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Producing Electric Power from the Wind: A Study of Flow Mechanics and Blade Efficiency

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Key words: Geometric angle of attack, Dynamic angle of attack, Horizontal Axis Windmill; Airfoil Flow Mechanics, Ratio of the Coefficients, Blade efficiency

Author Summary: In many locations, the installation of windmills to produce electric energy is not economic due to the efficiency of the machine to convert wind energy to electric energy. There is a theoretical limit (Betz's Law) of 59.3% of the energy of the wind that is available for conversion to electric energy. This makes sense since if you extract all of the kinetic energy of the wind, the wind comes to a stop and does not flow over the blade. If the blades of the windmill become more efficient, the windmill could become more economically viable for more installations. This is a study of the flow mechanics and efficiency of the windmill blade in the hopes that some design improvements might push these machine's output closer to the Betz Theoretical Limit.

Abstract

Electric power generated from the wind can help our society become less dependent upon the production of foreign oil. Windmills of old were made with blades that had a cross-section of a rectangle. These were inexpensive blades sweeping out small circles by today's standards. Windmill rotor blades today have airfoil cross-sections, which reduce drag and increase the performance [1].

My hypothesis is that the symmetrical airfoils will outperform the flat-bottomed airfoil and rectangular blades. This is important since increasing the efficiency of the windmill will increase its affordability and use. To test my hypothesis, I created a wind tunnel and windmill to test the different blades. Twelve inch long blades measuring 2 and 5 inches from front to back were used. The length of the blade was 12 inches. The windmill was made out of PVC pipe [2]. To smooth the airflow, I used an array of pre-cut pipes resembling the same in a 2009 US Department of Energy report on windmills and wind energy [3].

In each series of experiments, I waited for the wind tunnel and air smoother to reach a steady state flow of air. The airflow speed was 11.2 feet per second and 5.8 feet per second. I set the Static Angle of the blades on the rotor and then put the windmill into the airflow. I waited for the rotors to reach steady state and then recorded power data and measured the rotational speed of the rotor with a strobe light. I averaged the observations and graphed the output results. I calculated the net Dynamic Angle of attack for points along the leading edge of the rotors and graphed the ratio of the coefficients for each calculated net Dynamic Angle.

My hypothesis was correct as the symmetrical airfoils out performed the flat-bottomed airfoils and control blades. At the 11.2 ft/sec wind speed, the 2" symmetrical blade produced 28% more power than the 2" flat-bottomed blade at a 5-degree static angle; 56% more power at a 10-degree static angle. The 2" symmetrical blade also produced twice the power of the 5" symmetrical blade.

At the 5.8 ft/sec wind speed, the 2" symmetrical blade produced 11% more power than the 2" flat-bottomed blade at 5-degree static angle; 84% more power than the flat-bottomed blade at a 10-degree static angle. The 2" symmetrical blade power output increased 12.5% at the 10-degree static angle over the 5-degree static angle. The 2" blade produced 23% more power than the 5" symmetrical blade at the 5.8 ft/sec wind speed.

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Introduction

Historians have determined that the use of the wind as an energy source dates back centuries. At the end of the 19th century in Europe, it is estimated that over 30,000 windmills were in use pumping water or grinding grain. With the advent of the industrial revolution, interest in wind energy waned as engines proved to be a more reliable and potent source of power. However, in the 1970's came the first oil shortage and interest in wind energy revived. Today, electricity generated from the wind can help our society become less dependent upon the production of foreign oil. Wind movement on earth is due to the sun's rays heating the atmosphere unevenly, so wind energy is a renewable source of energy. Since the 1970's the circles swept out by the blades of the windmill and the windmill efficiency have increased significantly [4].

Windmills of old were made with blades that had a cross-section of a rectangle. These were inexpensive blades sweeping out small circles by today's standards. Blades today have airfoil cross-sections and sweep out large circles. Airfoil cross sections help reduce drag and increase the performance of the blade [1]. But which blade cross section is the most effective?

My hypothesis is that the symmetrical airfoil will produce superior electrical output. The following study compares the performance of a symmetrical and flat-bottomed airfoil to that of the rectangular control blade. The study will look at two inch and five inch blades measured from the leading edge to the trailing edge, at static angles to the wind from 5 degrees to 30 degrees, and in two wind speed conditions, 5.8 feet per second and 11.2 feet per second.

Materials and Methods

To test my hypothesis, I created a wind tunnel (Figure 1) and windmill to test the different blades. The blades were readily available from Flying Foam, of Colorado Springs, Colorado, in both 2 and 5 inches from front to back. The blades are all 12 inches long. The thicknesses of all the 2-inch blades are the same; the thicknesses of all the 5-inch blades are all the same. One rotor had four blades. There was one rotor for each blade cross section. For example one rotor had four, 2" (from front to back) symmetrical blades and one rotor had four, 2" flat-bottomed blades. Multiple trials were done with each rotor in each static angle configuration; where the static angle was set (between 5 and 30 degrees) prior to the experiment. The static angle is the angle between the centerline of the blade and the plane just in front of the rotor, perpendicular to the approaching wind. There are 10 observations for each data point on the graphs. The standard error is shown with a bar. The windmill was made out of PVC pipe, inspired by a US Department of Energy Report [3]. To smooth the airflow, I used an array of pre-cut pipes. The cross section ended up resembling that in a 2009 US DOE report [3].

The hub of the windmill was made of PVC. I drilled a hole in the hub for the shaft that turned the generator. The blades were glued to short pieces of PVC and then twisted into the hub at measured "static angles" [2]. The foam blades were reinforced with file folder cardboard and pre-stressed so the blades did not hit the frame in the high wind condition [5]. The glue used was recommended by the owner of Flying Foam. As it dried, the glue filled voids between the parts. I taped the blade to the short PVC piece, holding it in place as the glue set. The resulting laminations and glue voids is similar to those experience by Sandia Labs in 2010 [5].

For each series of experiments, I waited for the wind tunnel to reach a steady state flow of air. The airflow was measured at 12 points along the face and averaged. The Static Angle, the angle the blade centerline makes with respect to the plane of the circle swept out by the blades, was set and then the windmill was set into the airflow. After reaching steady state, I measured the power 10 times and averaged the results and graphed power output vs. static angle. I measured the rotational velocity of the rotor using a strobe light and calculated the dynamic angle of attack. The dynamic angle of attack is the sum of two vectors, the airspeed approaching the rotor and the vector due to the rotation of the rotor [4]. The vector due to rotation changes along the leading edge of the blade [6] from very small at the hub to a maximum at the blade tip. I calculated the net dynamic angle of attack each inch along the leading edge for each static angle set before the experiment, and graphed those resulting angles. For each net angle of attack, I also graphed

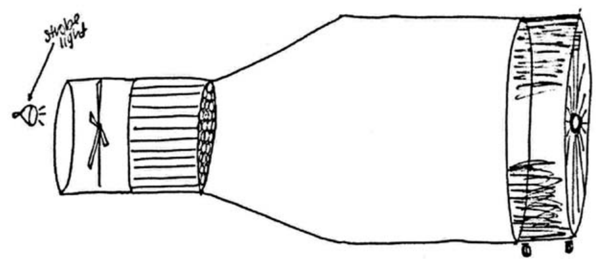

Figure 1

The sketch to the left (Figure 1) is the equipment set up. A four foot diameter fan is to the right in the sketch. Over 25 feet, the the wind tunnel necks down the airflow and passes the air through the smoother (DOE Report 2009). To the left is the strobe light I used to measure the rotational velocity of the rotor blades.

Figure 1. (both boxes above)

of the ratio of the coefficients (Lift/Drag) from the Flying Foam graph (Figure 2) [7] along the leading edge to see the effectiveness of the blade at that specific point.

For an airfoil, the ratio of the coefficients is the Coefficient of Lift divided by the Coefficient of Drag. This is a measure of blade effectiveness. At zero degrees angle of attack, the airfoil produces no lift, only drag. The ratio then rises steeply from 0 to 4 degrees angle of attack, as shown above. Then the graph of the Ratio of the Coefficients rounds out and reaches a maximum of 12.5 at 6 degrees angle of attack. From 6 degrees to 12 degrees, the ratio of the coefficients declines but the value is greater than 10. From 12 degrees to 19 degrees angle of attack the Ratio steadily declines at approximately the same rate until flow separation or "stall" occurs. For each point along the leading edge of the blade, I graphed the ratio of the coefficients value from this graph.

Results

My hypothesis was correct: the symmetrical airfoil out performed the flat-bottomed airfoil at 11.2 and 5.8 feet per second wind speeds. See Figures 3 and 4.

At the 11.2 ft/sec wind speed, the 2" symmetrical blade produced 28% more power than the 2" flat-bottomed blade at a 5-degree static angle; 56% more power at a 10-degree static angle. The 2" symmetrical blade also produced twice the power of the 5" symmetrical blade. See Figure 3.

At the 5.8 ft/sec wind speed, the 2" symmetrical blade produced 11% more power than the 2" flat-bottomed blade at 5-degree static angle; 84% more power than the flat-bottomed blade at a

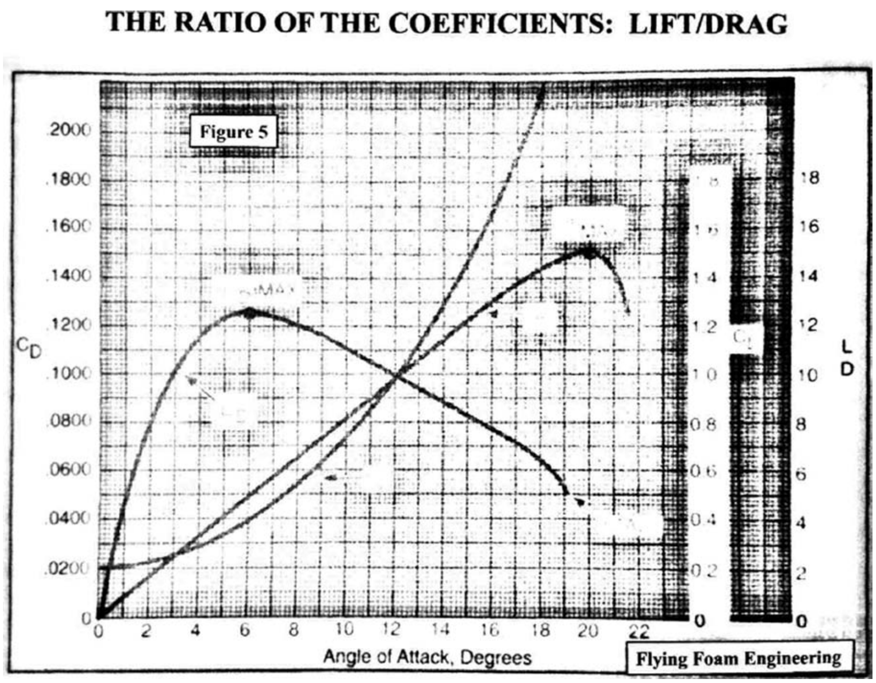

Figure 2. The Ratio of the Coefficients Graph [7].

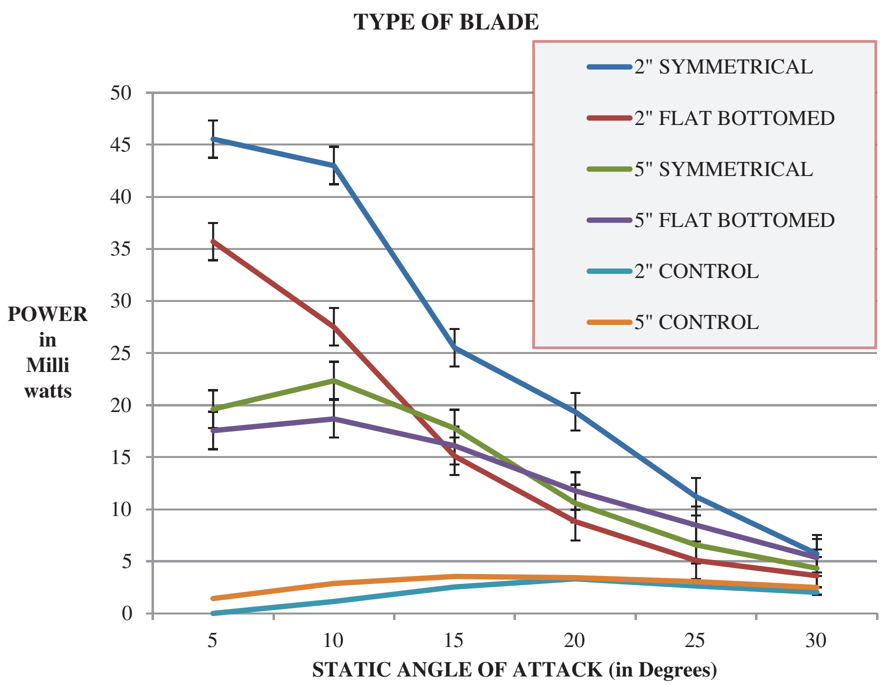

Figure 3. All Blades at 11.2 feet per second wind speed

10-degree static angle. The 2" symmetrical blade power output increased 12.5% at the 10-degree static angle over the 5-degree static angle. The 2" blade produced 23% more power than the 5" symmetrical blade at the 5.8 ft/sec wind speed. (Figure 4)

Discussion of Results

At the 11.2 ft/sec wind speed, the 2" symmetrical blade produced 28% more power than the 2" flat-bottomed blade at a 5-degree static angle; 56% more power at a 10-degree static angle. (Figure 3) This indicates the significance of drag on the blades in these experiments. The silhouette of the blades for each size is the same. However, the clockwise flow around the airfoil has a sharp turn for the flat-bottomed blade making flow separation a higher probability event during the experiments. At 10 degrees static angle, the increase from 28% to 56% is more due to a fall off in output rather than an increase in efficiency of the symmetrical blade. To better understand the flow mechanics of these results, I used the observed rotational velocity of the rotor and the observed speed of the wind approaching the blade to calculate the dynamic angle of attack.

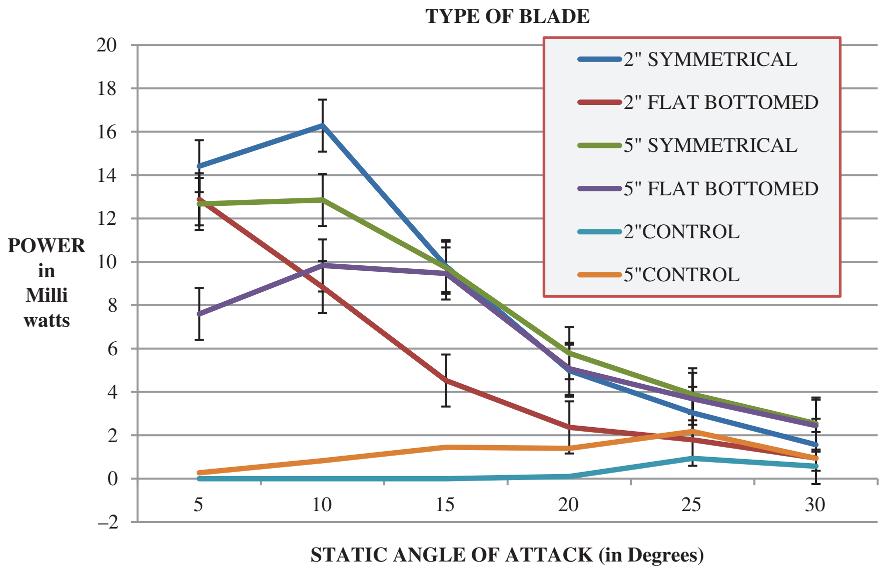

Figure 4. All Blades at 5.8 feet per second wind speed

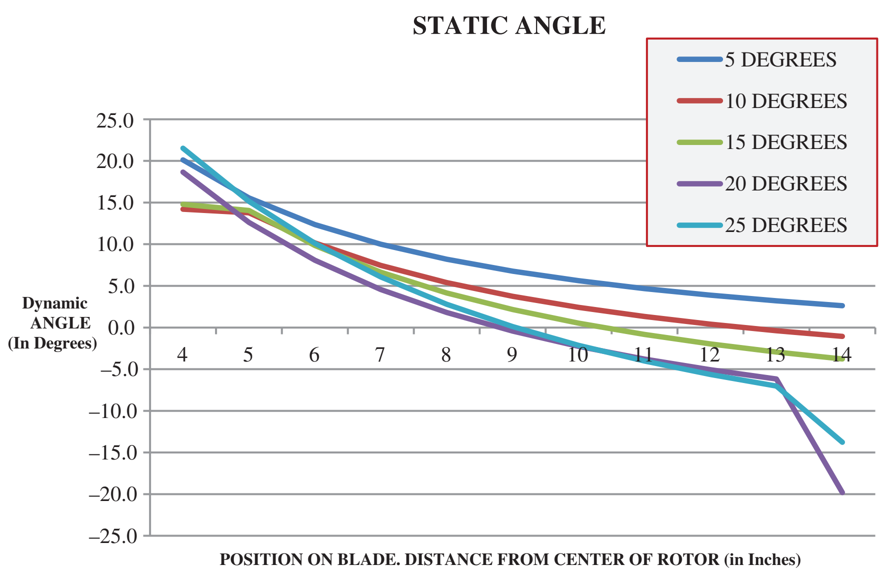

Figure 5. Dynamic Angle of Attack for the 2" symmetric blade in 11.2 feet per second wind.

Net Dynamic Angle of Attack Along the Blade Leading Edge

The Dynamic Angle is graphed for every inch along the leading edge of the rotor blade [8]. Different colors represent the static angle set for that series of experiments. The first dynamic angle calculation is located 4 inches from the center of the rotor. I calculated the dynamic angle once again one inch further out, and so on. The different static angle settings are shown by different color lines.

From the center of the rotor out to a distance of 5 inches along the rotor, the net dynamic angle of attack is greater than 15 degrees and not very effective. When the static angle was set at 15 degrees, 20 degrees and 25 degrees, the dynamic angle of attack for the last 3 inches of the rotor blade is less than zero and produces drag and no lift [9].

For the first 2 inches of the blade, the dynamic angle is too large to be effective and for the last 3 inches of the blade static angles of 20 and 25 degrees produces drag and no lift [9].

For the first inch of the blade, the dynamic angle is too large to be effective and for the last 4 inches of the blade static angles of 15, 20 and 25 degrees produces drag and no lift [9].

For the first 2 inches of the blade, the dynamic angle is too large to be effective and for the last 5 inches of the blade static angles of 15, 20 and 25 degrees produces drag and no lift [9].

To this point, we have evaluated the flow mechanics of lift along the blade qualitatively. To better analyze the flow mechanics of lift and drag at each of these points along the leading edges of these blades, I used the ratio of the coefficients [4]. So for each graph in figures 5 through 8, I graphed the resulting Ratio of the Coefficients for each of the calculated dynamic angles, and produced figures 9 through 12.

Graphing the Ratio of the Coefficients vs. The Point Along the Leading Edge (Distance from the Center of the Rotor)

At every Static Angle setting there is some section of the rotor that is producing a maximum ratio of the coefficients, which

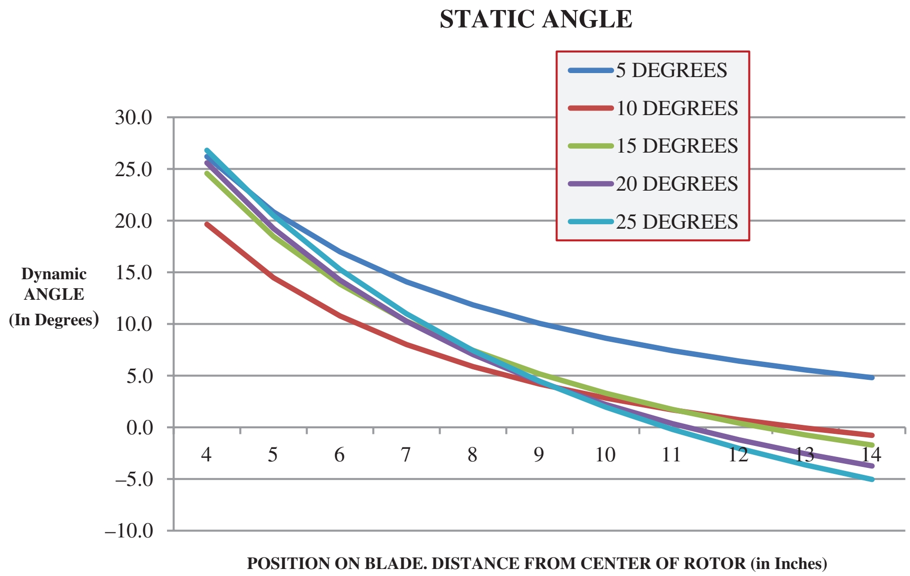

Figure 6. Dynamic Angle of attack for the 5" symmetric blade in 11.2 feet per second wind.

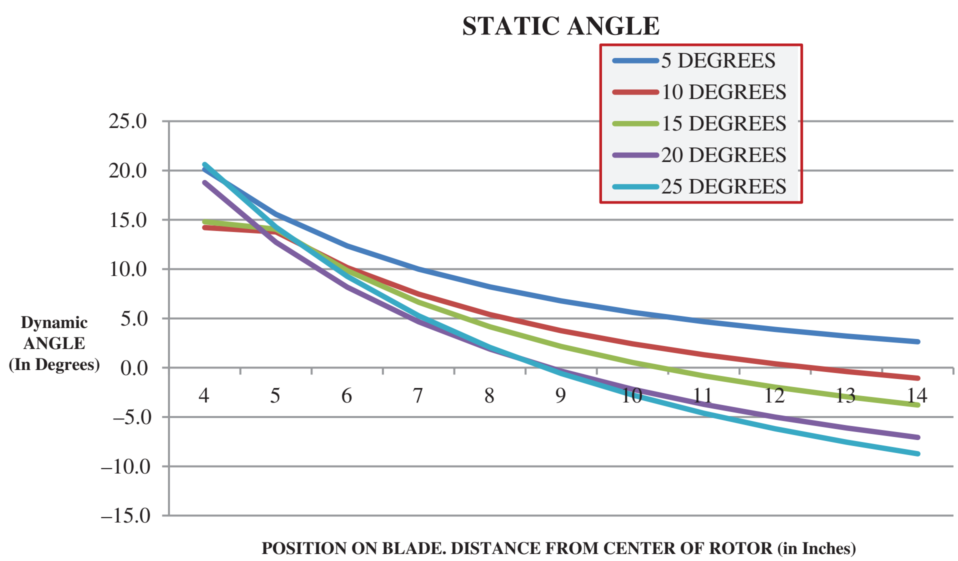

Figure 7. Dynamic angle of attack for the 2" symmetric blade in a 5.8 feet per second wind.

accounts for the blades turning and producing some level of power. Also, it is apparent that the area under the curves is related to total observed output because the more lift the greater the production of power.

Comparing this graph, Figure 9 to Figure 3, you can see the greatest output was for the blue, 5-degree static angle line. That blade had dynamic angles along the blade that produced a ratio of 8 from 6 inches all the way out to the end of the blade at 14 inches. This is also a maximum of area under the curve for this series of experiments. The 10-degree static angle produced the second highest output in Figure 3. In Figure 9, the dynamic angles along that blade produced a ratio of 8 only from 5 inches to 10 along the blade

Comparing Figure 10 to Figure 3, the outcome is the same as the 2-inch blade above. That is, the area under the blue line (5 degree static angle) is dominant and so too was the output. The second largest output was 10 degrees static angle, which is the red line above. The 10 and 15-degree static angle output shown in Figure 3 show a much smaller output difference than in the 2-inch blade and the ratio of coefficient graph above bears this out. From 10 inches out to the tip of the blade, the lines are very close, and the areas under these curves are also very close. But from a position 5 inches to 8 inches along the blade, the 10-degree static angle line (red line) is greater than the 15-degree static angle line (green line).

Comparing Figure 11 to Figure 4, the ratio of coefficients predicts the 5-degree static angle observed power output would be greater that the 10-degree static angle output. But in Figure 4, the power output was greater at the 10-degree static angle. The 2" symmetrical blade power output increased 12.5% at the 10-degree static angle over the 5-degree static angle. The increase in performance from a static angle of 5 degrees to 10 degrees is interesting since the results are not seen in the graph of the coefficients. In the graph of the coefficients, the area under the curve is related to the

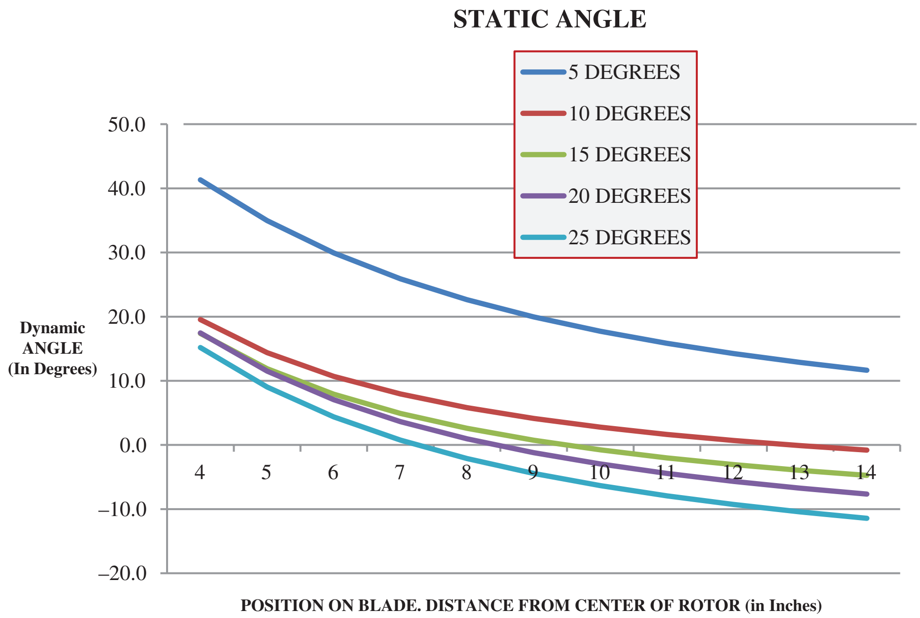

Figure 8. Dynamic angle of attack for the 5" symmetric blade in a 5.8 feet per second wind.

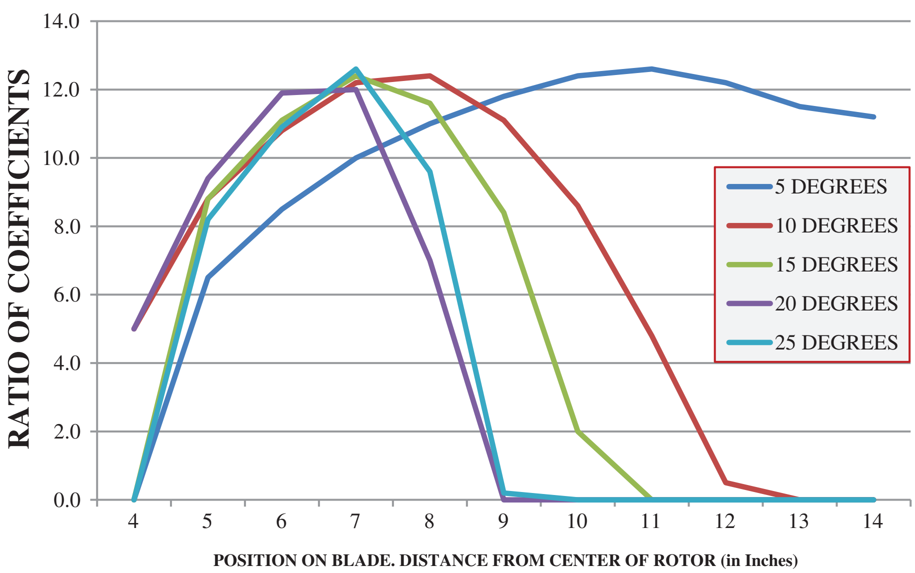

Figure 9. Ratio of the Coefficients for the 2" symmetric blade in an 11.2 feet per second wind.

performance of the blade [8]. The area under the curve for the 10-degree static angle is actually 25% less than the area under the 5-degree static angle curve (Figure 11). At this lower air speed, the vector of flow caused by the starting vortex is more significant than in the 11.2 ft/sec wind experiments. This additional flow vector lowers the angle of attack from that shown in the ratio of the coefficients, thereby increasing the area under the curve and improving the performance at the 10-degree static angle [6]. What pushes the red line to the blue line in Figure 11 is an additional flow vector I cannot measure or calculate but is there due to the influence of the starting vortex. This additional vector, when added to the net Dynamic angle produces the net Geometric angle of attack for the rotor.

Drag

The 2" blade produced 23% more power than the 5" symmetrical blade at the 5.8 ft/sec wind speed. (Figure 4) This indicates a reduction in the influence of drag on the power output for the 5.8 ft/sec, the lower air speed [10].

The 2" symmetrical blade also produced twice the power of the 5" symmetrical blade at 11.2 ft/sec, (Figure 3) indicating the influence of drag on the experiments using the 11.2 ft/sec high wind condition [8]. The 5" blade had more surface area and drag.

From the center of the rotor out to a distance of 5 inches along the rotor, the net dynamic angle of attack is greater than 15 degrees [9]. When the static angle of attack is greater than 15 degrees, the last 3 inches of the rotor blade produces drag only. This is also

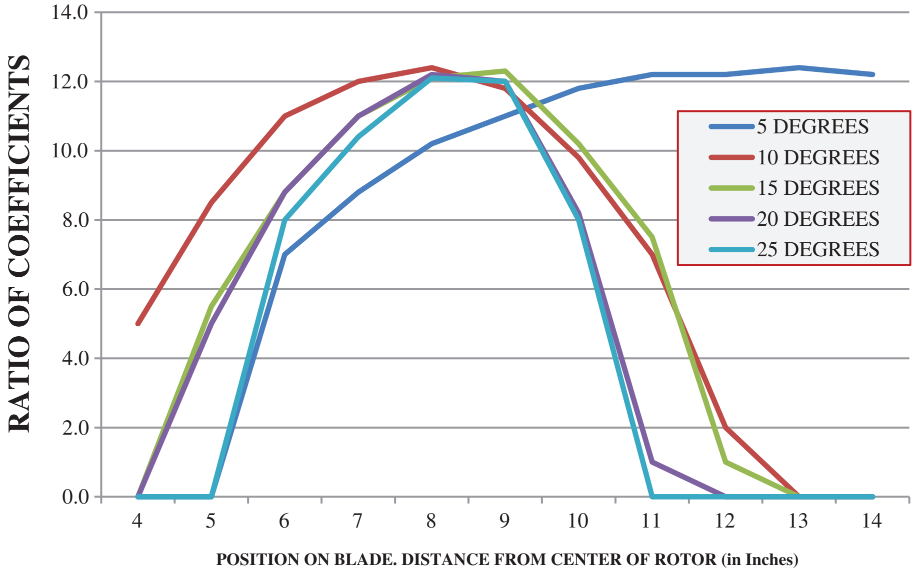

Figure 10. Ratio of the Coefficients for the 5" symmetrical blade in an 11.2 feet per second wind.

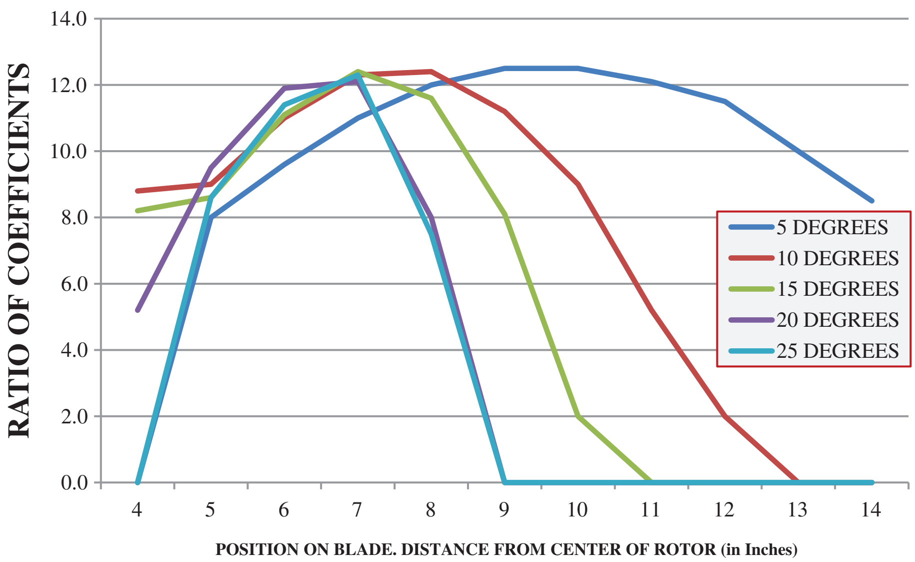

Figure 11. Ratio of Coefficients for the 2" symmetric blade in a 5.8 feet per second wind.

shown in the graphs of the coefficients. The net dynamic angle close to the rotor produces a separated flow as does the end of the blade when the static angle is 20 degrees or more [11]. (See Figures 5 to 8)

What is interesting, however, is that no matter what the static angle set for the blade, there is a point along the rotor blade where there is a maximum ratio of Lift to Drag. The blades having points along the blade where the Ratio of the Coefficients is greater than 10 are set to a static angle of 5 and 10 degrees. This demonstrates the importance of the ratio of the coefficients [4]. That is, the rotor still turned producing power even though most of the blade flow mechanics along most of the blade were in separation. (See Figures 7 to 10). In some experiments only a few inches of the blade had a ratio of the coefficients above 10, yet this was enough to turn the rotor and produce energy.

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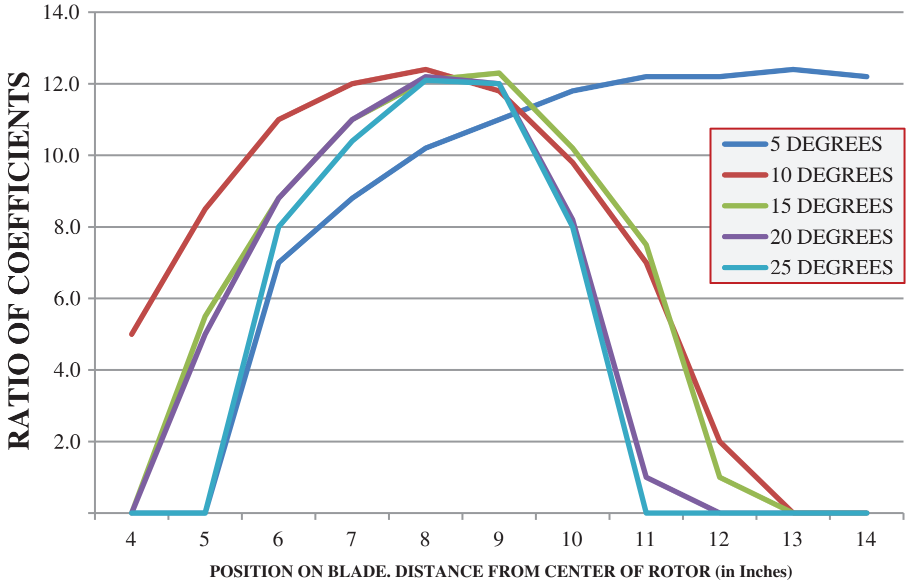

Figure 12. Ratio of the Coefficients for the 5" symmetric blade in a 5.8 feet per second wind.

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