Aerodynamic Design and Optimization of Wind Turbine Rotor Blade for Different Wind Speed

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ABSTRACT

Wind turbine blade must be designed aerodynamically to achieve optimum performance in both design and off design conditions. Eight different blades for 700 watts power capacity with scaled ratio of 1:4 were fabricated. The sections of wind turbine blade are selected from NACA series. The blades are tested in wind tunnel and their lift and drag at various angle of attacks were observed. By using test results, power for various blades were calculated and compared to get the optimum blade for 700 watts wind turbine. For a small scale wind tunnel experimental work can be carried out to find out the optimized rotor blade for the selected configurations.

KEYWORDS: Wind turbine, Aerofoil blade, wind tunnel, CFD, attack angle, Maximum power.

INTRODUCTION

A wind turbine is a rotary device that extracts energy from the wind. Wind energy has been shown to be one of the most viable sources of renewable energy. With current technology, the low cost of wind energy is competitive with more conventional sources of energy such as coal. Rotor blade is a key element in a wind-turbine generator system to convert wind energy into mechanical energy. Most blades available for commercial-grade wind turbines incorporate airfoil shaped cross sections. These blades are found to be very efficient at lower wind speeds in comparison to the potential energy that can be extracted.

Computational Fluid Dynamics (CFD) has grown from a mathematical curiosity to become an essential tool in almost every branch of fluid dynamics, from aerospace propulsion to weather prediction. CFD is commonly accepted as referring to the board topic encompassing the numerical solution, by computational methods, of the governing equations which describe a fluid flow, the set of the Navier-Stokes equations, continuity and any additional conservation equations, for example, energy or species concentrations. As a developing science, Computational Fluid Dynamics has received extensive attention throughout the international community since the advent of the digital computer. All CFD analysis starts by defining the geometry to be used. However, for CFD, the geometry is the geometry where the air (or fluid) will flow. This means that it is often necessary to define artificial boundaries for inlets, outlets, far-field conditions, etc.

A wind tunnel is a tool used in aerodynamic research to study the effects of air moving past solid objects. A wind tunnel consists of a closed tubular passage with the object under test mounted in the middle. A powerful fan system moves air around the object; the fan must have been straightening vanes to smooth the airflow. How blades capture wind power just like an airplane wing, wind turbine blades work by generating lift due to their
shape. The more curved side generates low air pressures while high pressure air pushes on the other side of the aerofoil. The net result is a lift force perpendicular to the direction of flow of the air as shown fig.

Fig. 1: Lift & Drag Vectors

The lift force increase as the blade is turned to present itself at a greater angle to the wind. This is called the angle of attack. At very large angles of attack, the blade “stalls” and the lift decreases again. So there is an optimum angle of attack to generate the maximum lift.

Fig. 2: Blades at Low, Medium & High Angles of Attack

Karam Y. Maalawi [1] presents the analysis of an existing model, and this result is then compared with those obtained by other investigators. By analytical method, the optimum chord and twist distribution across the blade is calculated, which plays an important role in the annual power production. The angle of attack of the blade is varied, and the results are computed analytically. The equations in this work are then successfully applied to the existing work. Chalothorn Thumthae [2] performed the numerical simulation of Horizontal Axis Wind Turbines (HAWTS) with untwisted blade to determine the optimal angle of attack that produces the highest power output. The power generated by the blade at various angles of attack. For various wind speeds the angle of attack will vary at which the power generated will be maximum. At a particular angle of attack, the lift to drag will be a maximum which is found out by CFD analysis. Fangfang Song [3] has solved aerodynamic contour by using MATLAB tool based on the design process of Wilson’s method. Aiming at the dynamic performance analysis of a composite blade, a modeling method of combining Solid Works with ANSYS was proposed referred to the actual Layer structure. The result is applied over 20Kw composite wind turbine blade. V. Mahawadiwar [5] carried out CFD analysis of wind turbine blade made of cedar wood. For various airfoils the lift and drag will vary. In this work, various aerofoils are taken and their coefficient of lift and drag values are calculated, and their corresponding power is calculated for various angles of attack. The rated speed is varied, and power is calculated. The maximum power generated by each aerofoil is found out by CFD analysis. From the analysis, it is found that the power developed increases from 0 to 7 degrees at a velocity of 8 m/s. Jovan Oseas [6] describes the problem of designing an output feedback regulation control scheme of a variable-speed wind energy conversion system with rotor speed measurement is addressed. The wind power is limited to the rated power by the pitch and the torque controller. By this method, the required power and the speed regulation is attained while the load is limited.

II. Drafting and Fabrication of Aerofoil Blade Profile:

A simple aerofoil blade profile is shown in the figure3 below. Using this profile, 8 NACA series aerofoil’s have been designed for fabrication. Then the blade dimensions are scaled down by the ratio 4:1 for wind tunnel testing.
Fig. 3: Front view of blade with dimensions

Fig. 4: Three-dimensional view of the blade (I.V)

Fig. 5: NACA 0010 Three dimensional view of the blade (S.V)

Fig. 6: NACA 4412 Three dimensional view of the blade (S.V)

Fig. 8: NACA 4415 Three dimensional view of the blade (S.V)

Fig. 9: NACA 4418 Three dimensional view of the blade (S.V)

Fig. 10: NACA 23012 Three dimensional view of the blade (S.V)
The blades are fabricated using Red Cedar wood. It has the advantages of less weight, cheap and strong. The density of the material is $465 \text{ kg/m}^3$.
Fig. 15: Fabricated NACA 23012, 23015, 23018, 63218 aerofoil profiles blades (S.V)

III. Method of Flow Analysis:

The flow analysis has been conducted experimentally in a wind tunnel, and the specification of the test wind tunnel is shown in Table 1.

<table>
<thead>
<tr>
<th>Table 1: Specification of the wind tunnel</th>
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</thead>
<tbody>
<tr>
<td>Test section</td>
</tr>
<tr>
<td>Type</td>
</tr>
<tr>
<td>Max Rpm</td>
</tr>
<tr>
<td>Max Velocity</td>
</tr>
</tbody>
</table>

Blade velocity triangle showing lift and drag forces on blade element are shown in figure 16.

Fig. 16: Blade element force velocity diagram

The experiments have been conducted on a wind tunnel, and the specification of the test wind tunnel is shown in Table 1. The model is mounted on the wind-tunnel test-section using suitable fixtures. The fixtures are designed in a way that the angle of attack of the blade can be adjusted. The fixtures are designed in a way that the angle of attack of the blade can be adjusted flow velocity is increased from 3 m/s to 11 m/s. Pressure at various locations are noted, and lift and drag values are calculated from the pressure values.

Fig. 17: Wind tunnel testing

The lift and drag coefficients (C_L & C_D) for the fabricated blades are been calculated at various inlet velocities (ranging from 3 m/s to 11 m/s) and at various angle of attack (-5deg to 15 deg).
IV. CFD Analysis of Wind Turbine Blade:

Computational fluid dynamics (CFD) is a branch of fluid mechanics that uses numerical methods and algorithms to solve and analyze problems that involve fluid flows. Computers are used to perform the calculations required to simulate the interaction of liquids and gases with surfaces defined by boundary condition. CFD enables scientist and engineers to perform numerical experiments, i.e. Computer simulations in a virtual flow laboratory. A considerable reduction of time and costs for solving the problems as compared to traditional approaches.

Modeling of the blade is done in Solid works. This blade is imported into Ansys Fluent software where meshing and flow analysis is carried out. Inlet wind velocity and angle of attack values are input values provided to fluent. Values $C_L$ and $C_D$ are evaluated by Fluent software.

**Fig. 18: Completed Mesh**

**Model Calculations:**

For NACA 23015 AEROFOIL,

\[
\begin{align*}
\alpha &= 10^\circ \\
V_0 &= 9 \text{ m/s} \\
V &= r\omega \\
&= r\cdot\pi\cdot N/60 \\
V &= 9.0921 \text{ m/s} \\
V_r &= (V^2 + V_0^2)^{0.5} \\
&= 12.79 \text{ m/s}
\end{align*}
\]

From wind tunnel testing we get values of,

\[
\begin{align*}
C_L &= 0.584 \\
C_D &= 0.02476 \\
\text{Lift force} &= 0.5\times \rho \times V_r^2 \times C_L \\
F_L &= 58.54 \text{ N} \\
\text{Drag force} &= 0.5\times \rho \times V_r^2 \times C_D \\
F_D &= 2.48 \text{ N} \\
F_R &= (F_D^2 + F_L^2)^{0.5} \\
F_B &= 58.59 \\
\text{Power} &= P_N = \text{Torque} \times \omega = F_B \times V \\
&= 58.59 \times 9.0921 \\
&= 532.7 \text{ watts}
\end{align*}
\]

**RESULTS AND DISCUSSIONS**

The variation of power with inlet velocity and angle of attack for various aerofoil configurations for experimental analysis is shown in figure 18-25.
**Fig. 18:** Comparison of inlet wind velocity and Power for NACA 0010

NACA 0010 aerofoil profile blade can generate maximum power of 313 W, at an angle of attack of 10° and at an air velocity of 10 m/s.

**Fig. 19:** Comparison of inlet wind velocity and Power for NACA 4412

NACA 4412 aerofoil profile blade can generate maximum power of 308 W, at an angle of attack 10° and at air velocity of air, 10 m/s.

**Fig. 20:** Comparison of inlet wind velocity and Power for NACA 4415

NACA 4415 aerofoil profile blade can generate maximum power of 199 W, at angle of attack 10° and at velocity of air 10 m/s.
Fig. 21: Comparison of inlet wind velocity and Power for NACA 4418

NACA 4415 aerofoil profile blade can generate maximum power of 308 W, at an angle of attack 10° and at velocity of air, 10 m/s.

Fig. 22: Comparison of inlet wind velocity and Power for NACA 23012

NACA 23012 aerofoil profile blade can generate maximum power of 374 W, at angle of attack 10° and at velocity of air 10 m/s.

Fig. 23: Comparison of inlet wind velocity and Power for NACA 23015

NACA 23015 aerofoil profile blade can generate maximum power of 675 W, at angle of attack 10° and at velocity of air 10 m/s.
NACA 230118 aerofoil profile blade can generate maximum power of 193 W, at angle of attack 10° and at velocity of air 10 m/s.

NACA 63218 aerofoil profile blade can generate maximum power of 168 W, at an angle of attack 10° and at velocity of air, 10 m/s.

The variation of power with inlet velocity and angle of attack for various aerofoil configurations for computational analysis is shown in figure 25-33.
Fig. 25: Comparison of inlet wind velocity and Power for NACA 0010

NACA 0010 aerofoil profile blade can generate maximum power of 319 W, at an angle of attack of 10° and at an air velocity of 10 m/s.

Fig. 26: Comparison of inlet wind velocity and Power for NACA 4412

NACA 4412 aerofoil profile blade can generate maximum power of 325 W, at an angle of attack of 10° and at an air velocity of 10 m/s.

Fig. 27: Comparison of inlet wind velocity and Power for NACA 4415
NACA 4415 aerofoil profile blade can generate maximum power of 225 W, at an angle of attack of 10° and at an air velocity of 10 m/s.

Fig. 28: Comparison of inlet wind velocity and Power for NACA 4418

NACA 4418 aerofoil profile blade can generate maximum power of 327 W, at an angle of attack of 10° and at an air velocity of 10 m/s.

Fig. 29: Comparison of inlet wind velocity and Power for NACA 23012

NACA 23012 aerofoil profile blade can generate maximum power of 380 W, at an angle of attack of 10° and at an air velocity of 10 m/s.

Fig. 30: Comparison of inlet wind velocity and Power for NACA 23015

NACA 23015 aerofoil profile blade can generate maximum power of 873 W, at an angle of attack of 10° and at an air velocity of 10 m/s.

Fig. 31: Comparison of inlet wind velocity and Power for NACA 23018
NACA 23018 aerofoil profile blade can generate maximum power of 199 W, at an angle of attack of $10^\circ$ and at an air velocity of 10 m/s.

![Fig. 32: Comparison of inlet wind velocity and Power for NACA 63218](image)

NACA 63218 aerofoil profile blade can generate maximum power of 197 W, at an angle of attack of $10^\circ$ and at an air velocity of 10 m/s.

<table>
<thead>
<tr>
<th>S.NO</th>
<th>AEROFOIL CONFIGURATION</th>
<th>ANGLE OF ATTACK (degree)</th>
<th>VELOCITY OF AIR (m/s)</th>
<th>MAXIMUM POWER (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NACA 0010</td>
<td>10</td>
<td>10</td>
<td>319</td>
</tr>
<tr>
<td>2</td>
<td>NACA 4412</td>
<td>10</td>
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<td>325</td>
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<td>380</td>
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<tr>
<td>7</td>
<td>NACA 23018</td>
<td>10</td>
<td>10</td>
<td>197</td>
</tr>
</tbody>
</table>

**Conclusion:**

The following conclusions are been made from this experimental and computational investigation.

1. It was observed that the power increased with the angle of attack up to $10^\circ$ and after that it reduces. Hence, the critical angle of attack is $10^\circ$.
2. The power increases with the air velocity from 3 m/s to 10 m/s and after that the power decreases in computational analysis and experimental testing.
3. Among all blades, NACA 23015 shows a maximum power of 873 Watts in computational analysis and 675 Watts in experimental work at an air velocity 10 m/sec and at the $10^\circ$ angle of attack.

**Nomenclature**

- NACA = National Advisory Committed For Aeronautics
- $C_l$ = coefficient of lift
- $C_d$ = coefficient of drag
- $V_r$ = Resultant wind velocity (m/s)
- $F_L$ = Lift Force
- $F_D$ = Drag Force
- $F_R$ = Resultant force (N)
- $\rho$ = density of air (kg/m$^3$)
- $c$ = chord length (m)
- $\lambda$ = tip speed ratio
- $V_0$ = velocity of wind (m/s)
- $r$ = radius of blade (m)
- $\omega$ = angular velocity of blade

**REFERENCES**