WIND TUNNEL ANALYSIS OF A COUNTER-ROTATING WIND TURBINE

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Abstract

Wind power is a reliable form of energy, and increases in wind turbine efficiency have helped to provide cost-effective power to an ever-growing portion of the world. However, there are physical limits to the amount of energy that can be removed from an airstream using a single wind turbine system. This paper explores the possibility of increasing power production using two counter-rotating sets of wind turbine blades. A review of design characteristics, such as number of blades, blade angle of twist, chord length, and generator efficiencies, resulted in the design of a counter-rotating wind turbine using three different National Renewable Energy Laboratory (NREL) cross-sectional blade profiles for the blades. A three-blade front system and two three-blade rear systems were studied. The blade prototypes were modeled in SolidWorks®, produced using a Dimension® 3D printer, and then tested using two Parallax™ four-pole stepper motors as generators in a model 406B ELD wind tunnel. Initial testing showed a power increase of 101.4% at 25 mph. This power increase can be attributed to the addition of the second generator and a rear-blade system that was a mirror image of the front system. Testing was performed between 15 mph and 40 mph in 5-mph increments. The counter-rotating system reached its optimum operating efficiency at 25 mph, at which 12.6% of the energy in the air was converted into usable power. This outcome compares to a 6.25% power conversion for the front-blade system. Preliminary results indicate that a counter-rotating assembly is promising for increasing energy extraction from a column of air. Additional testing should focus on system efficiency based on blade angle of twist, chord length, and generator efficiencies. A power increase of 101.4% with the addition of the rear-blade system indicates that the front-system efficiency has not been maximized. The next logical step is designing blade systems for maximum total system efficiency at specified wind speeds. Additionally, it would be valuable to determine if counter-rotating systems could expand the range of possible turbine locations by lowering the required average wind speed.

Introduction

As the prices for conventional fuels continue to increase, renewable energy sources have become a focus for our electricity production. Wind power is especially in-focus, as it only requires an initial investment and maintenance, with no long term fuel cost. Wind power is expanding rapidly throughout the world, especially in Europe, where land is at a premium, thus if a single tower can extract a greater amount of power, it creates a great amount of value. The power in the wind is given by Equation 1.

$$W_{wind} = \frac{1}{2}\pi * r^2 * \rho * C^3 \quad (1)$$

Where W_{wind} is the power in the wind in watts, r is the radius of the column of air in meters, ρ is the density of the air in kg/m^3, and C is the velocity of the wind in m/s. Theoretically, only 59.3% of the total energy in a column of air can be extracted. This limit is referred to as the Betz limit. For a dual rotor system the Betz limit is increased to 64%[1]. Currently, however a single bladed system is at maximum 40% efficient.

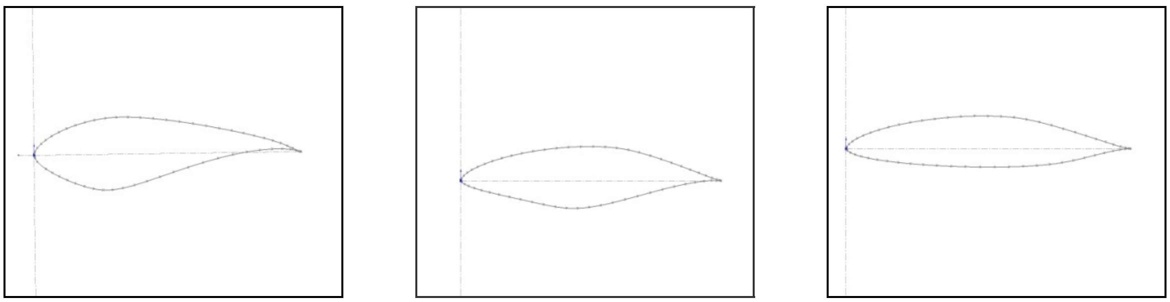
Figure 1. Counter-Rotating Wind Turbine Test Apparatus

The goal of this study is to test whether a counter-rotating, dual fan system can extract a greater amount of the winds power than a single fan system. A counter rotating system, as shown in Figure 1, was chosen, as there is swirl imparted on the wind after the initial fan, which can be extracted with a counter-rotational motion. Two back fans were tested to see which would extract more power from the air.

Within the market today, there is an increasing demand for small scale (under 100 kW) wind systems, for home or farm use. If a sizable increase in power output for the CRWT over a conventional system can be shown, it would be very applicable to this market, as blade costs are a very small portion of the total price on the system. Conversely for large scale applications, blade prices can be up to 80% of the total cost. To test the efficiency of these blades, the peak power extracted from the wind was taken for both fans, using differing loads. This was compared to the total power in the wind, to find the system efficiency.

Experimental Methods

For the blade design process, NREL airfoil profiles S818, S827, S828 were used as shown in Figure 1. These profiles were specifically designed for use for large-scale wind turbines with a 35m blade length[2]. The chord lengths used for the different profiles were 1.5 times the recommended size[3]. This was done to ensure the structural integrity of the test blades.



S818 S827 S828

Figure 2. Profiles S818, S827, and S828

The twist angle was designed for the front set of blades using the velocity triangle technique, along with assumptions on rotational velocity based on a previous study[4]. The profile distribution and the angles used in this study are as shown in Table 1.

Table 1. Profile Distribution and Angle of Twist			
Wind Tunnel Conditions			
Wind Speed (mph)	60		
RPM	1600		
Profile	**Dist from center (mm)**	**Optimum Angle (deg)**	**Twist Angle (deg)**
S818	11.75	9	4.80
S818	16.45	9	3.13
S827	58.75	5	-15.15
S827	117.5	5	-31.28
S828	176.25	6	-41.75
S828	235	6	-49.74

Two sets of back blades were manufactured, a blade set that was designed based on the rotational velocity assumptions, and a pure reflection of the designed front blade set. The profiles were entered into SolidWorks® using the coordinates provided by NREL. The blades were then designed by combining the different profiles with a loft function. The blades were printed using a Dimension 1200 Series SST printer along with a central hub for both front and back with dove-tail slots for the blades, as shown in Figure 3. Due to resolution limitations of the Dimension

1200 Series SST printer the printed blades had a rough texture. This rough texture would cause turbulent air flow across the blades, therefore decreasing the efficiency of the blades. Consequently the blades were wet sanded using 400 grit automotive sand paper, primed with automotive primer, and finished with oil-based enamel spray-paint.

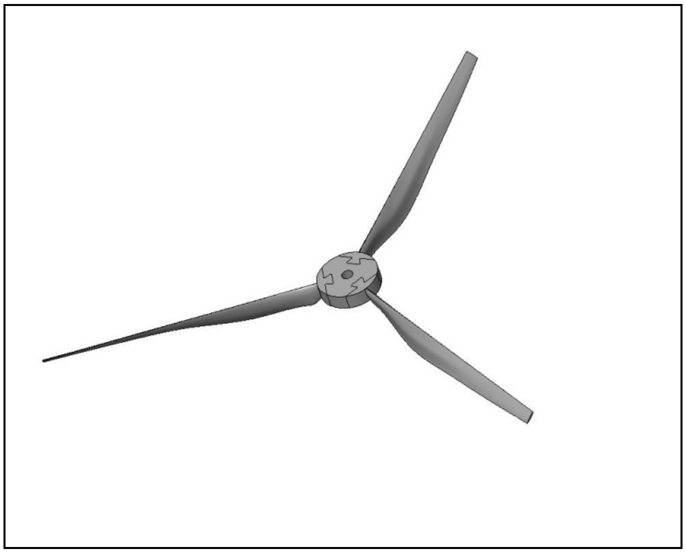


Figure 3. Hub Assembly with Angle of Twist

Two four-phase Parallax™ stepper motors were used to obtain the output power of the system. These motors were high-impedance, and thus the total power output was not as high as the mechanical energy.

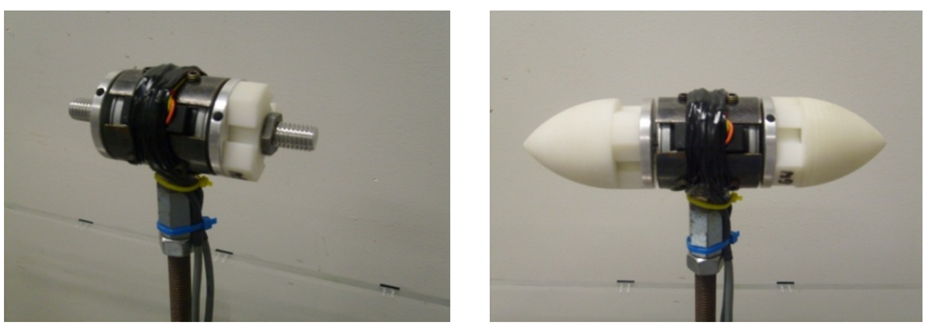


Figure 4. Mounting System

The mounting system, shown in Figure 4, was designed in three parts. A base, which bolted into the Plexiglas bottom of the wind tunnel, a post to center the apparatus within the tunnel, and a case for the two stepper motors. The removable base allowed for the ability to quickly remove the test system from the Plexiglas. The center post was manufactured using ½ - 13 all-thread rod. A two inch nut was welded to both the stepper motor mounting case and the base. The all-thread rod in combination with the nuts allowed the test system to be adjusted to the exact center of the wind tunnel. The stepper motors were attached to the inside of a cylindrical steel casing with

three set-screws mounting each stepper motor. The steel mounting system insured that the testing system did not move during testing.
Two aluminum t-mounts were designed as mechanisms to mount the blade hub assemblies to the stepper motors. These t-mounts consisted of a ½ inch threaded post with a 1.9 inch diameter spacer. This t-mount attached to the stepper motor shaft using a single set screw driven into the brass gear on the stepper motor shaft. Spinners were also designed and printed on the Dimension 1200 Series SST printer. These spinners were tapped with a ½ - 13 tap and screw onto the t-mount pressing the blade dove-tail against the t-mount spacer.

Table 2. Experimental Instruments		
Device	**Model Number**	**Serial Number(s)**
ELD Wind tunnel	406B	2000 Baylor University
Clarostat Power Resistor Decade Boxes	240-C	Stations 1,7
Newport TrueRMS Supermeter	HHM290/N	6000034
Newport TrueRMS Supermeter	HHM290/N	6000040

Testing equipment consisted of two Parallax™ four-pole stepper motors, four schottky diodes, one 5000μfd capacitor, and the instruments shown in Table 2. Each generator was attached to the testing equipment as shown in Figure 5.

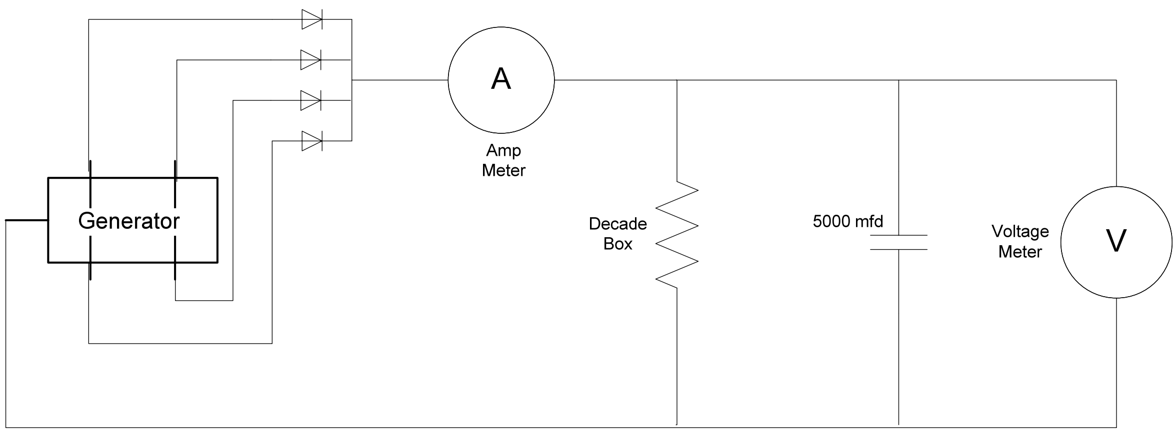


Figure 5. Testing System Schematic

The first step in testing was to experimentally determining power curves for the front blade set and generator at various wind speeds. To find a mathematical function representing the power curve for the front blade and generator, the front blade was tested at a constant wind speed while the resistance of the decade box was varied. Voltage and current were measured for thirty-one different resistances between 0Ω and 20000Ω. These data points were then plotted in Excel. A best fit trend-line was applied and the resulting polynomial equation (power equation) and R^2 values were recorded. An example of this can be seen in Figure 6. The maximum power for the corresponding wind speed was calculated using the power equation. The function power equation was then multiplied by x where x represents the output voltage. The derivative of the function was then determined. The resulting second order polynomial was set equal to zero and solved. This numerical solution represented the output voltage at the maximum power point.

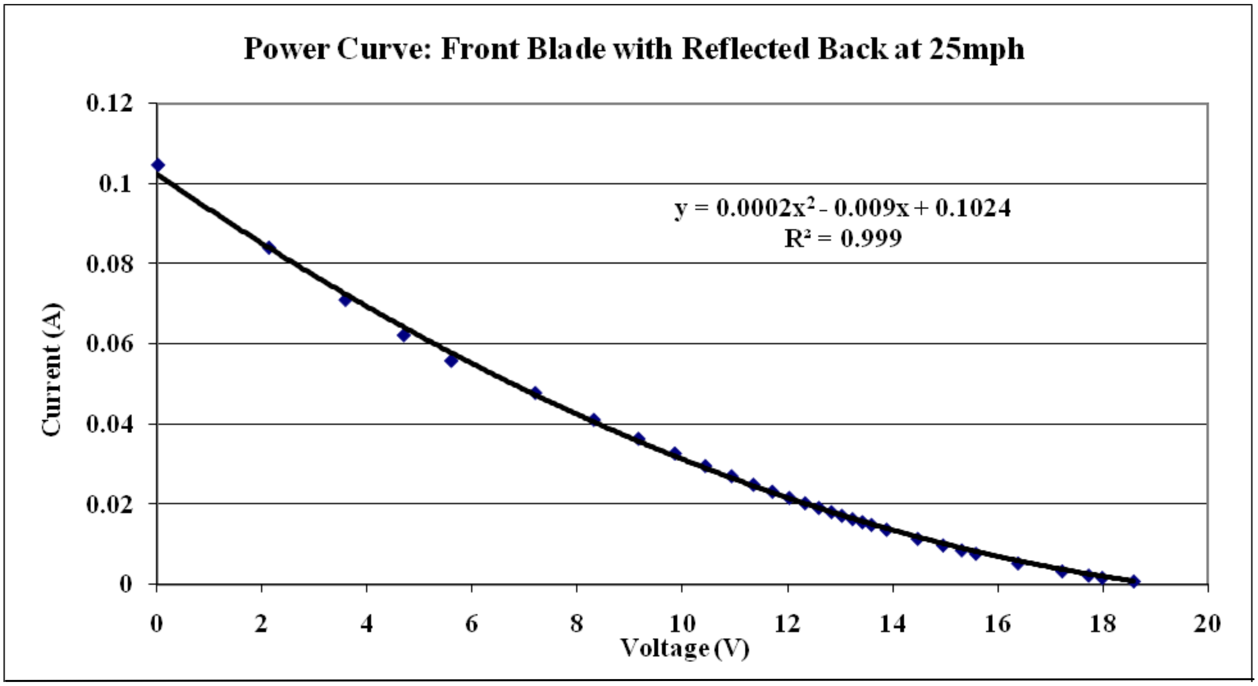


Figure 6. Power Equation of Front Blade at 25mph

The decade box was then adjusted until the measured voltage matched the calculated voltage for maximum power. The resulting resistance on the decade box was then recorded. This resistance represented the load at which the generator operates most efficiency for the given wind speed. Additionally, the measured voltage and current were multiplied in order to find the power output at the maximum efficiency point.

The front blade system was disconnected from the test system and connected to the second decade box. The decade box was set to the resistance corresponding to the maximum efficiency point. Then the back generator was attached to the test system and the testing process was repeated to find the maximum efficiency point for the back blade and generator. This process of testing the front blade system for maximum power output, setting the front blade at its maximum power output level, and testing the back blade system for maximum power output insured that the total maximum power output for the total system was accurate. The process was performed and repeated at 5mph increments from 15mph to 40mph.

Results

The performance of each blade system depended on the angles of twist built into each blade. Early in the design process an assumption of 1600 rpm at a wind speed of 60 mph was made as a basis for velocity triangle calculations. These assumptions were based upon a previous study done at Baylor University[4]. The rotational velocity assumptions did not convey from the previous study due to the fact that different blade profiles were used when designing the CRWT blades. Additionally, the bearing friction of the CRWT rig was substantially less than the bearing friction in the former testing rig. It is also possible that in the previous study a harmonic was being measured causing the rotationally velocity measurement to be higher than the actual rotational velocity. Rotational velocities of the CRWT were measured and plotted in Excel as shown in Figure 7. Based upon the equation of the trend line, a rotational velocity of 1070 rpm is expected at 60 mph. The difference between the rotational velocity and the experimental rotational velocity caused the front blade set to have an angle of twist error. This twist angle error caused the system to have a lower power output than an optimized system would have.

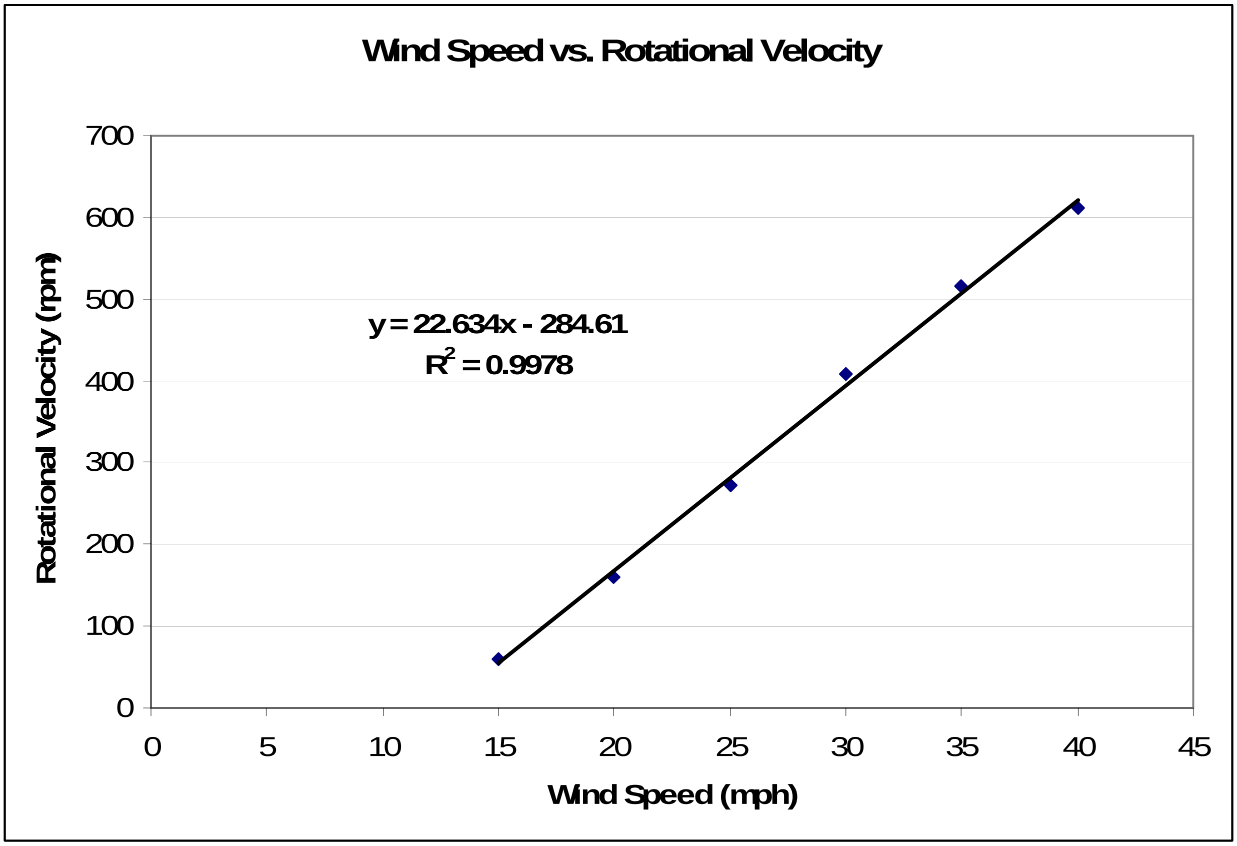


Figure 7. Measured Rotational Velocity

However, when doing velocity triangle calculations, the calculated angle of twist is less dependent on rotational velocity at the root of the blade. Consequently, the root of each blade operated within a realistic range of twist. The angle of twist at the tip of each was not close enough to the angle of twist calculated based upon 1070rpm at 60mph for maximum lift to be achieved.

In this study two rear blade systems were tested. The reflected system was a pure reflection of the front system. The alternative system attempted to approximate swirl in the column of air due to the rotation of the front blade. The reflected back blade system produced substantially better results and will therefore be the focus of these results.

The CRWT test system performed at maximum efficiency at 25mph as shown in Table 3. This efficiency was calculated by dividing the power generated by the system by the power available in the column of air. Additionally, Table 3 shows that at 25mph the energy in the column of air defined by the diameter of the test system is 5.50 watts. At the maximum efficiency velocity the front blade system produced 0.3437 watts with an efficiency of 6.25%. The reflected back blade system produced 0.3486 watts with an efficiency of 6.34%. The total efficiency of the combination of both systems was 12.58%. This means that 12.58% percent of the energy in the column of air was being converted into useful power.

Table 3. Reflected Blade System Efficiency

Wind Speed (mph)	$\text{Power}_{\text{column}}$ (W)	$\text{Power}_{\text{output}}$ (W)			System Efficiency		
		Front	Back	Total	Front	Back	Total
15	1.154	0.0374	0.0455	0.0829	3.24%	3.94%	7.18%
20	2.654	0.1323	0.1606	0.2929	4.98%	6.05%	11.04%
25	5.502	0.3437	0.3486	0.6923	6.25%	6.34%	12.58%
30	9.242	0.4989	0.4738	0.9727	5.40%	5.13%	10.52%
35	14.406	0.6691	0.6351	1.3042	4.64%	4.41%	9.05%
40	22.349	0.8356	0.7848	1.6204	3.74%	3.51%	7.25%

Testing a system of blades designed using 1070 rpm at 60 mph should improve the power output of the total system. Theoretically, the front blade system would show an improvement in the percent of energy being extracted from the column of air. This would leave less energy available for the rear blade but the total energy converted to power should increase.

Conclusions and Recommendations

Assumptions regarding rotational velocity are error prone as they are entirely based on a previous study that used a different testing apparatus. The expected point of maximum efficiency for the CRWT test apparatus was 60 mph based upon the rotational assumption made during the design process. However, the CRWT test apparatus achieved maximum efficiency at 25 mph and approximately 270 rpm. Therefore, at the tested wind speeds the angle of twist of the blades was not producing the maximum lift over the length of the entire blade. Based upon the rotational velocity design error, the root of the blade created lift more effectively than the blade tip and thus the system power output was decreased. However, even with a test system that did not perform at its optimum efficiency the results of this preliminary study are encouraging and clearly show that this topic warrants more serious study.

As mentioned in the Experimental Methods section, the motors used were high-impedance stepper motors, which generate a significant amount of reverse electromagnetic force. Thus, the mechanical power generated by the fans was much greater than the total system efficiency.

For future research, it is recommended that the front and rear blade systems be designed for this testing apparatus using the rotational velocities discovered in this study. Additionally, the efficiency of the generator should be determined. This will allow for an overall system efficiency comparison to be made with regard to conventional wind turbines and the Betz limit. This will allow for an economic feasibility analysis of the counter rotating turbine over a single fan system.

Lastly, due to the test section size of the Baylor University wind tunnel, a similarity comparison between the CRWT apparatus and a full-scale wind turbine, based upon Reynolds number, is not possible. A larger wind tunnel combined with blades capable of withstanding higher velocities would make this possible. This larger scale testing would help to determine the possible application of the CRWT technology.

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