Design and Optimisation of a Low Reynolds Number Airfoil for Small Horizontal Axis Wind Turbines

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Abstract. Horizontal axis wind turbines (HAWTs) are scaled down to incorporate rotor blades that usually have a diameter ranging from two to four meters in length. A common misconception with regard to selection of airfoils followed by subsequent designing of rotor blades involves the use of NACA airfoils and other conventional high Reynolds number airfoils. Micro horizontal axis wind turbines usually operate at low Reynolds number conditions along the blade length. Conventional aerodynamic schemes cannot be applied to rotor blades operating under low Reynolds number conditions as compared to those occurring under high Reynolds number conditions since certain unusual aerodynamic phenomena predominate in the case of the former. The efficiency of a wind turbine is largely dependent on blade optimization, which is why airfoil selection of the rotor blade is of considerable importance. The difference between high and low Reynolds number operation is the onset of boundary layer transition. In the case of high Reynolds number operation, as is the case of aircraft propellers and other high speed turbines, boundary layer transition takes place before laminar separation, which is in direct contrast to low Reynolds number boundary layer phenomena, wherein laminar separation takes place before boundary layer transition.

Keywords. Horizontal Axis Wind Turbine, Computational Fluid Dynamics, Airfoil Analysis

1. Introduction

Wind power is one of the most prevalent forms of renewable energy, second to only solar energy. The incumbent idea of extracting kinetic energy from surface wind currents, and converting this energy into electric energy is carried out using a combination of gear drives and an electrical generator, apart from other secondary systems. Using a suitable power electronic converter, this electricity may then be integrated directly into the grid, or may also function to supply power to a recharging station. With the depletion of fossil fuels, widespread awareness of the need for a transition to renewable energy is gaining ground. This transition, coupled with the augment of global warming, particularly due to the combustion of fossil fuels to provide electricity, has resulted in multiple small scale installations of wind turbines [5]. These wind turbines occur as individual installations atop buildings in urban environments, as well as in open areas such as farms and parks.

The onset of the boundary layer transition is different for both high and low Reynolds number flow considerations. It is because of this phenomenon that substitution of one airfoil from the high Reynolds number regime, to that of a low Reynolds number regime, or vice versa cannot be carried out.
In high Reynolds number regime, the order of transition is one that is favourable with regard to the formation of stable trailing edge vortices, whereas if laminar separation occurs first, the trailing edge vortices formed are shaky and subsequently unstable [1]. Hence conventional airfoils cannot be used as a direct substitute.

There does exist documentation of airfoils that address low Reynolds number flow dynamics and are modelled around this behaviour. One of the first families of low Reynolds number airfoils was designed for solar planes. This specification then grew substantially into a family of six airfoils developed by NREL. Despite the rudimentary literature and design specifications we currently have on low Reynolds number airfoils and the dynamics of the laminar separation bubble, there exist multiple families of both thick as well as thin airfoils that can be used on micro horizontal axis wind turbines (HAWTs) such as the airfoil family developed by Delft University, Netherlands. There is, however, one restriction with regard to the limit of power that may be produced from such an airfoil-rotor simulation [11]. This power rating stands between 0.7 to 4 kW, which is a number determined both experimentally, as well as verified using computational fluid dynamics.

As stated previously, the laminar separation bubble and its associated drag forms the most important and distinguishing factor when it comes to low Reynolds number applications. Laminar separation bubble drag is unpredictable even in the most controlled environments. Although micro wind turbines are usually set up in urban environments, fluctuations in ambient pressure and temperature can lead to different attributes of wind speed across the length of the blade. Another aspect that influences the formation of the bubble is the degree of roughness of the blade or airfoil surface. These flow conditions, as well as their effect on rotor blade design characteristics have been discussed in the subsequent sections of this paper. This purpose of this paper is to conduct the analysis of multiple airfoil families, modify them, and produce a database of airfoils that may be referred to whilst designing a small horizontal axis wind turbine.

2. Flow Conditions

2.1. Angle of Attack

The calculation of lift and drag along the blade length is not of much practical importance. A well designed HAWT blade has tip twist close to zero. The starting torque and incident angle of attack is important in determining the behavior at low Reynolds numbers. Using computational fluid dynamics, the lift and drag coefficients of the NACA 0012, 0015, 4415 and 4418 were obtained through simulation at a local Reynolds number of 500000. The angle of attack was also made to vary from -5 till 20 degrees, with one degree steps for the entire interval. Figures 1 to 4 depict the variation of Cl with angle of attack for varying Reynolds numbers of operation for the NACA 0012, 0015, 4415, 4418 respectively.

Since the local angle of attack changes with incoming gusts of wind, a higher than operation value of angle of attack is taken into consideration during the design phase. It is to be noted that the phenomenon stated above is only applicable to upwind turbines. For downwind turbines, the opposite process takes place, that is, the local angle of attack is lesser than the theoretical angle of attack of operation. The horizontal axis wind turbine being modelled through this paper is an upwind turbine, hence the angle of attack range was chosen to be from -5 to 20 degrees. As provided by NREL, the ideal pitch for a rotor blade of a small horizontal axis wind turbine was experimentally determined to be close to 1.25 degrees. Figure 7 shows the operational values of the coefficient of lift and drag for the four airfoils at a pitch of 6.25 degrees at varying boundary layer trip configurations. With accordance to the Cl/Cd ratio, the NACA 4412 provided the best performance for an operational blade pitch of 6.25 degrees.

A particular flow regime is said to follow low Reynolds number when the drag is substantially dominated by the corresponding laminar separation of that particular airfoil [4]. Hence this is more of a local, airfoil dependent quantity in comparison to a constant
parameter that does not vary across all airfoils under consideration. Thick airfoils and those designed for higher Reynolds numbers usually have an undesirable wider Reynolds number range for which the range is subcritical as compared with thin and low Reynolds number airfoils. The entire angle of attack simulation was modelled taking into account a laminar separation dominated drag flow regime [3]. Along with the variation of lift with the angle of attack, the consequent drag and wake patterns for the setup were also examined.

Table 1: The operational parameters of the four airfoils taken into consideration

| Airfoil   | Cl      | Cd      | Cl/Cd   |
|-----------|---------|---------|---------|
| NACA 0012 | 0.744771| 0.0121905| 61.094 |
| NACA 0014 | 0.734925| 0.0117351| 62.626 |
| NACA 4412 | 1.13154 | 0.0110877| 102.054|
| NACA 4418 | 1.11605 | 0.0116191| 96.053 |

2.2. Circulation Over the Rotor Blade

For simplicity of optimizing a particular blade for a definite value of circulation, we assumed 2-D airfoils situated at quarter-chord lengths of the root from the tip of the blade. For all practical theoretical
scenarios, a given blade may be divided into an infinite train of airfoil subsections, which is a standard practice followed by previous experimentation and computational setups. In addition to this, instead of determining the circulation of the blade as a whole, which may lead to erroneous values of circulation, we can define the circulation of a sub-section of the rotor blade, which would further be dependent on the local freestream velocity of the wind [1].

Circulation of a closed system is given by the line integral of the local freestream velocity coming in contact with a particular subsection of the blade taken into consideration.

\[ \Gamma = \oint U \, dl \]

The term ‘dl’ signifies the increase in length from the subsection in consideration to the next subsection along the blade length. The area integral of vorticity within the closed system is confined to the suction and pressure surfaces of the blade. The system can also be further divided into two sections namely upstream of the blade and downstream of the blade. The first section does not contribute to circulation since the incident wind stream is one dimensional and has a steady nature. On the other hand, wind downstream of the turbine is quite turbulent. This was an extremely important design condition to determine the torque on various sections of the blade through an in-house computational mapping algorithm based on the Viterna method. Since basic Blade Element Momentum (BEM) theory fails to predict the operational parameters of the turbine in deep stall condition, the Viterna method was employed to provide a more accurate solution.

2.3. Deep Stall and High Incidence

Flow separation occurs at high angles of attack, and consequently reduces the aerodynamic performance and the power producing capabilities of the rotor blade as depicted by the sudden fall in the value of power coefficient. Deep stall is a phenomenon that occurs when the separation point moves toward the leading edge. Since small HAWTs operate at low Reynolds Numbers, the separation is often instantaneous and unexpected. A hysteresis loop is created when an airfoil in a condition of deep stall is reverted back to its original position. For a NACA 23012 airfoil, deep stall starts at an angle of attack of 21 degrees. During the condition of deep stall, the lift produced by the turbine blade is low, and the consequent drag polar is irregular, with a high in-situ drag [10]. This loss of lift requires a greater starting torque. It was experimentally verified by Philippe Giguere and Michael S. Selig that the deep stall angle depends on four parameters namely Reynolds number of operation, root chord, tip chord and the effective pitch of the blade.

![Fig. 5 Variation of the power coefficient with the wind velocity for different blade pitch angles for the NACA 23012](image)

![Fig. 6 Isometric view of CAD Model of rotor system](image)
Mueller and Dellauer explain that airfoil performance below a Reynolds number of 500000 is governed primarily by the effects of laminar separation bubble that forms on the upper surface of the rotor blade. As Re increases from 200000 to 500000, the bubble gets shorter and the drag produced by it reduces, leading to higher lift to drag ratio. Between about 70000 and 200000, it is possible to achieve laminar flow without a bubble, which can lead to impressive performance. Each of the SG6040, SG6041 and SG6043 suffer from the obvious effects of the laminar separation bubble at their lowest measured Re. Between 30000 and 70000, the thickness of the airfoil has a direct influence on bubble formation, which is why thin sections behave better in this region. Below about 50000, the transition in the separated flow may not occur before the trailing edge and there is no reattachment.

To understand the impact of location of formation of the transition bubble, flow experimentation was carried out and the bubble was induced at different lengths along the airfoil surface. Flow simulation was performed for the NACA 23012 as well as the SG6043 for a Reynolds number of 200000 and 1000000. The corresponding value of the coefficient of lift, coefficient of drag, and the resultant lift to drag ratio were compared across the Reynolds number of flow for a boundary layer trip at 0%, 20%, 50%, 70% and 100% of chord length on both the upper, as well as the lower surface. It was seen that there is not a considerable variation between the parameters of boundary layer trips placed at 20, 50, 70 or 100% of the chord. The single point of contrast is the value of the drag coefficient for the initial lift coefficient varying from 0 to 1.3. The greater the relative percentage of the placement of the boundary layer trips, smaller will be the value of drag. Although this variation is small, it gains considerable importance when the incumbent flow has a varying Reynolds number of operation as the fluctuating value of drag then affects the wind shade region of the turbine. It is also seen that the value of Clmax for the trip placed at the leading edge is considerably lesser as compared to the results for boundary layer trips placed at subsequent percentages of the chord.

![Fig. 7 Variation of the coefficient of lift with the coefficient of drag for different locations of the boundary layer trips](image)

3. Design Characterisation

For simulation and analysis, Fluent and XFOil were used in conjunction. XFOIL uses numerical source panel method in combination with boundary layer equations. For small wind turbines, especially those operating under low Re conditions, the effects of boundary layer roughness are important in evaluating the potential of airfoil for wind turbine application. A set of five airfoils were analysed for a small wind turbine installed in the Institute. The airfoils tested were NACA 0012, 0014, 4418, SD 6048, SD 7032 and SD 7062. The size of the drag bucket, and the resultant values of lift and drag served as an important parameter while narrowing down on two airfoils that were validated in the MIT wind tunnel. The analysis of the NACA 0012, 0014, 4412 and 4418 yielded the NACA 4412 airfoil as the most efficient
in its class with regard to rotor design of a small horizontal axis wind turbine as shown in Table 1. The results were then compared with experimentation at the NASA Langley wind tunnel in conjunction with Phillip Gicke. Based on concurrency as well as the results obtained for the modelled rotor system, the SD 6048 was seen as the optimum airfoil for the rotor system.

4. Conclusion

An in-depth analysis with regard to the aerodynamics of a low-speed horizontal axis wind turbine has been presented. A clear contrast was made with regard to the performance characteristics under high and low Reynolds number flow parameters. Optimal induction factors of a particular horizontal axis wind turbine depend largely on the operating conditions such as the prevalent wind flow direction as well as the presence of other buildings and non-aerodynamic objects within fifty to a hundred meters of the installation side [8,9]. The design optimization in the study took into account tip hub losses as well as variability in pitch and consequent locations of boundary layer trips.

Furthermore, optimization of certain design characteristics including starting performance and camber was discussed to explain and experimentally determine the performance of a small rotor system. Since high Reynolds number airfoils are incorrectly used by a large number of small wind turbine manufacturers, especially in developing economies, a clear distinction has been made with regard to the performance characterization of both types of airfoils on a wind turbine intended to operate under low Reynolds number flow. A continuation of the work presented in this paper is the possible capability of harnessing wind drafts from a direction other than the direction of prevalent wind, making the turbine more efficient with regard to electricity generation. The approach followed in this study blended both blade design as well as airfoil analysis of both high Reynolds number as well as low Reynolds number flow.

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