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ANALYSIS OF A COUNTER-ROTATING WIND TURBINE

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ABSTRACT

Increases in wind turbine efficiency have helped to provide cost-effective power to an ever-growing portion of the world. This paper explores the possibility of increasing power production using two counter-rotating sets of wind turbine blades. The system tested incorporates three cross-sectional National Renewable Energy Laboratory (NREL) blade profiles along the blades; these blades were chosen as they were more efficient than the surveyed alternatives [1]. Preliminary results indicate that a counter-rotating assembly is promising for increasing energy extraction from a column of air. The counter-rotating system reached its optimum operating efficiency in wind tunnel testing at 25 mph, at which 12.6% of the energy in the air column was converted into usable power. In contrast, a front blade system has an efficiency of 6.25%. Additional testing will focus on air column behavior behind the upstream and downstream blade systems for optimizing the design and increasing total system efficiency.

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 important, as it only requires an initial investment and ongoing maintenance, with no long term fuel cost or harmful emissions. 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 great value. 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 counter-rotating wind turbine (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 of the system. Conversely for large scale applications, blade prices can be up to 80% of the total cost.

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 the utility-scale single bladed systems have a maximum efficiency of approximately 40%.

Figure 1. Counter-Rotating Wind Turbine Test Apparatus

The goal of this study is to test whether a dual fan system can extract a greater amount of the wind's 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 rear blade designs were tested to see which would extract more power from the air.

To test the efficiency of these blades, the peak power extracted from the wind was taken for both sets of blades, using differing loads. This was compared to the total power in the wind, to find the system efficiency.

The power in the wind is given by Equation 1.

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

NOMENCLATURE

W_{wind}	Power in Wind [W]
r	Radius of Air Column [m]
ρ	Air Density [kg/m^3]
C	Wind Velocity [m/s]

BODY OF PAPER

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

Figure 2. Profiles S818, S827, and S828

The twist angle was designed for the front set of blades using the velocity triangles based on a predicted RPM of 1600 and wind speed of 60 mph 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		
Profile	Distance from Central Axis (mm)	Angle of Twist (deg)
S818	11.75	4.80
S818	16.45	3.13
S827	58.75	-15.15
S827	117.5	-31.28
S828	176.25	-41.75
S828	235	-49.74

Two sets of rear 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, and blades were designed by combining the different profiles using a loft function. Finally, blades were printed using a Dimension 1200 Series SST printer along with a central hub for both front and rear blades which are attached with dove-tail slots, as shown in Figure 3. Due to resolution limitations of the Dimension 1200 Series SST printer the printed blades had a rough surface. This rough surface 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 as generators 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 energy extracted from the air.

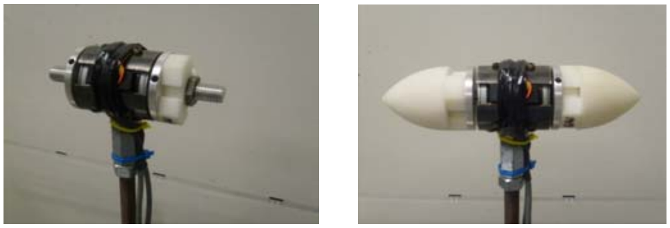

Figure 4. Mounting System

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 center post was manufactured using a ½-13 all-thread rod. A 2 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 used to mount each stepper motor. The steel mounting system ensured that the testing system did not move during testing.

Two aluminum t-mounts were designed 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 screwed onto the t-mount, which pressed 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 5000 μfd capacitor, and the instruments shown in Table 2. Each generator was attached to the testing equipment as shown in Figure 5.

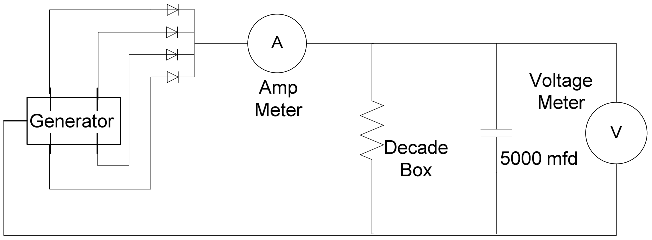

Figure 5. Testing System Schematic

The first step in testing was to experimentally determine 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 31 different resistances between 0 Ω and 20000 Ω. These data points were then plotted using Excel. A best fit trend-line was applied and the resulting polynomial equation (power equation) and determination coefficient values (to measure the goodness of fit) 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 resulting function 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.

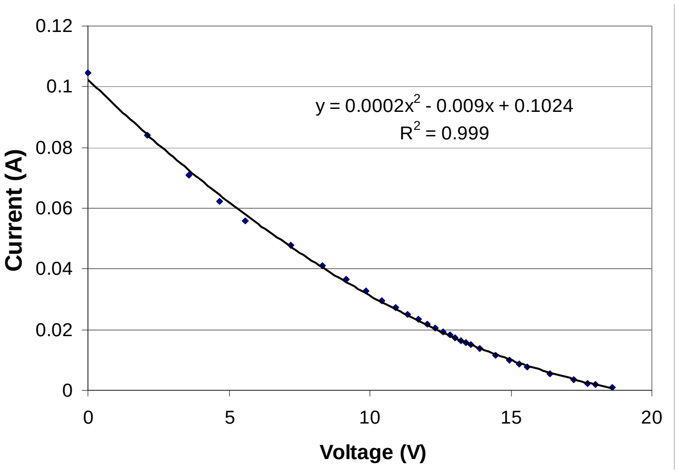

Figure 6. Power Equation of Front Blade at 25 mph

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 efficiently 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 a second decade box. This decade box was set to the resistance corresponding to the maximum efficiency point. The rear generator was then attached to the test system and the testing process was repeated to find the maximum efficiency point for the rear 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 rear blade system for maximum power output ensured that the total maximum power output for the total system was accurate. The process was performed and repeated at 5 mph increments from 15 mph to 40 mph.

Results A major issue with interpreting the results is the method of scaling. The Reynolds number is not a feasible way to scale these turbines to a large scale. To scale with the Reynolds number, the wind tunnel speed would have to be high enough to make testing impossible. 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. The high wind speed was initially chosen to maximize the applicability of Reynolds number scaling. These assumptions were based upon a previous study done at Baylor University [4]. The rotational velocity assumptions did not hold from the previous study because 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 a multiple of the actual rotational velocity. Rotational velocities of the CRWT were measured and plotted using 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 operate at less than optimum twist angle. This difference in twist angle caused the system to have a lower power output than an optimized system would have.

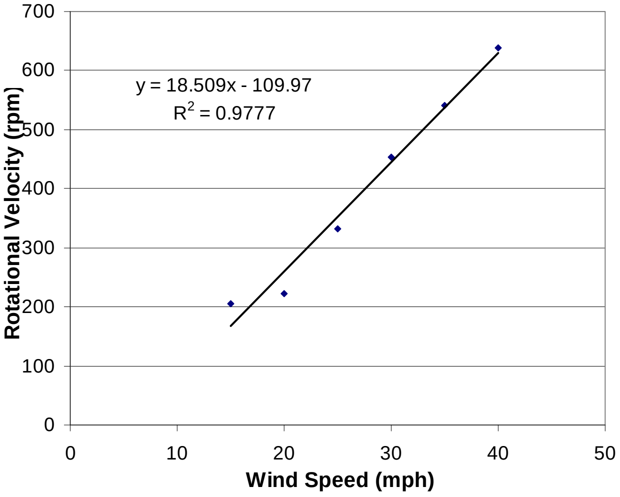

Figure 7. Measured Rotational Velocity

When calculating twist using velocity triangles, the calculated angle of twist is not a strong function of 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 realistic based upon 1070 RPM at 60 mph for maximum lift to be achieved. This speed was chosen so that the Reynolds number would be closest to turbines in operation.

Of the two rear blade systems tested, the mirror reflection of the front system had much better performance than the blade customized for approximate swirl.

The CRWT test system performed at maximum efficiency at 25 mph 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 25 mph the energy in the column of air defined by the diameter of the test system is 5.50 W. At the maximum efficiency velocity, the front blade system produced a maximum power output of 0.371 W with an efficiency of 6.74%. When operating the system with both sets of blades, the front blade system produced .3437 W with an efficiency of 6.25% and the reflected rear blade system produced 0.3486 W 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)	Power in Air Column (W)	Output Power (W)			System Efficiency		
		Front	Rear	Total	Front	Rear	Total
15	1.154	0.037	0.046	0.083	3.2%	3.9%	7.2%
20	2.654	0.132	0.161	0.293	5.0%	6.1%	11.0%
25	5.502	0.344	0.349	0.692	6.3%	6.3%	12.6%
30	9.242	0.499	0.474	0.973	5.4%	5.1%	10.5%
35	14.406	0.669	0.635	1.304	4.6%	4.4%	9.0%
40	22.349	0.835	0.785	1.620	3.7%	3.5%	7.3%

Using this experimental data to redesign the blades should improve the power output of the total system. Theoretically, the front blade system would show an improvement in extracting energy, thus leaving less energy available for the rear blade. But, both blades would be more efficient in converting the available energy, and so the total efficiency of the system should increase.

Conclusions and Recommendations 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. Due to the difference between the assumed and actual angular velocities, the blade design was not operating at the optimum angle over the entire blade. 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 further investigation.

Using the results from these tests, future iterations of the design process will be greatly improved. The new data will remove any error caused by the previous rotational velocity assumptions. These assumptions were error prone as they are entirely based on a previous study that used a different testing apparatus.

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 sets of blades was much greater than the total system power output. To put an exact value on the mechanical efficiency of the CWRT, the efficiency of the generator should be determined.

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. 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 turbine system.

Additionally, the fact that the alternative rear blade system did not perform as expected suggests that the momentum method used to approximate swirl was overly simplistic. To truly determine the behavior behind the front blade, water tunnel testing will be performed with dye injection to determine the nature of the swirl. Once this is determined, an optimized rear blade can be created and tested.

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 valid alternative scaling method must be determined. This scaling model would help to determine the possible application of the CRWT technology.

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