AC 2010-2282: A PRACTICAL BLADE MANUFACTURING TECHNIQUE FOR A WIND TURBINE DESIGN PROJECT IN A RENEWABLE ENERGY ENGINEERING COURSE

Mario Gomes, Rochester Institute of Technology (COE)

A practical blade manufacturing technique for a wind-turbine design project in a renewable energy engineering course

1 Abstract

A blade design project for a horizontal-axis wind-turbine was developed for a renewable energy course. The objective of the project was to design a set of blades for a turbine rotor to extract the maximum amount of power from a given 12 m/s wind speed while being constrained to a circular swept area of 1 m diameter or less. The rotors were designed using the traditional blade-element-momentum method. The performance of the blade was predicted and then the blades and hub were constructed and tested at the given windspeed for several loads. These tests provided data which allowed for a comparison between the predicted turbine design performance to its actual performance. Previous manufacturing techniques which formed each blade by removing material from a single rough block of material proved unsatisfactory since they were either too costly, required large amounts of machining time, or were too inaccurate due to hand construction. These problems led to the development a new technique using recyclable molds to quickly and accurately cast the blades using a durable and readily available urethane resin. The result was a process that minimized machining time, reduced cost and waste, and resulted in accurate and repeatable blade manufacture.

2 Project Goals and Constraints

- Design a 1 m diameter horizontal-axis wind turbine rotor to extract the largest amount of power from a 12 m/s incoming windspeed
- rotor diameter must be less than or equal to 1 m
- number of blades of the rotor must be less than or equal to four
- rotor hub must fit on the provided test-stand

Figure 1: A student-designed horizontal-axis wind-turbine rotor mounted on the teststand

- materials must cost less then $150 per rotor

The last two constraints listed above used to be constraints that the student groups had to meet for the design project, but for which they are no longer responsible given the new manufacturing procedure. The new hub design allows the students to focus more on the aerodynamic design and also, possibly in the future, on the transmission design. Shifting the responsibility for cost constraint from the students to the instructor greatly eased logistical difficulties and allowed cost sharing between groups for an overall improvement in the quality of the end-product.

3 Blade design background

This paper will focus on the manufacturing technique and not the design procedure(blade element momentum theory) since that can be readily found.[1] However, the following is brief background of the design procedure used by the students to design the blades which we then manufactured and tested. Students in the course designed blades for a horizontal-axis wind-turbine using a combination of 2-D aerodynamic simulation(using XFOIL) and standard blade element momentum(BEM) theory. Using the BEM method, the chord and twist distributions were determined for a chosen airfoil and angle of attack for that airfoil.

The lift and drag characteristics of the student chosen, or designed, airfoil are determined using the well-known and freely available XFOIL airfoil design software written by Mark Drela.[2] Note that this requires a design choice of the desired angle of attack. Figure 2 shows a single estimated lift, drag, and moment coefficient using XFOIL for a given airfoil and set of operating conditions.

When the aerodynamic characteristics of the airfoil has been determined, the optimal scaling and rotation of that airfoil for each location on the span of the blade is determined from the BEM design procedure. An example of the chord and twist distributions for a given blade design is shown in Figure 3. Next a 3-D solid model of the blade can be created using CAD software (e.g. Solidworks). Figure 3 shows an isometric view of one of the blades for a student-designed rotor. Note that many of these optimally designed blades have very thin trailing edges (due to the chosen airfoil used for the design). Such blades are almost impossible to accurately manufacture by hand, although hand construction was attempted by students before this blade manufacturing technique was developed. Most of the student designed rotors consisted of 3 to 4 identical blades, although a single bladed rotor (with a counter-weight) was built. Since most rotors had several blades, a casting technique is suitable to quickly and repeatedly manufacture the identical blades for the rotor. Also, the use of a two-part mold easily allows for the creation of extremely thin trailing edges on the cast blades.

4 Materials and manufacturing methods

Industrial wind-turbine blade manufacturing can be done in many possible ways, however since the individual blades are usually quite large(>2-3 m), methods used for their fabrication may not be appropriate for producing turbine blades on the order of half a meter in diameter. Although such small turbines do exist, their method of blade production may also not be appropriate, since the production volume is much larger than then the 3 to 4 prototype blades we require. Stereolithography[3] and 3-D rapid prototyping methods have been used to produce blade shapes for other projects which require blades of a similar size. However the disadvantages of cost, availability, and possible low-strength of final products do not allow these blade manufacturing methods to be widely adopted.

4.1 Previously used materials

Previously in this project, each individual blade was CNC machined out of a laminated block of hardwood which was made up of approximately three to four 1 inch boards which were glued together. The machining of these blocks was a time consuming process and utilized a

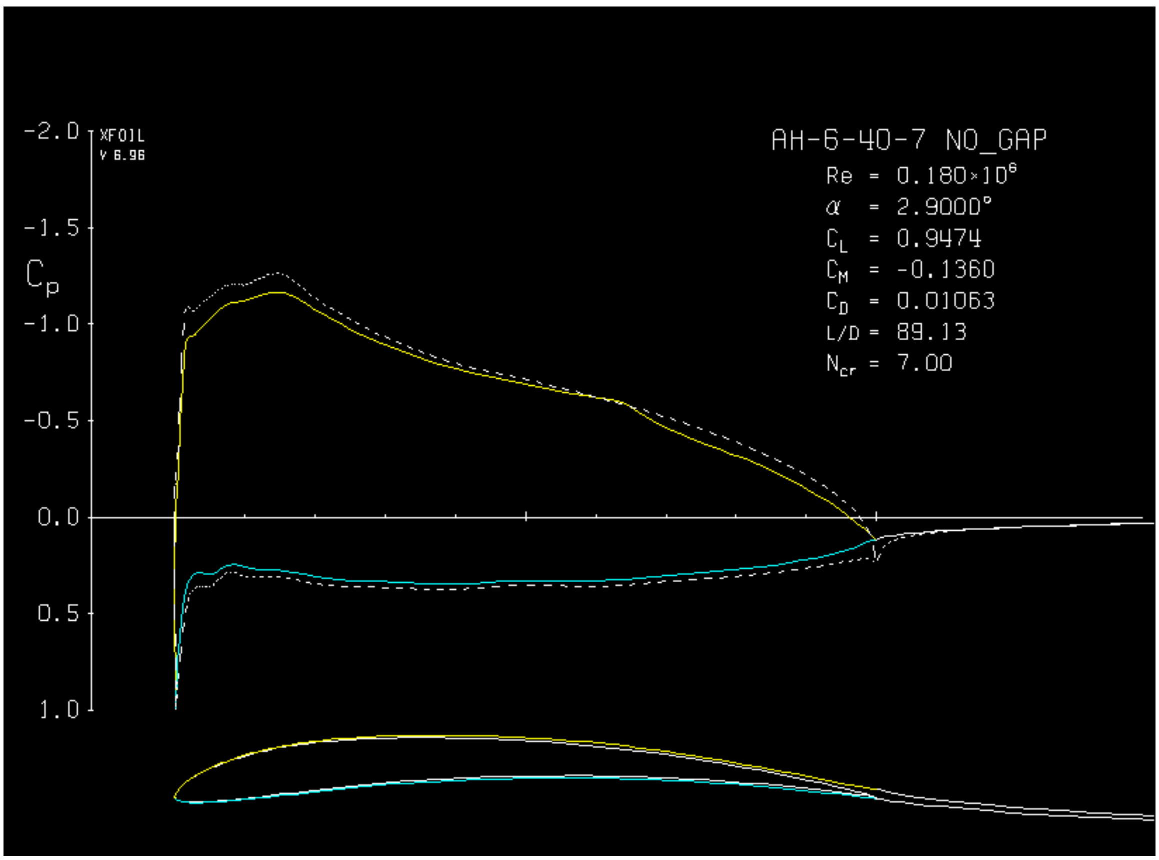

Figure 2: Estimated lift, drag, and moment coefficients for an AH-6-40-7 airfoil at the angle of attack which gives the largest lift-to-drag ratio for the given operating conditions

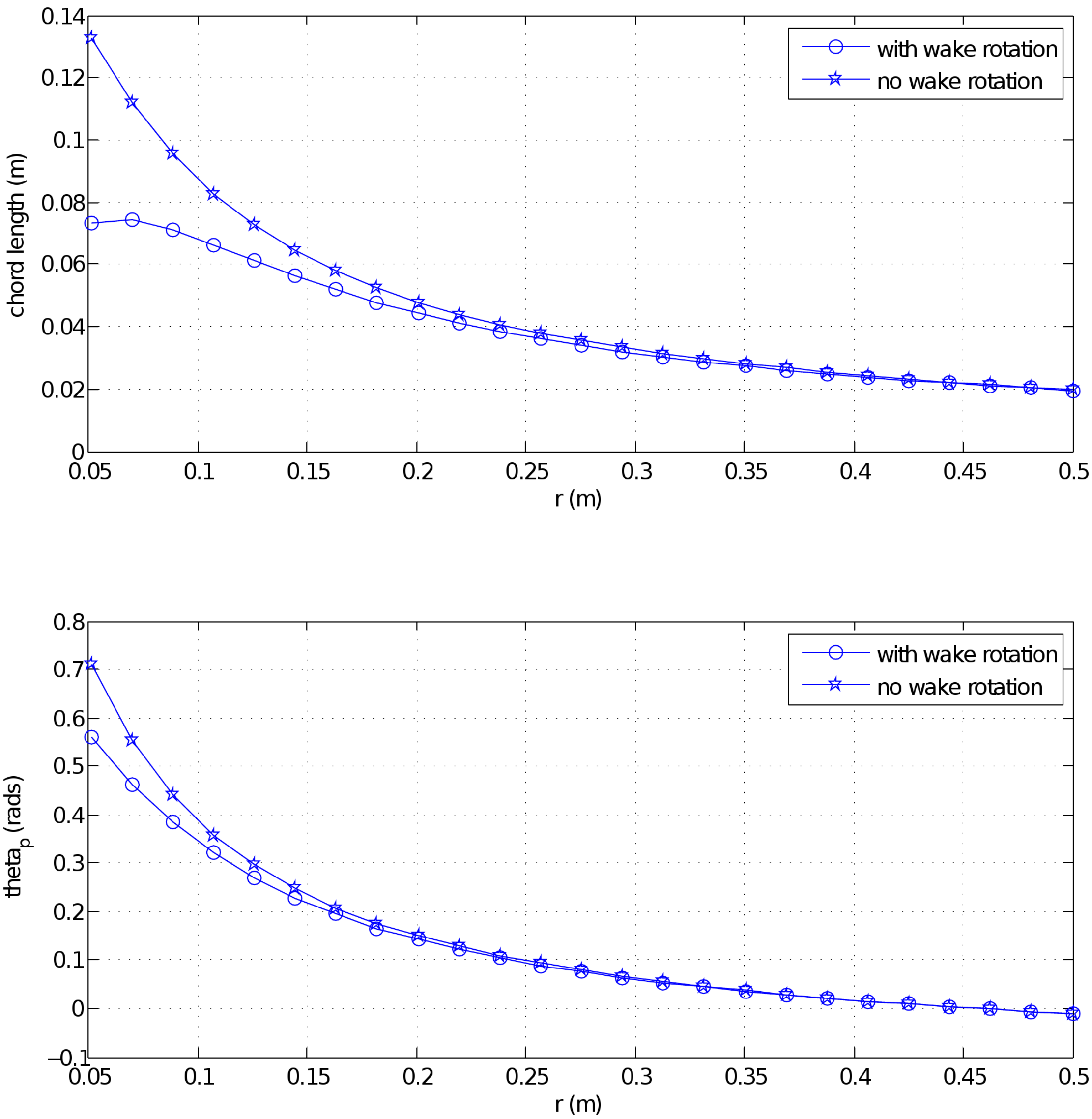

Figure 3: An example of non-constant chord and twist distributions versus span for a BEM optimally designed blade both with and without wake rotation for an incoming windspeed of 12 m/s, a tip speed ratio of 6, 3 bladed rotor, using a NACA 9506 airfoil cross-section, with a desired angle of attack equal to 6.9°, and having a lift coefficient at that angle of attack equal to approximately 1.3. Note that the rotor's non-zero hub diameter specifies that the blade not start at a span-location of zero.

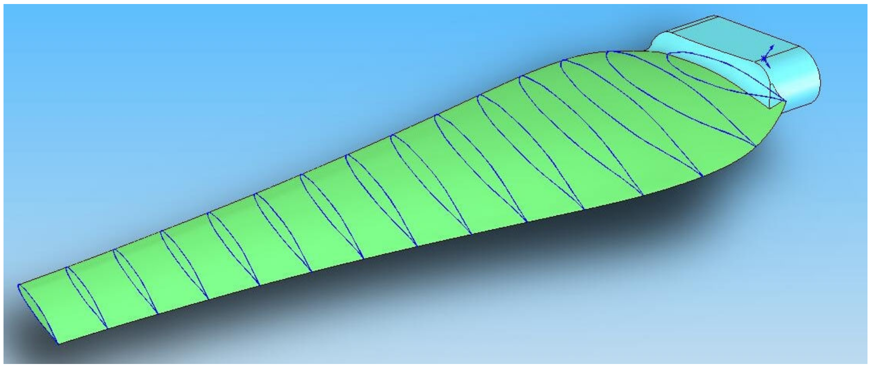

Figure 4: A student-designed horizontal-axis wind-turbine blade modeled in Solidworks.

metalworking CNC milling machining for machining wood. CNC milling machines are not designed for the dust which is created by machining wood. If this method were to be used again, a CNC router may be a more appropriate tool. Regardless of the tool used, machining of the second side of the blade is non-trivial since the bottom of the block is now no longer flat. The blade must be set in a bed of material which will conform to the shape of the blade in order to mount the partially machined blade to the bed of the milling machine. This process must then be repeated up to four times for a single rotor in order to make all of the needed blades. These experiences provided the motivation for developing an improved blade manufacturing technique.

4.2 Blade

The enabling technology for the casting process was two-part liquid urethane plastics. These materials can be mixed and then poured into a mold while in their liquid state. They then cure at room temperature to a durable solid. The material properties of the urethane plastics vary widely and many different varieties are readily available. For this project, we chose to use the urethane plastics manufactured by Smooth-On, Inc. The TASK-2 urethane plastic was chosen to be the blade material due to its low mixed viscosity (150cps), low demold time (60 min.), high tensile strength (6650 psi), low shrinkage (0.0012 in./in.), and moderate price ($120 per 2 gallons). Thus the blade cost for the urethane plastic resin material is approximately $7-$10 per blade depending on the shape of the blade and the size of the risers and vents in the mold.

4.3 Mold

Since each blade of the turbine rotor is identical, a casting procedure using a two-part mold is an appropriate choice. The sharp trailing edge that the rotor blades have is also very easy to produce using a casting method but is more difficult to support when machined. The size of the material for half of the mold for a typical blade is about 3" x 6" x 24". Two such blocks of mold material are needed for each blade.

Several materials were considered for the mold, aluminium, RenShape, Delrin plastic, and machineable wax. Aluminium is readily available, machines easily, and can take a very smooth surface finish. However, the cost of the aluminum exceeded the budget requirements for the projects. Recycling of the aluminium would reduce cost over time for this project, however, since there was no foundry on campus, and we had not space to develop a foundry, aluminium could not be used for the mold material.

RenShape modelling boards were proposed by the machinists who made the initial wood blades as a replacement material for the wood they were machining. RenShape material is designed to be formed by metalworking tools and is composed of polyurethane and some of the denser varieties can be machined to a smooth surface finish. However, RenShape was also outside the budget constraints and could not be recycled to reduce cost. Delrin plastic was also considered. It had the same advantages and disadvantages as RenShape and could not be used.

Machinable wax is not a strong as any of the previously considered materials, but it is designed for use in CNC milling machines and can take a smooth surface finish. It's cost, about $160-$200 per set of 2 blocks (enough material for 1 blade mold), is also outside of the budget constraints of the project. However, this wax has a low melting point, 300 °F - 310 °F, and can thus be easily recycled and reused for the next blade design. We had some initial concern about mold deformation due to urethane plastic heating during curing but we discovered that due to the thinness of the castings, this was not a problem. Machinable wax was chosen as the mold material and it worked quite well, as can be seen in Figure 4.3.

4.4 Hub

A common hub design was developed so that machining time during the semester could be reduced and student analysis could focus primarily on the blade design. The hubs consisted of a single cylinder of aluminium (4 in. diameter) and 3 in. long. Each blade is cast with an integral tab which then fits into slots machined into the hub at the appropriate angle for the blade design. Aluminium was chose due to its low cost, availability, strength, and machineability.

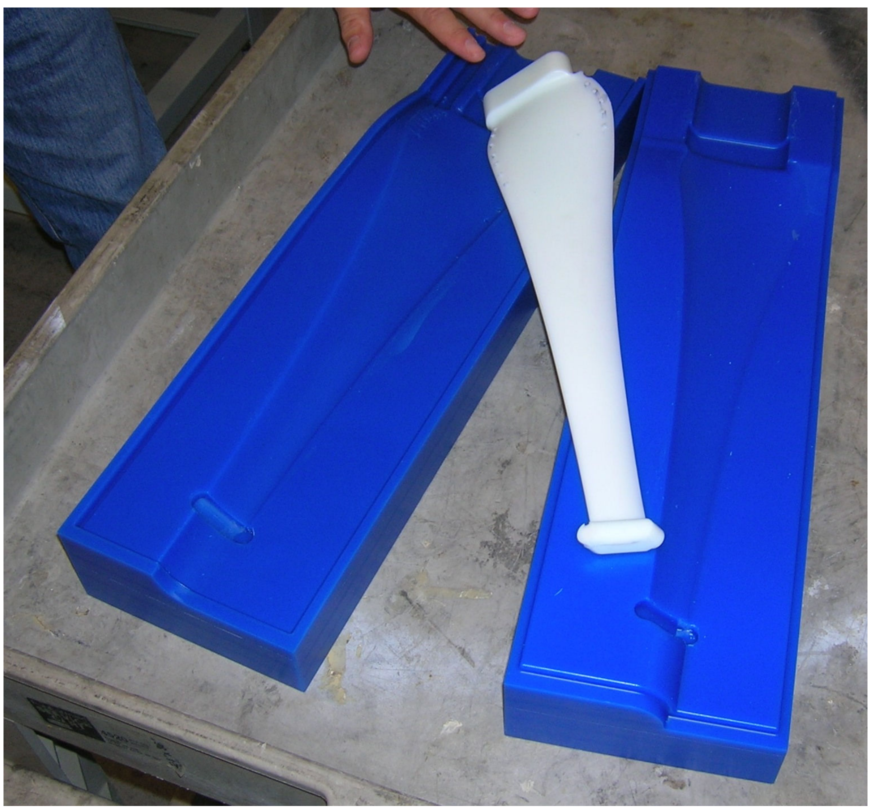

Figure 5: A machinable wax mold used for casting blades for a student-designed rotor

5 Results and Recommendations/Future Work

A total of four turbine blade sets were made over the course of two offerings of this course and the performance of each set was measured using our test-bed. Figure 1 shows a photograph of one of the student designed windmill rotors mounted on our test-stand. Overall, these blade sets and their manufacturing process were a success. One student designed rotor achieved an electrical output power of approximately 180 Watts at the given 12 m/s windspeed which for the efficiency of the generator used for the test-bed is approximately 55% of the Betz Limit.

Developing an appropriate venting strategy for the molds is crucial in obtaining high quality cast blades with a minimum number of voids. Degassing the liquid urethane plastic would help in reducing the number of voids, and pressurizing the molds should reduce the size of the voids. The thinner blades creeped under their own weight when subjected to Arizona summer temperatures over time periods of several months. Post-curing the blades should reduce this effect. More accurately quantifying material properties for the urethane plastics is necessary for developing a set of safe design criteria for this project using these materials. A detailed and more rigorous solid modeling analysis is crucial to determine a set of safe design parameters for the blades of this project. Additionally, the development of a stationary teststand is also critical for the continuation and dissemination of this design project. The development of a different manufacturing technique for the blade molds which does not use a CNC milling machine is necessary if such a design project is to be executed by students in schools without access to such tools or the skilled personnel to operate them.

6 Acknowledgements

The author would like to thank Dr. Valana Wells for the course design concept and use of the initial student designed test stand. The author would also like to thank Leonard Bucholtz for assistance with the Solidworks mold design and for machining the molds, hubs, and pouring of the blades.

References

[1] Manwell, J. F., McGowan, J. G., and Rogers, A. L. *Wind Energy Explained: Theory, Design, and Application.* John Wiley and Sons Ltd., (2002).

[2] Drela, M. In *Lecture Notes in Engineering,* Mueller, T., editor, 1–12. Low Reynolds Number Aerodyanmics, Springer-Verlag, June (1989).

[3] Rector, M. C. and Visser, K. D. *45th AIAA Aerospace Sciences Meeting and Exhibit; 8-11 January 2007, Reno, NV* , 16240–16248 (2007).