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Effect of Leading Edge Radius and Blending Distance from Leading Edge on the Aerodynamic Performance of Small Wind Turbine Blade Airfoils

Mahasidha R. Birajdar, Sandip A. Kale

Mechanical Engineering Department, Trinity College of Engineering and Research, Pune, India

Email address:
mrbirajdar88@gmail.com (M. R. Birajdar), sakale2050@gmail.com (S. A. Kale)

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Abstract: The aerodynamic performance of a wind turbine depends upon shape of blade profile blade airfoils. Today, small wind turbine industries are extensively focusing on blade performance, reliability, materials and cost. The wind turbine blade designers are required to give emphasis on accurate analysis of flows around the blade and loads on wind turbine blades. Low Reynolds number airfoils suited for small wind turbine applications must be designed to have a high degree of tolerance in avoiding high leading suction peaks and high adverse pressure gradients that lead to flow separation. This paper presents a study to investigate the effect of leading edge radius and leading edge blending on the aerodynamic performance of wind turbine airfoils. In the present work NACA 4412 airfoil is considered as base airfoils. In this work six modified airfoils having different new to the old ratio of leading edge radii are considered for performance analysis. The performance of these six profiles is compared with basic airfoil performance. In this paper, the effect of blending distance from leading edge of airfoil on aerodynamic performance is also determined. Different five blending distances from leading edge are analyzed and compared with basic profile. The performance analysis of airfoils is carried out using Blade Element Momentum. In the present analysis, chord length of airfoils and Reynolds number are kept constant.

Keywords: Airfoil, Aerodynamic Performance, Leading Edge Radius, Leading Edge Blending

1. Introduction

A condition for an efficient conversion of the wind energy into mechanical energy with wind turbines is the optimal design of the rotor blades. Quick, reliable and simple methods for predictions of the aerodynamic characteristics and simulation of the flow conditions around a rotor blade are essential for this design work [1-3]. Wind flow around blade is complicated in nature. In addition to these, complicated wind turbine flows, wide range of operating conditions, rotating lifting surfaces, transitional blade flows and low Mach numbers are the major challenges in performance analysis. The wind turbine blade designers are required to force accurate analysis of flows around the blade and loads on wind turbine blades. The wind tunnel testing of the wind turbine blade airfoils with or without flow control and load control is time consuming and expensive. The two dimensional computational tools are based on viscous flow theory having, steady flow, smooth surface and limited flow separation condition. The three dimensional computational tools are majorly based on Blade Element Momentum (BEM) theory. Q-blade is a one of the examples of these 3D tools [4-6]. The passive flow control and load control methods are leads to improve the performance of the turbine, to mitigate the loads on the structure and reduce the stress levels in the structure. Passive control techniques includes the laminar flow control, Passive porosity, Riblets, Vortex generators, Stall strips, Gurney flaps, Serrated trailing edges, Aero elastic tailoring, Special purpose airfoils such as restrained maximum lift, high lift, blunt trailing edge, modified leading edge etc. Passive load control is extensively used in wind turbine design, for the most part focused on power production [7-8].

Numerical Analysis of new airfoils for small wind turbine blade is carried out successfully by Birajdar et. al [1]. Two new blade airfoils are designed for small wind turbine and comparison of new airfoils and blade performance using different techniques is carried out. It is remarked that Q-blade is a reliable tool for analysis of wind turbine airfoils and blade [2]. In the wind turbine airfoils the parabolic leading edge affects the performance of airfoils. The blunt leading edge portion is fair into a pressure surface characterized by leading edge radius i.e. leading convex portion [3].

The thin airfoils are chosen for low Reynolds number application to decrease the suction peak near the leading edge of the airfoil to decrease the adverse pressure gradients on the upper surface of the airfoils. The low Reynolds number airfoils operate below a Reynolds number of 500,000, where the flow across the upper surface of the airfoil is predominantly laminar. Airfoils within this Reynolds number range suffer from laminar separation bubble and are susceptible to laminar flow separation that occurs when the laminar separated flow does not reattach to the surface, resulting in a loss in aerodynamic performance. Low Reynolds number airfoils suited for small wind turbine applications must be designed to have a high degree of tolerance in avoiding high leading suction peaks and high adverse pressure gradients (APG) that lead to flow separation. A small degree of roughness needs to be associated with airfoils operating at low Reynolds number conditions as explained by Lissaman, where the introduction of turbulators or trip wire devices, promote early transition from laminar to turbulent flow to eliminate laminar separation bubbles and delay the possible chances of separation from the upper surfaces at higher angles of attack [3].

The use of specifically sized trip wires has been employed near the leading edges of low Reynolds number airfoils to show this effect as studied by Giguere and Selig, where the devices ‘trip’ laminar flow into the high energy turbulent flow able to negotiate the adverse pressure gradients (APG). Roughness can easily be introduced to airfoils at low Reynolds number as it does not appear significant in relation to boundary layer thickness whereas the opposite happens at high Reynolds number. Since the boundary layer thickness is inversely proportional to Reynolds number, a small amount of roughness would appear noticeable with decreasing boundary layer thickness as Reynolds number is increased since the physical size of the introduced roughness stays the same [8-23].

Wind turbine blades are exposed to precipitation that occurs in a variety of forms and myriad abrasive airborne particles that can, over time, erode their surfaces, particularly at the leading edge. These airborne particles can cause significant blade erosion damage that reduces aerodynamic performance and hence, energy capture. Moreover in some environments, insect debris and other airborne particles can accrete on the leading edges of wind turbine blades. Leading edge blade erosion and debris accretion and contamination can dramatically reduce blade performance particularly in the high-speed rotor tip region that is crucial to optimum blade performance and energy capture. The erosion process on wind turbine blades typically starts with the formation of small pits near the leading edge, which increase in density with time and combine to form gouges. If left to the forces of nature, the gouges, then grow in size and density, and combine to cause delamination near the leading edge [4].

This paper presents the study to investigate the effect of leading edge radius and leading edge blending on the aerodynamic performance of wind turbine airfoils. The objective of this study was to test a wind turbine airfoil with shape modifications to simulate the leading edge radius going through the evolutionary stages of development. The goal was to develop a baseline understanding of the aerodynamic effects of various types and magnitudes of leading edge radius and to quantify their relative impact on airfoil performance. The ultimate aim of conducting the study was to examine the potential detrimental effects of leading edge radius and leading edge blending on the wind turbine airfoils.

2. Wind Turbine Blade Airfoils

2.1. Airfoil Nomenclature

The basic nomenclatures of airfoils are shown in Figure.1 and basic explanation is given as follows

Leading edge: The front edge of the airfoil is called leading edge. The leading edge is the part of the airfoil that first contacts the incoming air and the principal edge of an airfoil section.

Mean Camber line: The locus of the points that lie half way between the upper and lower surfaces is called the mean camber line.

Chamber: The maximum distance between the chord line and the mean camber line is called the camber. Camber is generally designed into an airfoil to increase the maximum lift coefficient.

Trailing edge: The back of the airfoil is called trailing edge.

Chord line: The straight line drawn from leading edge to trailing edge [1].

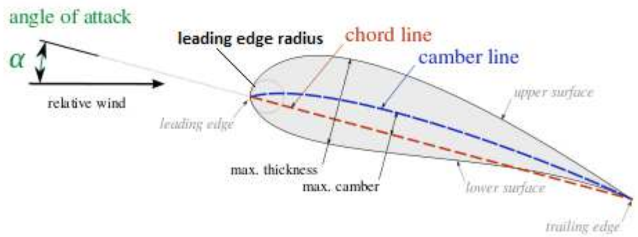

Figure 1. *Airfoil nomenclature.*

Airflow over any surface creates two types of aerodynamic forces drag forces, in the direction of the airflow, and lift forces, perpendicular to the airflow. Either or both of these can be used to generate the forces needed to rotate the blades of a wind turbine. The airfoil shape is designed to create a differential pressure between the upper and lower surfaces, leading to a net force in the direction perpendicular to the wind direction [2].

2.2. Airfoil Selection

In the present work NACA 4412 airfoil is considered as base airfoils as shown in Figure. 2. The NACA 4412 is a four digit airfoil. The first digit expresses the camber in percent chord, the second digit gives the location of the maximum camber point in tenths of chord, and the last two digits gives the thickness in percent chord. Thus 4412 has a maximum camber of 4% of chord located at 40% chord back from the leading edge and is 12% thick [24].

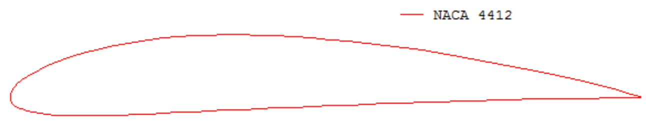

Figure 2. *NACA 4412 airfoil.*

2.3. Aerodynamic Analysis

Efficient wind turbines operate with the higher lift force and low drag force. If the angle of attack is less, then the lift force will be high and the drag force will be lower. But, if the angle of attack increases beyond a certain value, the lift force decreases and the drag forces increases. Hence, angle of attack plays a vital role in designing a blade. In this work, angle of attack is given as input in the Q-blade tool and the values of C_L and C_D were obtained. The analysis of airfoil is carried out by using Q-blade. Q-blade is a three dimensional computational tool is majorly based on Blade Element Momentum (BEM) theory [1]. The airfoil design has also taken place using Q-blade tool. Therefore an airfoil design requirements include information regarding C_{Lmax}as well as the operating range over which low drag is achieved.

These requirements can be translated into specific characteristics to be embodied in the pressure distribution. The low drag points require extended runs of laminar flow on the lower and upper surfaces, respectively, while the high lift requirement is achieved by limiting the leading edge suction peak behavior, each of which must be achieved at the corresponding design lift coefficient [6].

3. Effect of Leading Edge Radius

The front edge of the airfoil is called leading edge. The leading edge is the point at the front of the airfoil that has a maximum curvature means minimum radius. This minimum radius of the leading edge is called the leading edge radius. In this paper NACA 4412 airfoil is considered as base airfoils. In this work seven modified airfoils having different new to the old ratio of leading edge radii are considered for performance analysis.

Table 1. *Modified airfoil for different radii ratio.*

Airfoil	New to the old ratio of leading edge radii
AFR1	0.6
AFR2	0.8
NACA4412	1.0
AFR3	1.2
AFR4	1.4
AFR5	1.6
AFR6	1.8
AFR7	2.0

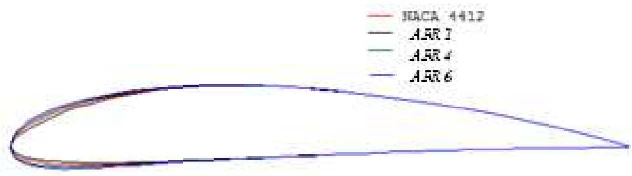

Figure 3. *NACA 4412 airfoil with varying leading edge radii.*

During this analysis the blending distance from leading edge is kept constant as 10 % of chord. The profiles with change in leading radius are named as AFR1 to AFR7. Here, AFR stands for an airfoil. Table 1.shows different radii and profile names analyzed. Figure 3 shows NACA 4412 and airfoils with few new to the old ratio of leading edge radii. The base airfoil NACA 4412 has radii ratio of 1. The effect of these variations is investigated and plotted in fig. 4.

The performance analysis of airfoils is carried out at constant Reynolds number of 250000 and constant chord length. Figure 4 describes the performance variations for different new to the old ratio of leading edge radius. At minimum new to the old ratio of leading edge radius i.e. less than one, the starting lift to drag ratio is higher compared to maximum new to the old ratio of leading edge radius i.e. greater than one. But the performance curve of these airfoils falls down at lower angle of attack compared to other. This shows that range of maximum performance is greater for higher new to the old ratio of leading edge radius. The wider performance curve provides lesser fluctuations in power output. The maximum lift coefficient to drag coefficient ratio is obtained for AFR1 airfoils, whereas the minimum lift to drag ratio is obtained for AFR7airfoils.

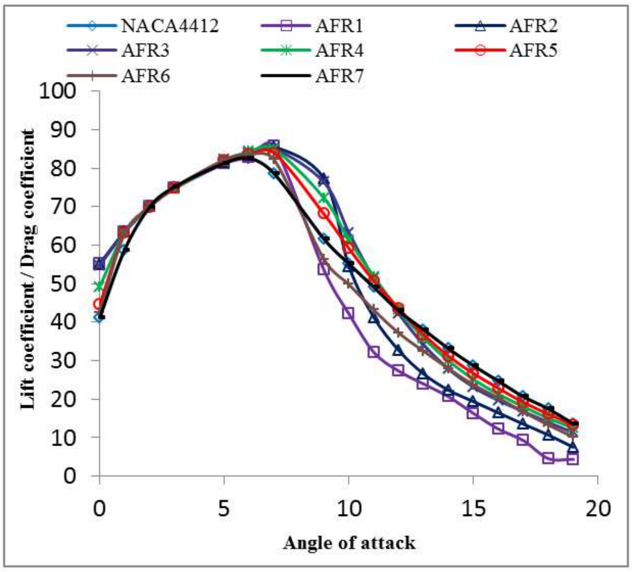

Figure 4. *Effect of leading edge radius on NACA 4412 airfoil.*

4. Effect of Blending Distance from Leading Edge

In the present work, the focus has been on designing airfoils that can be used along the entire blade span of small horizontal axis wind turbine. The NACA 4412 airfoil is considered as base airfoils. The changes in airfoils are carried out by changing the blending distance from the leading edge. For NACA 4412 airfoils the blending distance from leading is 10 percent of chord. Similarly AFB1, AFB2, AFB3, AFB4 and AFB5having the blending distance from leading is 06%, 08%, 20%, 30%, 40% of chord respectively. The nomenclature AFB stands for Airfoil blending. Figure 5 shows the cross section of NACA 4412 airfoils with varying blending distance from the leading edge.

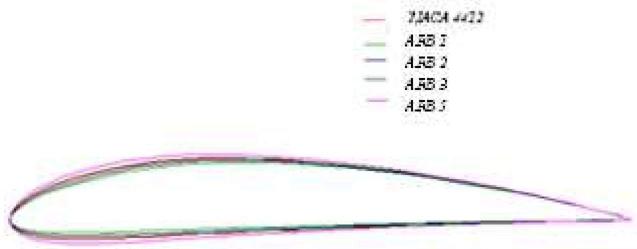

Figure 5. *NACA 4412 airfoils with varying blending distance from leading edge.*

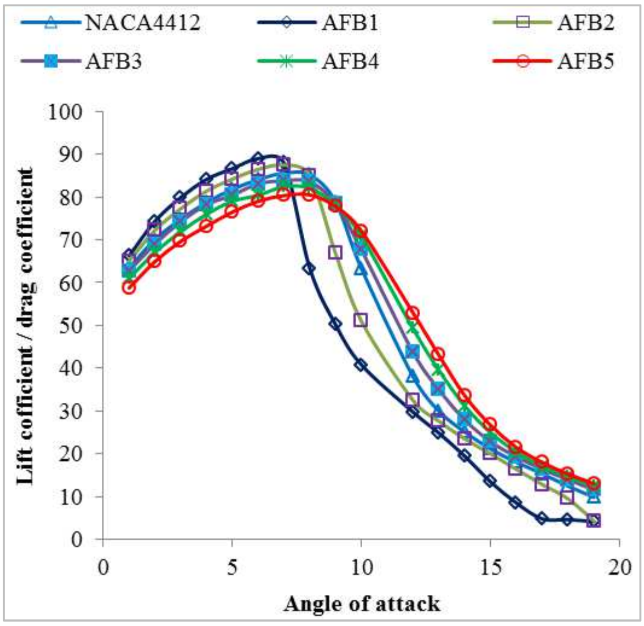

Figure 6. *Effect of blending distance from leading edge on NACA 4412 airfoils.*

The designed airfoils should provide optimum performance over a broad range of operating conditions. The analysis of airfoils is carried out at constant Reynolds number of 250000 and constant chord length. Figure 6 describes the performance variations of NACA 4412 airfoils with varying blending distance from the leading edge. At the lesser blending distance from leading edge higher lift coefficient/ drag coefficient ratio is obtained. With the increase in blending distance from leading edge the maximum lift to drag ratio is decreased. For the AFB1 airfoil the maximum lift to drag ratio 90 is higher than other airfoils, but the range of performance curve is very narrow. Whereas, for AFB5 airfoil the maximum lift to drag ratio is 79 is lesser than other airfoils, but the range of performance curve is too broad. The optimum lift to drag ratio is obtained for NACA 4412 airfoil with a wide range of performance curve and at the 10% blending distance from the leading edge.

5. Conclusion

For different seven leading edge radii and five blending distance from the leading edge on an aerodynamic performance of small wind turbine blade airfoils is determined through Q-blade simulation. From results obtained, some concluding remarks are as follows:

- With the increase in leading edge radius, the performance of the airfoil is decreases, but range of performance becomes broader.
- With the decrease in leading edge radius, the performance of the airfoil is increases, but range of performance becomes narrow.
- The ratio of lift to drag coefficient increases with reduction in blending distance from leading edge and decreases with increase in blending distance from leading edge for up to angle of attack value 7. After that the ratio of lift to drag coefficient increases with increase in blending distance from leading edge and increases with increase in blending distance from leading edge.

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