# Aerodynamic Efficiency Analysis of Small-Scale Wind Turbine Blades

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**Small-scale wind turbines are used to produce electricity to power smaller devices and create clean energy environment for many applications. The objective of this study is to investigate different wind turbine blade designs in order to optimize their ability to convert energy through experiments and simulations. Several blade designs with varying thickness and blade angles are comparatively analyzed through 3D printing, simulations and experiments. Computational fluid dynamics (CFD) simulations were carried out to analyze complex flow characteristics around turbine blades. Through these analyses, optimal blade design characteristics are obtained and will be presented in the paper.**

## Nomenclature

| | | |
|---|---|---|
| $R$ | = | Radius of Curvature |
| $r$ | = | Radial Length of Blade |
| $W_1$ | = | Width of Blade closest to center of turbine, location defined as point 1 |
| $W_2$ | = | Largest Width of Blade, location defined as point 2 |
| $W_3$ | = | Smallest and Final Width of Blade, location defined as point 3 |

## I. Introduction

While larger wind turbines typically have a radius of up to 100 meters, a small-scale turbine would be kept under a 10-meter radius [1]. small-scale breaks down further into micro (r from .5 to 1.25 m), mini (r from 1.25 to 3 m), and household (r from 2 to 10 m) [1]. These also break down into different styles of turbines. There are several parameters that influence the efficiency of a turbine. The orientation plays a large role in how well a turbine performs [3]. This involves the setup of the turbine and designing it to be able to adjust to wind patterns. There are several key factors in designing the shape of an air turbine. The size of the blade in terms of length and width affects design. Certain areas will be constrained by size which limits them to small-scale turbines, and other areas are perfect for the large turbines [1]. The width is important to the design when aiming for faster speeds. When designing a turbine to spin quicker, it is more optimal to have smaller widths [2]. This is convenient because it also lowers production cost by using less material. The aerodynamics of the blade also impact its ability to spin. Using air foils with larger lift coefficients aid in the spinning of the blade. Similar to an airplane using its airfoils to generate life, wind turbines use their airfoils to generate a torque force [2]. Another key design factor is the angle of twist in the blade. This affects the angle the wind strikes the blade. The blades twist in towards the wind closer to the center and are normal at the tips. This affects how the wind will push the blade, and is important to design in tandem with the orientation of the turbine relative to the wind [2]. This is more difficult to define an ideal range as it can vary for orientation and makes production more complex and expensive [2].

Small-Scale wind turbines are part of a growing push towards cleaner energy production. These smaller turbines can be suitable for office space, houses, apartment buildings, and other establishments to produce extra energy in a much cleaner way than the electricity normally used is typically produced. As businesses and governments continue to look for cost efficient and environmentally friendly ways to produce energy, it is necessary to look into the possibilities of turning natural energy into usable electricity. Wind turbine and solar panel fields can be found as communities try to create large scale energy sources. Scaled down, it would be a useful supplement to energy.

This project focuses on Horizontal Axis Wind Turbines due to their common nature as well as on 3-bladed designs because they are the most common and most stable and powerful style of turbine design [4]. The shape aspects that are simple to design and modify are the twist and the width, so those were chosen to narrow the project's focus. This can prove that width has an inverse relationship with the speed a wind turbine will spin at. An angle can be determined, and orientation can build on that afterwards.

This project looks to find shapes of small-scale wind turbines that optimize their output. This leads to a more efficient turbine that can produce more energy. This project will test if blade shapes with smaller widths and larger angles of twist from the center of the turbine to the end of the blade will lead to a greater rotational speed when spun by air flowing over the turbine.

The results of this project confirmed that smaller widths lead to more efficient turning of the turbine. The width had a much larger effect on this than the angle of twist did. The two angles that outperformed the others were at 30 degrees from start to end and 20 degrees from start to finish. The importance is that when designing a Small-Scale Horizontal Axis Wind Turbine, one should aim to make the blades as thin as the strength will allow. As the rotation and wind force will stress the blades of the turbine, it is necessary to assess the needed strength of the turbine to allow the turbine to remain functional. This has the added benefit of allowing for the use of less material and lowering the cost of production. The twist of the blade should fall between 25 and 35 degrees. For a more precise range, more testing would be needed.

## II. Methodology

The following section outlines the steps taken to test the effects of the shape of the blades on the ability to convert the wind into rotational kinetic energy. There are 12 designs that were created on Fusion360. They were created with 4 mm thick slots lofted together to form a solid. A circle was extruded with a hole, and the blades were moved to have as little of the blade in the circle as possible. A circular pattern created the other two blades. The radius of curvature was chosen to be a 1:1 ratio with the $W_1$ measurement to keep a consistent level of curvature relative to each design.

### A. Modeling

1) The first four designs have $W_1$ = 45 mm, $W_2$ = 60 mm, and $W_3$ = 30 mm. They vary with the angles being 45 degrees at point 1, 20 degrees at point 2, and 0 degrees at point 3. Another design has angles of 30 degrees at point 1, 10 degrees at point 2, and 0 degrees at point 3. A third design has angles of 20 degrees at point 1, 7.5 degrees at point 2, and 0 degrees at point 3. The last design of this group has angles of 10 degrees at point 1, 5 degrees at point 2, and 0 degrees at point 1. All of these designs had a R = 45 mm.
2) The second group of four designs have $W_1$ = 30 mm, $W_2$ = 45 mm, and $W_3$ = 15 mm. The angle groupings are the same. These designs had a R = 30 mm.
3) The final group of four designs have $W_1$ = 10 mm, $W_2$ = 15 mm, $W_3$ = 5mm. The angle groupings are the same. These designs had a R = 10 mm.

### B. Printing

4) The CAD models were reduced to 30% of their size to allow for two designs to be printed simultaneously. These were printed on a Dremel 3D printer. The prints were labeled when they came out.

### C. Testing

5) 3/8 inch hole was drilled in a wooden plank. The plank was then screwed to a plywood base, and a 3/8 bolt was placed in the hole.
6) The hole for the turbines was drilled out to be 7/16 inch so that it can spin on the bolt as an axis. These were placed on the bolt and spun with an air compressor hose.
7) A timer was set up in the background, and a slow-motion video recorded the spinning. For each blade, the video was used to determine the time for 50 rotations to take place to determine rotational speed. This was done by counting out 50 rotations and noting the start and stop time for the counting. This gave the data that was then compiled.

**Figure 1: Experimental Setup**

**D. Simulation**

8) Using the results from the experiment, simulations were carried out for the best and worst preforming designs. This data was compared with the results to see if the experimental and simulated data agree. The simulation was set up to run for low Reynold's numbers. The wind speed and material were set at arbitrarily to 100 feet per second and aluminum as this was to look at general flow characteristics.

## III. Results

Several experiments (results in table below) and simulations were carried out to analyze the aerodynamic efficiency of the blade designs. The experiments involved blowing air from an air compressor hose over the blades to determine the rotational speed of the blades under similar wind conditions. The simulations used Ansys Fluent to simulate airflow over a static turbine to view flow characteristics and compare with experimental results. These results are discussed further below.

| | A | B | C | D | E | F | G | H | I | J | K |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Blade | Width 1 mm | Width 2 mm | Width 3 mm | Angle 1 deg | Angle 2 deg | Angle 3 deg | Rotations | Time (s) | RPS | Rad/Sec |
| 2 | 1 | 45 | 60 | 30 | 30 | 10 | 0 | 50 | 7.24 | 6.906077348 | 43.39216372 |
| 3 | 2 | 45 | 60 | 30 | 20 | 7.5 | 0 | 50 | 7.52 | 6.64893617 | 41.77649805 |
| 4 | 3 | 45 | 60 | 30 | 45 | 20 | 0 | 50 | 6.19 | 8.077544426 | 50.75270846 |
| 5 | 4 | 45 | 60 | 30 | 10 | 5 | 0 | 50 | 8.05 | 6.211180124 | 39.0259957 |
| 6 | 5 | 30 | 45 | 15 | 45 | 20 | 0 | 50 | 5.98 | 8.361204013 | 52.53499421 |
| 7 | 6 | 30 | 45 | 15 | 30 | 10 | 0 | 50 | 5.48 | 9.124087591 | 57.32833309 |
| 8 | 7 | 30 | 45 | 15 | 20 | 7.5 | 0 | 50 | 5.49 | 9.107468124 | 57.2239099 |
| 9 | 8 | 30 | 45 | 15 | 10 | 5 | 0 | 50 | 5.92 | 8.445945946 | 53.06744347 |
| 10 | 9 | 10 | 15 | 5 | 45 | 20 | 0 | 50 | 3.45 | 14.49275362 | 91.06065663 |
| 11 | 10 | 10 | 15 | 5 | 30 | 10 | 0 | 50 | 3.08 | 16.23376623 | 101.9997615 |
| 12 | 11 | 10 | 15 | 5 | 20 | 7.5 | 0 | 50 | 3.4 | 14.70588235 | 92.39978393 |
| 13 | 12 | 10 | 15 | 5 | 10 | 5 | 0 | 50 | 3.58 | 13.96648045 | 87.75398474 |

**Table 1: Table of Results**

**A. Experimental Results: Width**

The experiment showed that the width of the blade is an important predictor of the ability to spin quicker from the wind energy. The four blades that were thinnest significantly outperformed the wider blades. Those thinner blades achieved more than 50% faster rotational velocity than the best performer from the other 8. The best performing blade was the 30-degree twist blade from the thinnest set. The worst performing blade was the 10-degree twist blade from the widest set. A linear fit line has an R squared value of .9162 and slope of -1.4431. The data is relatively linear. This predicts that the thinner the blade, the more rotation will occur. This makes sense with classic physics as there is less mass in the thinner blades. When acted upon by the force from the wind, the blade will be able to accelerate with a greater magnitude because there will be less mass to accelerate.

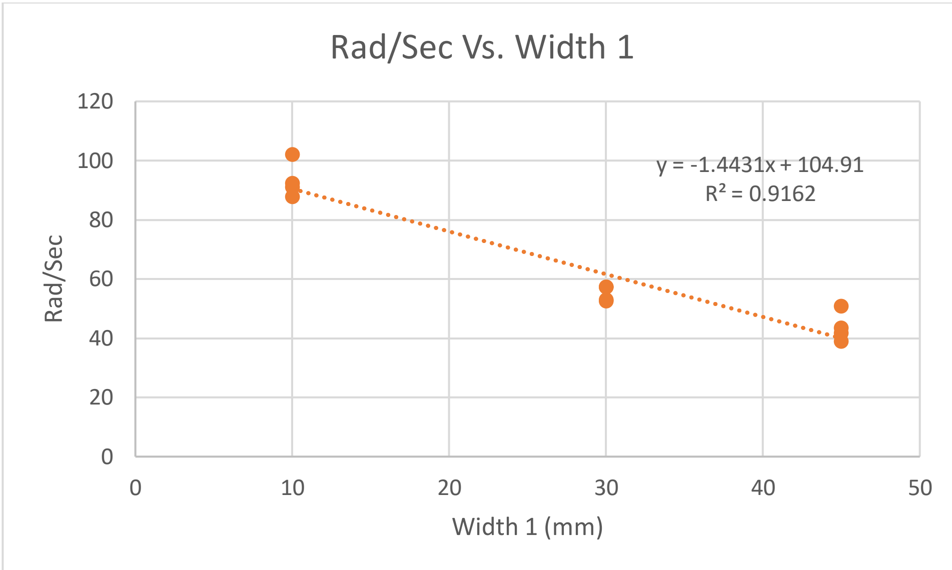


**Figure 2: Plot of Angular Speed Vs. Width**

### B. Experimental Results: Twist

The twist of the blade also has an effect on the blade's ability to spin. The best performing angles of twist were the 30-degree twist blades. This suggests that a twist in the blade less than 45 degrees, but greater than 20 degrees is ideal. The data was fit with polynomial lines, and suggests that the ideal range is between 25 and 35 degrees of twist. These blades have enough twist to allow for normal force from the wind to spin it while allowing an ideal amount of the air to flow over the blade. More tests on turbine blades with smaller increments of variation is necessary to narrow the ideal range down.

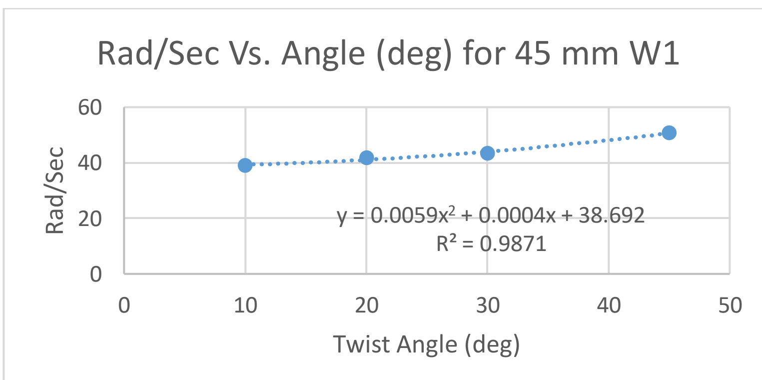


**Figure 2: Plot ofAngular Speed Vs. Twist for Widest Blades**

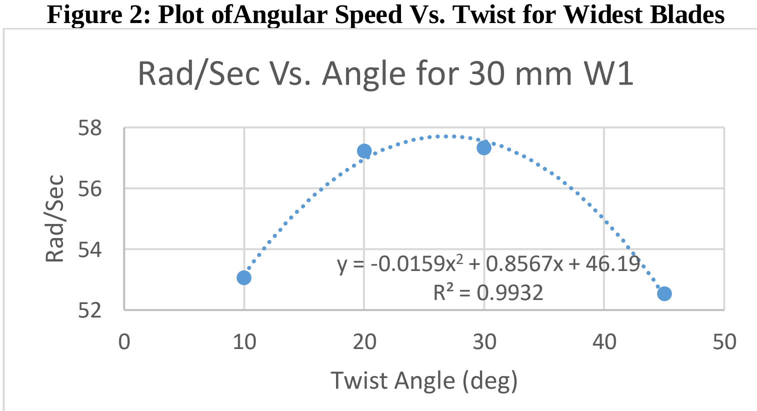


**Figure 3: Plot of Angular Speed Vs. Twist for Second Widest Blades**

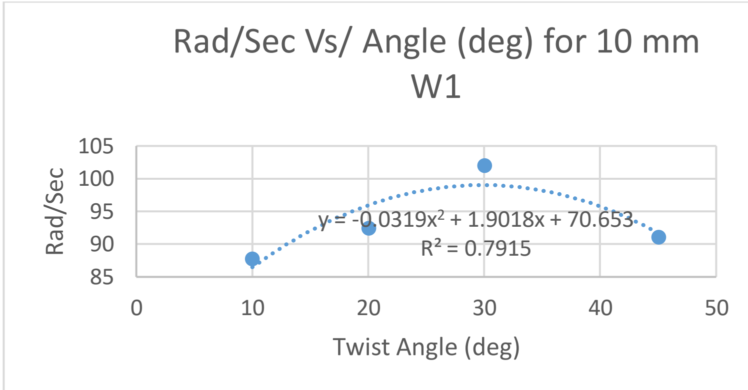


**Figure 4: Plot ofAngular Speed Vs. Twist for Thinnest Blades**

### C. Simulation Results

The results of the simulation on the best and worst blades support the experimental data. The minimum quality for the simulation on design 4 was .2003, there were 356,193 cells, and the solution converged after 113 iterations. The minimum quality for the simulation for design 10 was .2082, there were 313,166 cells, and the solution converged after 110 iterations. The forces on the blades are similar, so the smaller blade in mass should be able to accelerate at a greater magnitude. Also, the pressures are greater distributed on the side that would push the blade in a circular motion on design 10 rather than 4. This would result in the change in twist changing how the wind applies pressure on the blades. The velocity difference is also slightly higher for design 10 than 4. This is due to the twist in the blade and helps to push the blade in circular motion. They are still fairly similar, so it is likely that the difference in mass is the greatest contributor. This is a result in the decrease in the width between shapes.

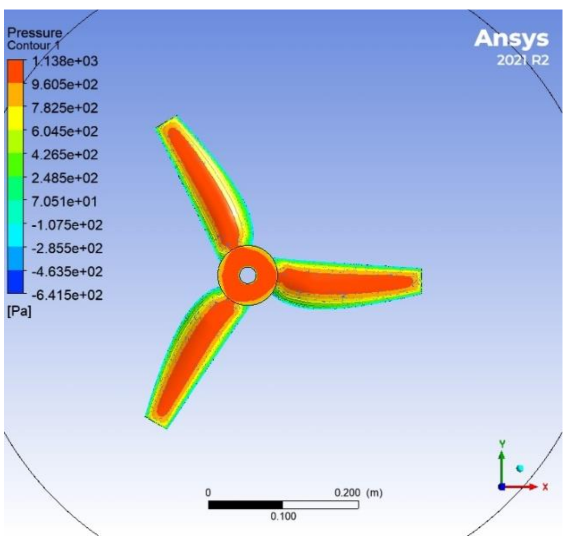


**Figure 5: Pressure Contours for Design 4 (10 Degrees of Twist, $W_1$ = 45 mm)**

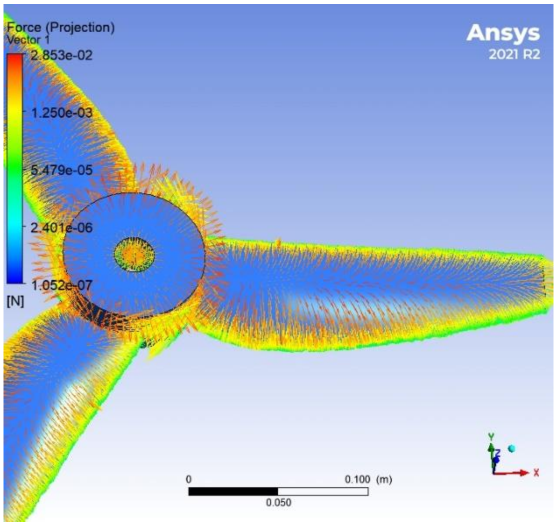


**Figure 6: Force Vectors for Design 4 (10 Degrees of Twist, $W_1$ = 45 mm)**

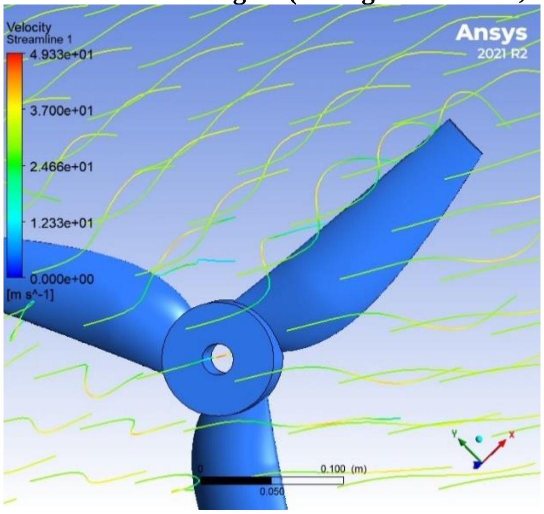


**Figure 7: Velocity Streamlines for Design 4 (10 Degrees of Twist, $W_1$ = 45 mm)**

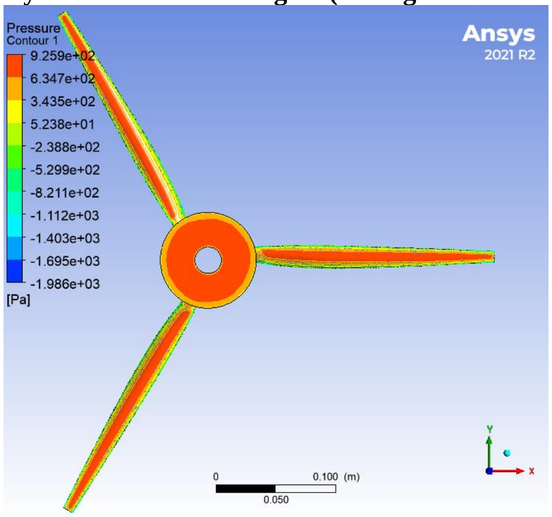


**Figure 8: Pressure Contours for Design 10 (30 Degrees of Twist, $W_1$ = 10 mm)**

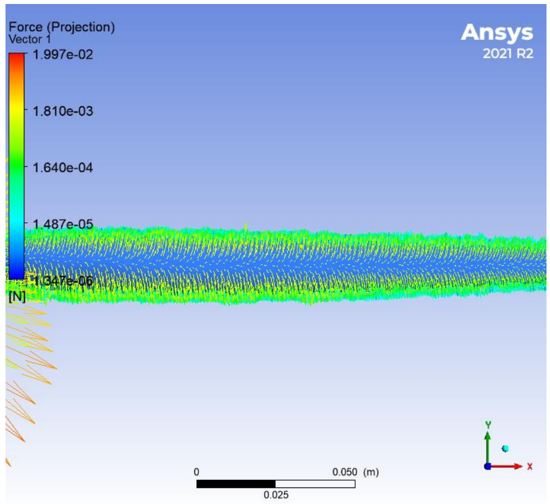


**Figure 9: Force Vectors for Design 10 (30 Degrees of Twist, $W_1$ = 10 mm)**

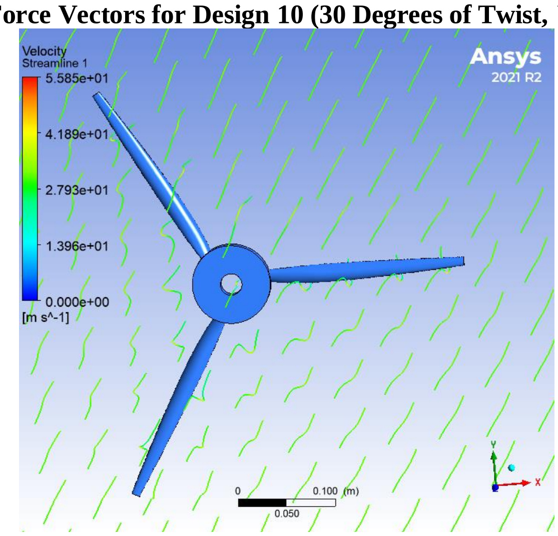


**Figure 10: Velocity Streamlines for Design 10 (30 Degrees of Twist, $W_1$ = 10 mm)**

## IV. Conclusions and Future Work

The results with reference to the width mean that the determining factor on the width of a blade design should be the strength desired. The turbine will need to deal with centrifugal forces and forces from the wind on top of body forces [2]. These forces place stresses on the turbine blades, so the blades need a cross-sectional area that can handle those stresses. It would be beneficial to approach zero width, but the blades would not be safe. This opens up a lane for future research on the subject. In order to maximize efficiency, it would be optimal to have research on the minimum cross-sectional areas for different materials in the use of small-scale wind turbines. Analyzing the stresses on the blades would create standards on the sizes to keep the turbine safe while minimizing material and maximizing the efficiency of the turbine. Manufacturers could use that information when producing turbines for different areas. With different sized turbines needing different levels of strength, there is a lot of variety in design. This requires a vast amount of knowledge when designing. Future research could make that easier for manufacturers. It also could allow businesses and households to make decisions when purchasing a turbine. They would be able to know which turbines would be most efficient and safe.

The results with reference to the twist have narrowed down the choices for twist in a blade's design. The range has been narrowed to between 25 and 35 degrees of twist. This sets a baseline that a manufacturer can set as a standard and base their orientation off of. This is still a very large range due to this study's use of four angles that are fairly spaced out. This opens the door for future research into the angle of twist. Studying at small increments would help researchers understand exactly the level of twist needed. This information would also aid manufacturers in their choices as well as consumers.

There are also other parameters that should be examined. Testing how different shapes respond to different wind conditions would be important to a manufacturer when deciding which turbines to build and where to market them. It would help consumers consider the wind locations for them when purchasing a turbine. These considerations make testing in different conditions a step that should be pursued. Another key component is the angle at which the wind hits the turbine. Turbines are being designed now to orient themselves for most efficient use based on the pitch angle relative to the wind [3]. Refining this method would allow for the most efficient use as a wind turbine would always orient itself to be able to produce the most energy.

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