On the Use of Cambered Plate Airfoils for Small Wind Turbines

Aaron Kummer¹, Jack DiMeo¹, Mark Hebel², Kenneth Visser¹

¹ Department of Mechanical and Aeronautical Engineering
² School of Engineering Lab
Clarkson University, Potsdam, NY 13699, USA

E-mail: kummera@clarkson.edu, dimeojd@clarkson.edu, mhebel@clarkson.edu, kvisser@clarkson.edu

Abstract. The use of constant thickness, cambered plates is being explored as a means to reduce the cost of rotors for small wind turbines. Literature suggests that at low Reynolds numbers there is an advantage over conventional airfoils, and tests conducted on a 2.5 m ducted rotor indicate a constant thickness airfoil to be a viable solution. An operational turbine with a 3 m rotor was developed and is currently being tested. Data supports predictions and shows encouraging results.

1. Introduction
In order to strengthen small wind as an economically viable, clean energy option, the cost per unit of energy ($/kWh) needs to be reduced to be competitive with solar installations. Turbines developed with this metric need to lower the manufacturing cost and increase the energy output. This is the current focus of the small wind turbine research being performed at Clarkson University. The need for improved performance has driven the baseline design towards a 3 m ducted turbine, pictured in Figure 1. The need for non-recurring, and recurring, cost reduction has led to, among other things, a focus on the design, manufacturing, and testing of uniform thickness blade geometries.

2. Background
To maximize the cost-effectiveness of a small wind turbine, the blades must be produced at reasonable cost with a blade geometry that is able to extract the most energy from the wind. Optimum blade designs typically employ an airfoil with a high lift/drag ratio (L/D). Giguere and Selig [1], for instance, have designed airfoils specifically for small wind turbine blades, such as the SG60XX series, but these airfoils can be a challenge to manufacture into a practical blade design.

Optimized blade designs require a geometry where the chord and twist vary as a function of radius. The initial capital costs for injection molds require the sale of many turbines to recover the investment, a
major disincentive for optimized designs. Compromises, such as the constant chord, untwisted blades of the Bergey XL.1 and 10 result from these manufacturing constraints and limit the potential performance.

R.T. Jones, in his book “Wing Theory”, has an illustration reproduced, with additions by the authors to highlight the differences between airfoils, as shown in Figure 2 [2]. Drawing on the work by Schmitz [3], he notes the large L/D benefits of curved plate airfoils compared to that of ‘conventional foils’ at low Reynolds numbers (Re). At a Re of 40,000, the curved plate behaviour in Figure 2 exhibits a max L/D approximately 3 times that of the conventional style airfoil. Although at the higher Re of 120,000, the maximum lift of the conventional foil is higher than the curved plate, the max L/D values, where the design point would occur, are very close.

Studies have reported the benefits of cambered plates over conventional foils at low Reynolds numbers [4] and their use for micro air vehicles [5][6]. Bruining concluded that as slow running wind turbines do not require high quality airfoils, the easier and cheaper manufacture of such cambered plates would be advantageous. 2-D tests were conducted on 10% cambered plate configurations and a maximum L/D of 23 was observed for the clean configuration at Re of 100,000 [7]. To the authors’ knowledge, the utilization of cambered plate airfoils for commercial, small wind turbines has been limited to drag driven machines, such as the Aermotor [8] and the studies by Kragten [9] for non-optimized rectangular planforms.

The results of Schmitz prompted the authors, in a previous study [10], to utilize a cambered plate airfoil, the GOE417a, with an optimized planform and twist distribution for a 2.5 m rotor ducted turbine wind tunnel test. Schmitz [3] had reported a maximum L/D of 26 at a Re of 42,000 and more recent
measurements by Fox as reported in [1] measured optimum L/D values in excess of 80 for Re of about 400,000. In order to ensure the performance results were not marred by manufacturing errors, the blades were machined from aluminium billets into constant thickness cambered plates. A sketch of the GOE417a airfoil is shown in Figure 3 along with the milled blade used in the wind tunnel test described below. It should also be noted that this type of airfoil, with a lower max L/D, also performs better at lower tip speed ratios, inherently driving the design to a lower RPM, and lower noise operating point [12].

The results from the 2016 wind tunnel test validated the performance predictions and the pertinent details are shown in Figure 4. The black triangles represent the published power curve of the Bergey Excel 1 turbine, also a 2.5 m rotor. The solid filled circles are the data for the Clarkson open rotor configuration. It can be seen that the performance of the current rotor is better than the Bergey, which is to be expected, as the Bergey uses an untwisted constant chord blade, while the Clarkson blade has an optimum twist and planform distribution. Both sets of data sit below the upper theoretical Betz limit for a 2.5 meter open rotor, as they should, which is denoted by the solid purple curve. Since the focus is not on ducted turbines in this study, the additional data can be read about in the referenced study [10].

Based on the promising test results, a fully operational 3 m rotor ducted turbine was constructed to operate under real world, ambient conditions.

3. Objectives
The focus of the present study was to examine manufacturing methods to produce the cambered plate blades, with an optimized chord and twist distribution, at a reasonable price. Their performance would then be evaluated as a means of improved $/kWh production. This involves the design, manufacturing, and testing of blades with the aim to create a turbine designed to maximize the annual energy output (AEO) while minimizing productions costs.
4. Methodology

The design of the blades utilized the Clarkson University inhouse program, mRotor, to predict wind turbine performance. Manufacturing focused on two methods: a carbon fiber layup method and the pressing of sheet aluminium. Since the blade is essentially a curved flat plate, each method can take advantage of the fact that the raw materials are also flat, simplifying manufacturing techniques.

4.1. Rotor Design

The rotor design was accomplished with an inhouse Blade Element Momentum (BEM) method, which divides the blade into span wise elements according to a given distribution. Each blade element is developed individually to balance the predefined incoming momentum against the loads generated on the blade. The total forces acting on each blade are summed, and the performance of the rotor can be evaluated. This optimum geometry maximizes the efficiency of the turbine by setting the optimum lift to drag ratio for each blade element. Details on the method used can be found in [12] and [13].

Two rotor geometries were generated with a tip speed ratio (TSR) of 2.9, one using 3 blades and one using 5 blades, as shown in Figure 5. This is because the optimum performance occurs at a lower TSR value for lower maximum L/D values of the GOE airfoil [12]. The addition of two blades for the 5 bladed rotor increased the solidity from about 16% for the 3 bladed design to a little over 19%. The 5 bladed design was accomplished not by simply adding 2 more blades from the 3 bladed configuration, but rather optimized for a TSR of 2.9, the same operating conditions as the 3 bladed design. No correction for this was made in the performance prediction for the 3% increase, as suggested in [14], and the experimental results will be examined accordingly. This lower TSR reduces the Reynolds number along the blade considerably. At the maximum operating point of 250 RPM, the tip Reynolds number for the 3 bladed turbine is on the order of 500,000 and approximately 400,000 for the 5 bladed design. Of note is the fact that the lower TSR also reduces the acoustic signature.

Figure 5: mRotor optimized design geometries  a) 3 bladed  b) 5 bladed
4.2. Blade Construction

The first rotor, a 3 bladed configuration, was built using carbon fiber and the second, the 5 bladed, with sheet aluminium pressed into shape. The latter should exhibit slightly better performance. According to theory, a slight increase in aerodynamic performance can be gained with an increase in blade number.

The 3 bladed configuration was manufactured by VISTEX [15] using a proprietary non-autoclave, carbon fiber hand layup, followed by a press. 8 plies were laid at 0° and 90° alternatively. Using a uniform pressure and temperature mold, the blades are pressed between a temperature controlled and a rigid compression mold. The press is designed so the composite undergoes uniform pressurization, to ensure uniform strength in the material.

The 5 bladed geometry was manufactured at Clarkson using sheet aluminium cut on a plasma cutter and stamped into the desired shape. Normally, an increase in blade number would not be considered due to the increased cost, but the stamping process chosen has proved to be more cost effective than the carbon fiber construction, thus decreasing the cost of production by an estimated ninety percent. The attractiveness of aluminium stamping stems from its uses in many manufacturing processes. The big drawback is the expense in creating the die, which needs to be designed such that the blade ‘springs back’ to the correct shape.

Several commercial software packages were investigated to calculate this die press geometry, but none were satisfactory. The inherent curvature in the chordwise direction and twist distribution along the blade makes it very difficult to predict the desired ‘jig’ geometry that results in the desired final shape.

A method was developed at Clarkson that utilized an iterative empirical calculation method to compensate for the spring back of the aluminium 5052 sheet metal. The process first started with dividing the blade geometry from mRotor into a series of airfoil slices. Each of these slices was then analysed to compute the curve that the metal needed to be bent to for the proper blade geometry to be achieved once the metal relaxes. Doing this for each airfoil yields a series of new curves that were then lofted into a form. The form was sliced into ribs and the aluminium pressed on the form. This form was constructed from a series of steel ribs, along with a rack to hold these ribs for the metal to be stamped over. The resulting relaxed shape was examined, and a next iteration performed. Coupon tests confirmed the viability and a full blade was delivered with acceptable results after 8 iterations. A sketch of the ribs with the top press can be seen in Figure 6.

5. Results

The test bed for the blades is the Clarkson University 3 m ducted wind turbine. Figure 7 illustrates the geometry and some specifications. Although the blades were designed for the ducted turbine, the focus of this paper is on the curved plate concept and other details of the turbine design will be shared at a later date.

Figure 6: Sketch of mold for aluminum blades
Figure 7. Three-meter ducted turbine at Clarkson University

5.1. Carbon Blade Set
The carbon blades were manufactured using VISTEX’s process and Figure 8 illustrates the result for the 3 bladed configuration. Initially, the blades had a carbon tab built into the blade at the root to attach to the hub. This proved to be structurally unsound due to the severe oscillations when mounted on the hub. The tabs were removed, and additional attachment plates were created to hold the blades in a ‘press-fit’, minimizing stress concentrations from the mechanical fasteners.

Figure 8: Cambered plate 1.5 m rotor blades  a) Blade in mold b) Blade mounting on hub
The rotor went online in April of 2019. Unfortunately, the carbon blades suffered a catastrophic failure and the turbine had to be shut down. Figures 9 and 10 illustrate the results after 45 minutes of testing. Before the blades failed however, a 45 min period of data was acquired that supported the performance observed in the wind tunnel. This data is presented in Figure 9. Note that at approximately 11:25 AM, the turbine recorded a value of about 3300W at a windspeed of 9.4 m/s. The turbine is designed to deliver about 3500W at 11 m/s. PDC is rectified DC power from the turbine. PAC is power to the grid. Here the performance indicated a better than predicted behaviour, which was encouraging.

![Figure 9. Time dependent power output for the 3 m Rotor](image)

After a thorough redesign, a sturdier blade to withstand the higher windspeeds was constructed and installed, as shown in Figure 11. These new blades consisted of 32 carbon layers at the root of the blade and 16 towards the tip. These new blades have been operating on the unit in Figure 7 since October 29, 2019. Data is currently being acquired and rated power outputs for the 3.5 kW generator have already been achieved, as shown by the energy and power curves in Figure 12.
The wind profile for the data of December 9 is shown in Figure 13 for comparison to Figure 12.

Figure 11: Strengthened carbon blade rotor

Figure 12: Clarkson University ducted turbine data - December 9, 2019

The wind profile for the data of December 9 is shown in Figure 13 for comparison to Figure 12.
5.2 Aluminium Blade Set

A press mold jig for the aluminium blades was made in Clarkson machine shop as shown in Figure 14a. The blade blank was cut out on the plasma cutter, using the ‘un-rolled’ geometry of the design from mRotor. The jig was then placed in a press, Figure 14b, and the blade pressed into the jig shape, from which it recovered elastically to the desired geometry. As mentioned previously, 8 iterations were required to successfully generate the correct geometry.

![Figure 14. Aluminium blade manufacturing](image)

- a) Blade blank
- b) Blade pressing

Figure 13: Clarkson University ducted turbine wind profile data - December 9, 2019
Current estimates put the metal blade tooling and fab at 1/10 the cost of the carbon, including labor. Although the 5 bladed rotor will not be tested until the summer of 2020, the manufactured result looks promising in terms of stiffness and shape. Figure 15 illustrates the layout of the pressed blades around the hub.

6. Concluding Remarks
The aerodynamics of cambered plate airfoils, and their use in the manufacture of small wind turbine blades with optimized chords and twists, indicate promising initial results. They appear to be very effective at the Reynolds number regime where most small wind turbines operate. Blades created with these airfoils can reduce the blade production cost substantially because of their low tooling and manufacturing costs.

Testing will continue in the summer of 2020 using the current 3 m test rig shown in Figure 16 (https://people.clarkson.edu/~kvisser/TACTurbine/) The 5 bladed aluminium configuration will be compared to the 3 bladed carbon fiber results, with the target goal of the project focused on a commercially viable turbine at half the $/kWh of the current market.

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