Design and Simulation of Wind Turbine Blades

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Abstract. A Wind Turbine Blade has been modelled in Solidworks and its simulation implemented in ANSYS frameworks. Structural, fatigue and Computational Fluid Dynamics (CFD) analysis has been carried out to determine the performance of this blade. The analysis incorporates a blade velocity of 100 m/sec. High Lift to Drag Parameter has been considered for obtaining optimal performance of this blade. The lift-to-drag ratio happens to be a key design parameter for benchmarking such blades. k-ε turbulent model was adopted for our CFD based simulation. Fine meshing was carried out for improving accuracy of results.

Keywords: Computational Fluid Dynamics, Meshing, Structural, Velocity, Lift, Drag

1. Introduction

T Wolff and R J Seume (2016) have recently presented a paper on “Modeling the transient aerodynamic effects during the motion of a flexible trailing edge”. In their research paper, they have developed an empirical model that takes into the account the transient effects while considering the trailing edge motion for the wind turbine. They have developed a wind turbine simulation considering all the load parameters. Main source of load is aerodynamic load that generally gets affected by relative velocity which occurs on the blade section. One of the solutions proposed in earlier studies by Troldborg and Wolf et. al. was a flexible trailing edge in proximity of the blade tip. They have conducted the simulations using 2D RANS for obtaining an optimal trailing edge. Due to this the stress variation was reduced on the blade roots concomitant with the dynamic forces acting in the vicinity of the trailing edges. Wind tunnel tests were carried out by Pechlivanoglou et. Al and Bak et. al. (2010) are reported in their paper “Active aerodynamic control of wind turbine blades with high deflection flexible flaps”. The research findings illustrated direct variations of lift of wind turbine airfoil with trailing edge geometry. According to Troldborg, who has carried out the study on EllipSys 2D solver, it has been inferred that curved trailing edge should have relative length between 5% - 10% of chord length. Wolf et. al. on the other hand, have suggested that a 20% relative length should be considered optimal. In this Bergami (2013) has presented a paper on “Adaptive Trailing Edge Flaps for Active Load Alleviation in a Smart Rotor Configuration”. He has developed an aerodynamic model while considering both steady state and dynamic effects. He has evaluated two different algorithms using his model in the aerelastic
simulation code HAWC2. His simulation predicted a load alleviation occurring up to 30%. It has been found that modelled lift coefficient was consistent with the CFD results only for the cases where angle of attack is less than 4 degree. (a < 4°). Achilles M. Boulamatsis et. al. (2018) have mentioned about regulating varying blade tip sweep using an active control. To minimize the aerodynamic and structural loads, the huge mass of the blades and relatively less energy production have always been considered as major parameters. Sanaa et.al have presented a paper on “Aerodynamics and Structural analysis of wind turbine blades”. Finite element analysis involving static structural and aerodynamic analyses of Horizontal Axis Wind Turbine (HAWT) have been carried out in the research content. This research content provides us a clear view on design and simulation of wind turbine blades. The aerodynamic models have been coupled with a nonlinear formulation. From the paper, it has been concluded that reliability of wind turbine blades has been increased through the development of the air foil structure to calculate an optimum blade shape. It has been concluded that air foils lift and drag performance depicts the angles of twist and chord lengths in order to improvise aerodynamic performance. Swapnil et al. (2020) have presented a paper on performance enhancement of wind turbine in which efficiency of Wind Turbine that has been optimized by changing the design parameters of wind turbine blade. Reduction of performance error was kept under consideration. Structural and vibrational simulation of wind turbine blades have been carried out in the research content. High lift to drag parameter has been optimized in the research content for better efficiency of wind turbine blades. Summer School held at Peter the Great St. Petersburg Polytechnic University, Russia, where the author (Swapnil) participated, has been a major source of technical information regarding horizontal axis wind turbine. Turbine rotor rpms are dictated by the generator synchronism speed for arriving at appropriate angle of attack at varying wind speeds. Wind Turbine blades are turned around their feathering axis and regulating the pitch (or blade) angle θ. The same mechanism allows to feather the blades, minimizing the aerodynamic load at extreme wind speeds. Variable speed turbines achieve best performance by allowing the rotor to work at the tip-speed-ratio $\lambda$ of maximum $C_p$. They are also much quieter because rotation is slower at smaller wind speeds. Airfoils used in HAWT are generally cambered. The angle of attack is a function of angular position $\theta$ and the tip speed ratio $\lambda$.

$$\alpha(t) = \arctan \left( \frac{\sin \theta(t)}{\cos \theta(t) + \lambda} \right)$$

Figure 1. Angle of Attack with respect to angular position and tip speed ratio
2. Mathematical Model

Equation of Continuity and Navier-Stokes equation are the governing equations used in the frame of reference of the rotating blade.

**Conservation of mass:**

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \]  

(1)

**Conservation of Momentum (Navier-Stokes):**

\[ \nabla \cdot (\rho \mathbf{v}) + \rho (2 \mathbf{\omega} \times \mathbf{v} \times \mathbf{v}) = -\nabla p + \nabla \cdot \mathbf{\tau} \]  

(2)

Where \( \mathbf{v}(r) \) is the relative velocity and \( \mathbf{\omega} \) is the angular velocity.

**Turbulence Model: The k-epsilon Realizable**

K-epsilon (k-\( \varepsilon \)) turbulence model has been used for Computational Fluid Dynamics (CFD) simulation.

For turbulent kinetic energy:

\[ \frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho k \mathbf{v}_i)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \frac{\mu_k}{\sigma_k} \frac{\partial k}{\partial x_j} \right] + 2 \rho \mu_t E_{ij} E_{ij} - \rho \varepsilon \]  

(3)

For dissipation:

\[ \frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho \varepsilon \mathbf{v}_i)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \frac{\mu_t}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial x_j} \right] + C_{\mu_1} \varepsilon \frac{\varepsilon}{k} 2 \rho \mu_t E_{ij} E_{ij} - C_{\mu_2} \rho \varepsilon^2 \]  

(4)

3. Design Model

Figure 2. Design Model – Wind Turbine blade
4. Material Selection

Silicon material has been considered as the test material for wind turbine blade.

Table 1: Material properties of Silicon

| S.No | Parameter                  | Values |
|------|----------------------------|--------|
| 1    | Density (Kg/m³)            | 2330   |
| 2    | Young Modulus (GPa)        | 112.4  |
| 3    | Poisson Ratio              | 0.28   |
| 4    | Shear Modulus (GPa)        | 49     |

5. Meshing & Analysis

![Figure 3. Meshing](image)

Table 2: Meshing results

| S.No | Parameter         | Values |
|------|-------------------|--------|
| 1    | Nodes             | 101850 |
| 2    | Elements          | 60770  |
| 3    | Mesh Quality      | High   |
| 4    | Mesh Type         | Solid  |

Arc length of wind turbine blade is 1.3 m.

Structural and Computational Fluid Dynamics analysis has been carried out by considering 1.5 atm pressure and 100 m/sec velocity.
a) Equivalent Stress  
b) Displacement

Figure 4. Equivalent Stress and Displacement behavior for wind turbine blade

c) Inlet Pressure  
d) Outlet Pressure

Figure 5. Inlet and Outlet pressure behavior for wind turbine blade
e) Inlet Velocity

f) Outlet velocity

Figure 6. Inlet and Outlet Velocity behavior for wind turbine blade

g) Dynamic Pressure for Inlet

h) Dynamic Pressure for Outlet

Figure 7. Dynamic pressure behavior of Inlet and Outlet for wind turbine blade
i) Radial Velocity for Inlet

j) Radial Velocity for Outlet

Figure 7. Radial Velocity behavior of Inlet and Outlet for wind turbine blade

k) Tangential Velocity for Inlet

l) Tangential Velocity for Outlet

Figure 7. Tangential Velocity behavior of Inlet and Outlet for wind turbine blade
6. Results & Discussion

Designing of CAD modelling has been carried out in Solidworks. Structural and Computational Fluid Dynamics (CFD) analyses have been carried in Solidworks and ANSYS, respectively. Stress and deformation contours are observed for wind turbine blades. Inlet and Outlet velocities and pressure behaviour could be deciphered using k-ε turbulent model. Inlet velocity has been considered as 100 m/sec as an input parameter. Fine meshing was considered for improving simulation accuracy. Second Order has been considered for ANSYS fluent simulation.

7. Conclusion

Fine Meshing was carried out for simulation of deformation response in wind turbine blades. Maximum equivalent stress induced in the wind turbine blades was deduced as 8.71e+06 from our studies. Inlet and Outlet velocities and pressure contours were exhibited in CFD simulation. High Lift to Drag Parameter was considered for optimum performance of Wind Turbine blades. Blades have been designed for Horizontal Axis Wind Turbines (HAWT). Dynamic Pressure, Radial Velocity and Tangential Velocity vs position plots were derived by executing ANSYS Fluent.

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