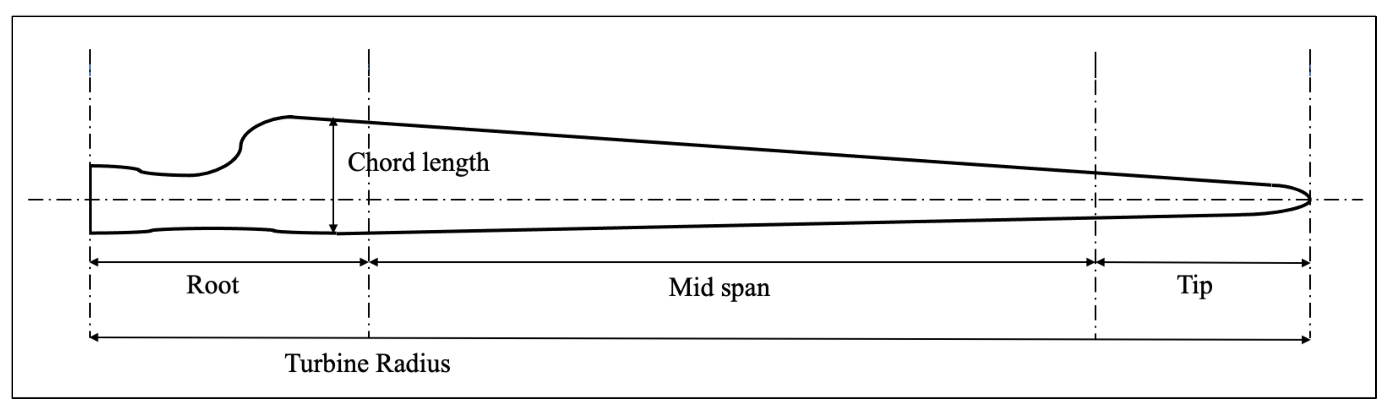


Figure 1. Wind Turbine Blade Sections

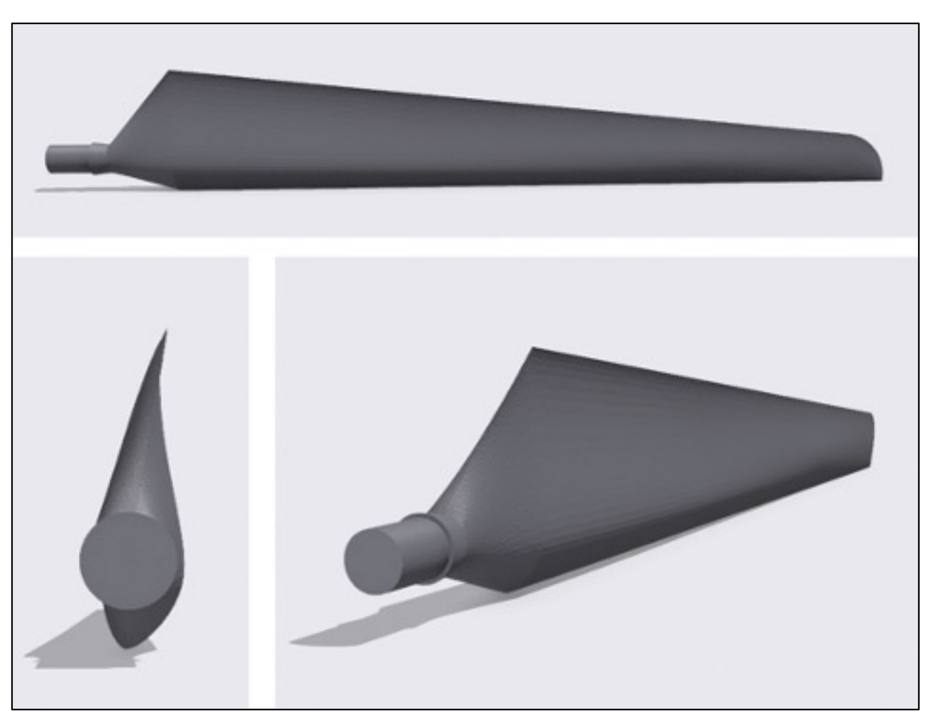


Figure 2. Turbine Blade CAD Model

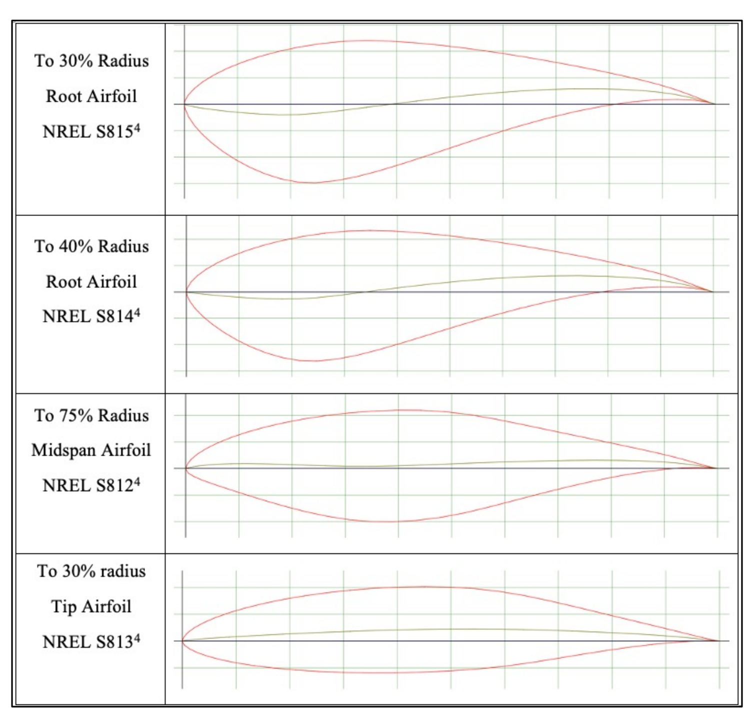


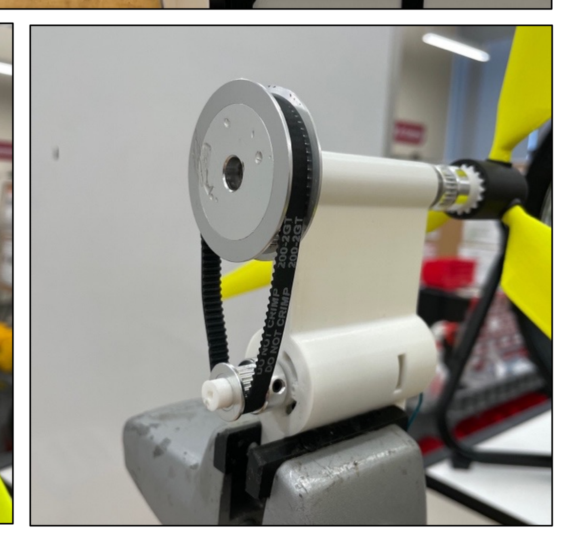
Figure 3. NREL Airfoils[4] used in the Blade Design

Using the CAD model several blade prototypes were made using multiple 3D printers. The final blade prototypes were made using a Markforged Mark Two 3-D Printer that is capable of printing CFR composites such as carbon fiber, Kevlar, and fiberglass. Three blade sets were printed for testing: Nylon with 100% infill, Carbon fiber reinforced Nylon with 37% infill, and ABS with 100% infill.

For the experiment, the blades were all mounted to the same hub and set to the same pitch. The hub was mounted to a small permanent magnet DC motor that can be used to generate electricity. Two different DC motor setups were tested, one with a pully system and one directly mounted to the generator shaft.

Testing

To test the blades, wind was supplied by a variable speed fan. Using an anemometer, the air velocity was measured at different locations and fan speeds. From the anemometer readings, the experimental distance from the fan to the turbine was set at 0.5 m and the air velocities for each speed were determined to be 5, 6, and 7 m/s. The procedure for the experiment was simple, two data measurements per blade set at each of the three fan speeds for both generator setups. The data measurements would be the voltage and current produced by the generator.



Figures 4- 8. From top left to right: 4. Experimental Setup, 5. Direct Generator Connection Setup, 6. Turbine Shaft Connection, 7. Pully Generator Setup, 8. ABS turbine blades in the pully experimental setup

Results

The power generated by the wind turbines needed to be compared to the available wind power. This was calculated using the air velocity and temperature readings from an anemometer. The available power was multiplied by the maximum coefficient of performance to see the maximum potential power generation for a turbine of this size. C_{Pmax} is known as the Lanchester-Betz limit, and this limit makes the highest possible power coefficient 0.593

$$Power = IV = \frac{1}{2}\rho U_\infty^3 A_D \qquad C_P = \frac{Power\ extracted}{Power\ Available} = \frac{Power\ extracted}{\frac{1}{2}\rho U_\infty^3 A_D} \qquad C_{P_{max}} = \frac{16}{27} = 0.593$$

Table 1. Available Wind Power at Various Air Velocities

Air Temperature (°C):			20
Air Density (kg/m^3):			1.20
Area of Disc (m^2):			0.126
Fan Speed	Average Air Velocity @ 0.5m (m/s)	Power Available (W)	Betz Limit P_{max} (W)
1	5	9.42	5.59
2	6	16.29	9.65
3	7	25.86	15.33

The experimental data and results of the three turbine blade sets are summarized in Tables 2 & 3. The tests were conducted from heaviest blades to lightest blades. The power measure by the generator was adjusted to negate the efficiency of the motor. This is the Adjusted power column.

Table 2.

Test Setup 1: Pulley Generator Connection							
Turbine Blade Type and Mass	**Air Velocity (m/s)**	**Voltage (V)**	**Current (mA)**	**Power (W)**	**Adjusted Power (W)**	**Power Available (W)**	**Power Coefficient**
Nylon 100% Infill 52.9g	5	0	0	0.000	0.000	9.42	0.000
	6	1.3	13	0.017	0.106	16.29	0.006
	7	6.0	60	0.360	2.250	25.86	0.087
CFR Nylon 37% Infill 50.5g	5	2.2	22	0.048	0.303	9.42	0.032
	6	3.1	31	0.096	0.601	16.29	0.037
	7	4.3	43	0.185	1.156	25.86	0.045
ABS 100% Infill 41.5g	5	4.1	41	0.168	1.051	9.42	0.111
	6	5.3	53	0.281	1.756	16.29	0.108
	7	7.0	70	0.490	3.063	25.86	0.118

Table 3.

Test Setup 2: Direct Generator Connection							
Turbine Blade Type and Mass	**Air Velocity (m/s)**	**Voltage (V)**	**Current (mA)**	**Power (W)**	**Adjusted Power (W)**	**Power Available (W)**	**Power Coefficient**
Nylon 100% Infill 52.9g	5	6.0	60	0.36	3.06	9.42	0.325
	6	7.7	77	0.59	5.02	16.29	0.308
	7	10.0	100	1	8.51	25.86	0.329
CFR Nylon 37% Infill 50.5g	5	4.9	49	0.24	2.04	9.42	0.217
	6	6.0	60	0.36	3.06	16.29	0.188
	7	7.5	75	0.56	4.79	25.86	0.185
ABS 100% Infill 41.5g	5	7.0	70	0.49	4.17	9.42	0.443
	6	8.2	82	0.67	5.72	16.29	0.351
	7	10.2	102	1.04	8.85	25.86	0.342

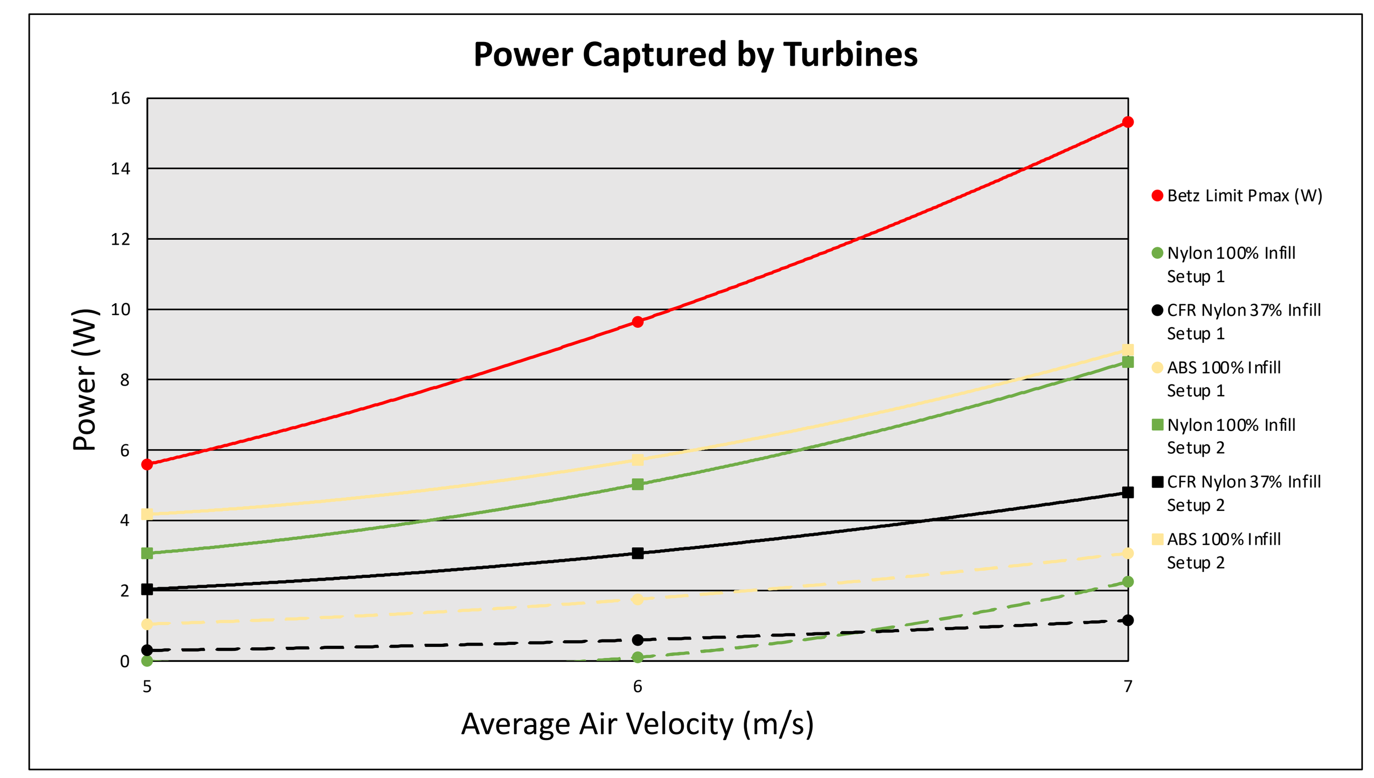


Figure 9. Experimental Turbine Power Captured Compared to the Betz Limit

Conclusions

The data from the experiment confirmed the hypothesis that lighter turbine blades are more efficient than heavier turbine blades. The ABS blades used in the experiment were the lightest and were able to generate the most power at every wind speed compared to the other blades, with a peak efficiency of 44.3%. Unfortunately, the weight reducing benefits of CFR polymer composites is not highlighted by this experiment. Further research and experimentation on a larger scale would help further support the research in this project. The research could have an impact on the next generation of wind turbines and the future of renewable power generation. Large scale CFR polymer composite manufacturing could result in lighter wind turbine blades, increasing the efficiency of wind power generation.

References

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