DESIGN AND DEVELOPMENT OF HORIZONTAL SMALL WIND TURBINE BLADE FOR LOW WIND SPEEDS

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Abstract

A wind turbine is a device that converts kinetic energy from the wind, also called wind energy, into mechanical energy in a process known as wind power. Wind energy is one of the most widely used renewable energy resources. Small wind turbines need to be affordable, reliable and almost maintenance free for the average person to consider installing one. Small-scale wind turbines produce more costly electricity than large and medium-scale wind turbines, especially in poor wind sites and in autonomous applications that require a high level of reliability. However, when sized properly and used at optimal working conditions, small-scale wind turbines could be a reliable energy source and produce socio-economically valuable energy not only in developing countries but also in autonomous applications in locations that are far away from the grid power in developed countries. Small-scale wind turbines are in fact becoming an increasingly promising way to supply electricity in developing countries. The small-scale wind turbines have quite different aerodynamic behaviour than their large-scale counterparts. Small wind turbines operating at low wind speeds regularly face the problem of poor performance due to laminar separation and laminar separation bubbles on the blades. This is due to the low Reynolds number (Re) resulting from low wind speeds and small rotor size. The use of specially designed low Re airfoils permits start up at lower wind speeds, increasing the start-up torque and thus improving the overall performance of the turbine. This paper elaborates the design and development of such a wind turbine blade for domestic application.

Index Terms: Wind Turbine blade design, Small Wind Turbine, Wind Turbine blade for Low wind speed, Low Re Airfoils

1. INTRODUCTION

Nowadays electricity is the major problem in this world especially in Tamil Nadu, India. In the present era of steadily rising fuel costs, wind energy is becoming an increasingly attractive component of future energy systems. The wind potential of India is very high. The wind turbines have been installed and wind energy is being harvested, predominantly in the high wind velocity areas. However, due to the restriction of space, the comparatively lower wind areas are beginning to populate with similar wind turbines. In order to ensure the extraction of maximum wind potential even at lower wind speeds, these turbine blades have to be designed and analyzed to suit the low wind areas. At present India stands fifth in the world of wind power generation. Taking into consideration that a large portion of the Indian land will not be viable for the use of traditional windmills due to low wind speeds, a generator which would produce the energy even at low wind speed is required. Also the transmission losses in India are very high. Hence, to reduce the losses due to transmission the turbine could be placed near the place of consumption. Most of the leading wind turbine manufacturers consider blades as their key components of wind turbine system and have concentrated their efforts on developing their own blade design and increasing the supply through in-house production facility. This paper elaborates the design and development of such a wind turbine blade profile for a domestic application by comparison with various profiles. This research work is for generating electricity at low wind speeds and that can be used to power the lighting requirements of a house.

1.1 Small Wind Turbines
Growing awareness of rising levels of greenhouse gases [1], global warming and increasing prices of fossil fuels have led to a shift towards investing into low-cost small wind turbines. Simple structured, compact in design, portable and low noise [2], the small wind turbines are now vital wind power extracting devices in the rural, suburban and even in the populated city areas where installation of large scale wind turbines would not be accepted due to space constraints and generation of noise. Small wind turbines achieve power coefficients of 0.25 or greater in comparison to large turbines which have $C_P$ values around 0.45 [3]. Small wind turbines have been integrated on domestic house roof tops, farms, remote communities and boats [4]. In contrast to larger horizontal axis wind turbines (HAWTs) that are located in areas dictated by optimum wind conditions, small wind turbines are required to produce power without necessarily the best of wind conditions [4-6]. A small wind turbine is one that relies on aerodynamic forces to start-up and has a tail vane for passive yawing. Small wind turbines are categorized as micro (1 kW), mid-range (5 kW) and mini wind turbines (20 kW+) [7]. A more detailed description of micro wind turbines is given by Cooper as being rated less than 2.5 kW and commercially produces power in the range of 0.4 kW-1.5 kW at 12.5 m/s wind speed [1,8].

2. AIRFOIL

An airfoil-shaped body moved through a fluid produces an aerodynamic force. The component of this force perpendicular to the direction of motion is called lift. The component parallel to the direction of motion is called drag. Subsonic flight airfoils have a characteristic shape with a rounded leading edge, followed by a sharp trailing edge, often with asymmetric camber. The lift on an airfoil is primarily the result of its angle of attack and shape. When oriented at a suitable angle, the airfoil deflects the oncoming air, resulting in a force on the airfoil in the direction opposite to the deflection. This force is known as aerodynamic force and can be resolved into two components: Lift and drag. Most foil shapes require a positive angle of attack to generate lift, but cambered airfoils can generate lift at zero angle of attack.

2.1 Airfoil Behaviour

Before introducing the airfoil behaviour, Mach number and Reynolds number need to be explained. Mach number is a ratio of speed of an object over sound and it is defined as:

$$Ma = \frac{v_s}{u_c}$$

Where $Ma$ is Mach Number, $v_s$ is object speed, $u_c$ is sound speed. Subsonic is defined as Mach ≤ 1, transonic is defined as Mach = 1, supersonic is defined as Mach ≥ 1, and hypersonic is defined as Mach ≥ 5.
The design of the turbines rotors is perhaps the most mathematical element of the entire turbine design. The rotors use aerodynamic lift to provide a turning moment and consequently an input torque to the gearbox. There are many different standardized airfoil profiles varying in cross-sectional profile and can be most recognizably characterized by their camber, thickness and chord length. The design of the blades used in this project will be based upon blade element theory and the Betz equation and will investigate the blade shape for ideal rotors with and without wake rotation. The following terms are used to characterize an airfoil:

- **Mean camber line** – The locus of the points half way between the upper and lower surfaces of the airfoil profile.
- **Leading edge** – The most forward point of the airfoil cross section
- **Trailing edge** – The tail end of the airfoil cross section (feather edge)
- **Chord line** – The chord line connects the leading edge to the trailing edge. The chord line is a straight line and its distance is known as the chord c of the airfoil.
- **Camber** – Camber is the distance between the chord line and the locus that represents the mean camber line measured perpendicular to the chord line.
- **The thickness** of the airfoil at any point along its chord line is the distance between the top and bottom surface measured perpendicular to the chord line.
- **Angle of attack (α)** - The angle of attack is the angle created between the chord line and the relative wind direction.
- **Span** – The term span refers to the length of the airfoil perpendicular to the cross section. In terms of a wind turbine the span of the blades make up the swept diameter of the turbine minus the hub diameter.

Airfoil behaviour can be described into three flow regimes: the attached flow regime, the high lift/stall development regime and the flat plate/fully stalled regime. In attached flow regime, flow is considered at the upper surface of airfoil, in this situation, lift increases with the angle of attack. In high lift/stall development regime, the lift coefficient peaks as the airfoil becomes increasingly stalled. Stall occurs when the angle of attack exceeds a certain value (depending on the Reynolds number) and separation of the boundary layer on the upper surface takes place. It is indispensable to study the airfoil behaviour: aerodynamic performances are different because of different geometry of airfoil, and according to different airfoil's behaviour, choosing an applicable airfoil for wind turbine blade will improve the efficiency.

3. AERODYNAMICS IN ROTOR DESIGN

3.1 Lift, drag and moment coefficients
In general, there are two forces and one moment that act upon an airfoil; these being lift, drag and pitching moment. The definitions of those three forces are explained in this section.

![Diagram of Lift and Drag Ratio](image)

**Fig-4: Definition of lift and drag ratio (Hansen, 2008, p. 8)**

Lift is the force used to overcome gravity (Hansen, 2008, p. 8) and is defined to be perpendicular to direction of the oncoming airflow (Manwell, et al., 2002, p.96). It is formed as a consequence of the unequal pressure on the upper and lower airfoil surfaces. The drag force is defined as a force parallel to the direction of oncoming airflow. (Manwell, et al., 2002, p.96) The drag force is due both to viscous friction forces at the surface of the airfoil and to unequal pressure on the airfoil surfaces facing toward and away from the oncoming flow. The lift is the force used to overcome gravity and the higher the lift the higher the mass that can be lifted off the ground. For an airfoil, Hansen (2008, p.8) stated that the lift to drag ratio should be maximized. As a result, it can improve efficiency when wind turbine generates electricity. Lift and drag coefficients $C_L$ and $C_D$ are defined as follows.

Lift coefficient $C_L = \frac{F_L}{\frac{1}{2}\rho V^2 c}$ (3)

Drag coefficient $C_D = \frac{F_D}{\frac{1}{2}\rho V^2 c}$ (4)

Where $\rho$ is the air density and $c$ is the length of the airfoil, often denoted by the chord, unit for the lift and drag in Equations (3) and (4) is force per length (in N/m). To describe the forces completely, it is also necessary to know the pitching moment $M$. It has been found both experimentally and theoretically by National Aeronautics and Space Administration (NASA) that, if the aerodynamic force is applied at a location $\frac{1}{4}$ chord back from the leading edge on most low speed airfoils, the magnitude of the aerodynamic pitching moment remains nearly constant with angle of attack. In most airfoil simulations, the pitching moment centre is set up at $\frac{1}{4}$ chord length to get an approximate value and the pitching moment coefficient is defined as follows.

Moment coefficient $C_M = \frac{F_M}{\frac{1}{2}\rho V^2 c^2}$ (5)

### 3.2 Betz limit

**Fig-5: The efficiency of an optimum turbine with rotation (Hansen, 2008, p. 40)**

The efficiency is defined as the ratio between power coefficient $C_p$ and the Betz limit, $Betz = \frac{16}{27} \approx 0.593$. This value was concluded by Albert Betz who was a German physicist in 1919. 0.593 is the maximum power efficiency of a wind turbine which converts the kinetic energy to mechanical energy. So, efficiency $\eta = C_p/0.593$. Seeing from Figure 5, the power loss is big for a low tip speed ratio wind turbine, for instance, a running wind turbine can only achieve 85% efficiency when the tip speed ratio is 2. The system will become more and more efficient if the tip speed ratio is higher. When the tip speed ratio reaches to 6, the efficiency is approximate 96%. It indicates that wind turbines with high tip speed ratio can extract more kinetic energy from wind by comparing with low tip speed ratio wind turbines.

### 4. BLADE DESIGN PROCEDURE

1. Determine the rotor diameter required from site conditions and $P = C_p \eta \frac{1}{2} \rho \pi R^2 V^3$ (6)

Where:
- $P$ is the power output
- $C_p$ is the expect coefficient of performance (0.4 for a modern three bladed wind turbine)
- $\eta$ is the expected electrical and mechanical efficiencies (0.9 would be a suitable value)
• $R$ is the tip radius
• $V$ is the expected wind velocity

2. According to the type of application, choose a tip speed ratio $\lambda$. For a water-pumping windmill, for which greater torque is needed, use $1 < \lambda < 3$. For electrical power generation, use $4 < \lambda < 10$. The higher speed machines use less material in the blades and have smaller gearboxes, but require more sophisticated airfoils.

3. Choose the number of blades, $B$, from Table-1. Note: if fewer than three blades are selected, there are a number of structural dynamic problems that must be considered in the hub design.

**Table-1: $\lambda$ and Number of Blades**

<table>
<thead>
<tr>
<th>$\lambda$</th>
<th>$B$</th>
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<tbody>
<tr>
<td>1</td>
<td>8-24</td>
</tr>
<tr>
<td>2</td>
<td>6-12</td>
</tr>
<tr>
<td>3</td>
<td>3-6</td>
</tr>
<tr>
<td>4</td>
<td>3-4</td>
</tr>
<tr>
<td>$&gt;4$</td>
<td>1-3</td>
</tr>
</tbody>
</table>

4. Select an airfoil. If $\lambda<3$, curved plates can be used. If $\lambda>3$, use a more aerodynamic shape.

5. Obtain and examine lift and drag coefficient curves for the airfoil in question. Note that different airfoils may be used at different spans of the blade; a thick airfoil may be selected for the hub to give greater strength.

6. Choose the design aerodynamic conditions for each airfoil. Typically select 80% of the maximum lift value, this choice effectively fixes the blade twist. On long blades a very large degree of twist is required to obtain 80% of the maximum lift near the hub. This is not necessarily desirable as the hub produces only a small amount of the power output, a compromise is to accept that the airfoils will have very large angles of attack at the hub.

7. Choose a chord distribution of the airfoil. There is no easily physically accessible way of doing this but a simplification of an ideal blade is given by:

$$ C = \frac{8\pi \cos \beta}{3BA_r} \quad (7) $$

This gives a moderately complex shape and a linear distribution of chord may be considerably easier to make.

8. Divide the blade into $N$ elements. Typically 10 to 20 elements would be used.

9. As a first guess for the flow solution use the following equations. These are based on an ideal blade shape derived with wake rotation, zero drag and zero tip losses. Note that these equations provide an initial guess only. The equations are given as follows:

$$ \beta = 90^\circ - \frac{2}{3} tan^{-1} \left( \frac{1}{\lambda r} \right) \quad (8) $$

$$ a = \left( 1 + \frac{4 \cos^2 \beta}{a C \sin \beta} \right)^{-1} \quad (9) $$

$$ a' = \frac{1-3a}{4a-1} \quad (10) $$

10. Calculate rotor performance and then modify the design as necessary. This is an iterative process.

**5. COMPARISON RESULTS OF VARIOUS PROFILES**

In this research, various profiles of NREL and NACA are analyzed by CFD for $Re=200000$ and compared with the profiles which give more lift coefficient and less drag coefficient ($S822$, $S833$, NACA 4412, NACA 4415) shown in Fig-5 to Fig-13.

1. First digit describing maximum camber as percentage of the chord.
2. Second digit describing the distance of maximum camber from the airfoil leading edge in tens of percents of the chord.
3. Last two digits describing maximum thickness of the airfoil as percent of the chord.

For example, the NACA 4415 airfoil has a maximum camber of 4% located 40% (0.4 chords) from the leading edge with a maximum thickness of 15% of the chord. Four-digit series airfoils by default have maximum thickness at 30% of the chord (0.3 chords) from the leading edge.
Fig-6: $C_D$ vs AOA for (S822,S833,NACA 4412 & 4415)

Fig-7: $C_L$ vs AOA for (S822,S833,NACA 4412 & 4415)

Fig-8: $C_L/C_D$ vs AOA for (S822, S833, NACA 4412 & 4415)

Fig-9: $C_D$ vs AOA for (NACA 4415& Modified Cases)

Fig-10: $C_L$ vs AOA for (NACA 4415& Modified Cases)

Fig-6 and Fig-7 show that NACA 4415 is having less drag coefficient and high lift coefficient. In NACA 4415 we are getting high $C_L$ up to 1.24500 and less $C_D$ upto 0.04069. For getting good efficiency select high $C_L$ profile and Fig-8 is showing that the NACA 4415 profile is having good $C_L/C_D$ ratio. So, NACA 4415 is chosen for further modification to increase the performances.

Fig-9 and Fig-10 are showing the results for comparison of NACA 4415 $C_D$ and $C_L$ with modified cases. NACA 4415 is analysed in different cases by modifying its thickness upto 30% and 50%. Fig-9 and Fig-10 are showing that the modified NACA 4415 case1 gives less $C_D$ up to 0.04025 and high $C_L$ up to 1.90440. Fig-11 shows that the modified NACA case1 profile is giving good $C_L/C_D$ ratio when compare to other.
Fig-11: $C_L/C_D$ vs AOA for (NACA 4415 & Modified Cases)

Fig-12: $C_D$ Comparison of Profiles

Fig-13: $C_L$ Comparison of Profiles

Fig-14: $C_L/C_D$ Comparison of Profiles

Fig-15: NACA 4415 Profile

Fig-16: Modified NACA 4415 Case 1 Profile

Fig-17: Modified NACA 4415 Case 2 Profile

Fig-18: NACA 4415 & Modified Profiles Comparison
Fig-19: NACA 4412 Pressure Pattern

Fig-20: NACA 4415 Pressure Pattern

Fig-21: S822 Pressure Pattern

Fig-22: S833 Pressure Pattern

Fig-19 to Fig-22 is showing the various pressure patterns of analysed profiles for understanding purpose. The upper region is negative pressure acting side and the bottom side positive pressure acting side then the Red is showing the maximum positive pressure acting region and these pressure patterns are taken for the angle of attack 8º.

CONCLUSION

Thus the various profiles of NREL and NACA are analyzed by CFD for Reas 200000 and compared with the profiles which give more lift coefficient and less drag coefficient (S822, S833, NACA 4412, NACA 4415). Among that NACA 4415 is having more lift coefficient and less drag coefficient. So, NACA 4415 has chosen and the profile is modified in two different cases by increasing the chord the thickness percentage by 30% and 50%. Finally modified case 1 profile (chord thickness increased by 30%) had given the best results when compare to other profiles and this modified NACA 4415 blade is designed for low wind speed.

REFERENCES


NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
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<tbody>
<tr>
<td>$C$</td>
<td>Airfoil chord length</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Tip speed ratio</td>
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<tr>
<td>AOA</td>
<td>Angle of Attack</td>
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BIOGRAPHIES

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