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Mass Optimization of HAWT Blades Using Composite Material and to Study its Aerodynamics Using CFD

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ABSTRACT

Wind energy is the fastest growing sector in market. The problem associated with the large scale implementation is the weight of the blades. The literature review shows that large amount of work has been done and going on, to reduce the weight of wind turbine blades. In this project work, objective is to reduce weight of a HAWT Blade using Fluid-structure interaction technique. HAWT of capacity 1.5MW was selected for analysis purpose. Blade design parameter was obtained from reliable sources and 3D modelling is done using Solidworks software. Parametric Blade model was designed to analyze it for different composite materials for optimized weight. Finite Element Analysis software ANSYS workbench 18.0 is used to study the effect of wind on blade and its feasibility for different materials. The results of FSI analysis shows that weight of HAWT blade is optimized without any damage to its performance. These reductions of weight of blade is useful to manufacture low altitude turbine, increasing its scope in renewable energy market.

Keywords: Wind Energy, Optimization, FSI Interaction, Blade design, CFD Analysis

I. INTRODUCTION

The manufacturing cost of WT blade is about 15–20% of wind turbine production cost. The expenses of innovations in design of blades represent the small amount of overall cost of wind turbine production. When designing a wind turbine, the goal is to attain the highest possible power output under specified atmospheric conditions. From the technical point of view, this depends on the shape of the blade. The change of the shape of blade is one of the methods to modify stiffness and stability, but it may influence aerodynamic efficiency of wind turbine. Other method to change dynamic and mechanical properties of wind turbine is modifying the composite material, which the blade is made of. For increasing power output of wind turbine, blade has to be increased but increasing blade length increases weight of blade exponentially. So numerical tools can be utilized to increases length of blade with suitable optimization technique. The mass of blade can be reduced by replacing current material with lighter but strong material. Advance material can be used for this purpose. Composite material is light in weight but stronger that normal material.

Objectives

- ✓ To Design a Wind turbine blade and studying its aerodynamics in CFD analysis.
- ✓ To perform Mass optimization on these blades to increase performance without compromising blade structural strength using FSI analysis in ANSYS Simulation software.

Problem Definition

Due to depletion of conventional source of energy, development of non-conventional sources of energy has become a necessity for survival. Wind turbines are one of major sources of energy. But due to its heavy blade and large structure, it becomes a costly source of energy. Also, transportation and handling of this heavy blade causes problems. Mass reduction of these blade could help in reducing this problem to some extent. We are using mass optimization technique

Methodology

A GE's 1.5MW wind turbine blade is used as a reference wind turbine blade and our objective is to develop an optimization process for FSI system and obtain optimum blade design to minimize weight, eventually reducing cost and maximizing power output. 3D model of actual size of wind turbine is modelled in 3D modelling software of Solidworks. This model was further used to develop CFD model to get effect of incoming wind at 12 m/s on blade surface. Boundary conditions for CFD analysis are selected from the literature papers done on wind turbines.

II. SELECTION OF WIND TURBINE

1.5xle wind turbine of General Electric Company is selected for the design and Analysis. GE's 1.5 MW wind turbine is the most widely used turbine in its class. This wind turbine was selected because Geometry Specification was readily available (Courtesy of GE Energy). 1.5xle was selected because higher capacity turbine would prove to be computationally expensive.

Technical Specification of 1.5xle Wind turbine

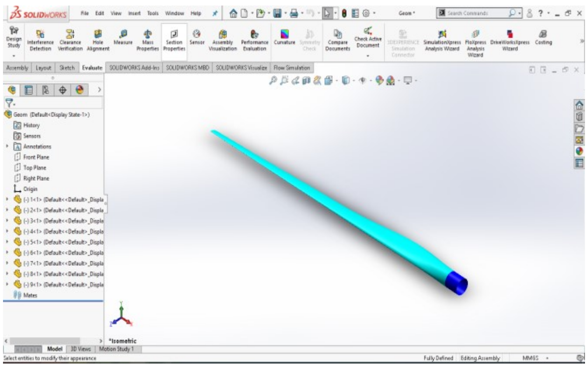

Figure 1. Final 3D model of HAWT Blade in Solidworks

Rated Capacity	1,500 kW
Temperature range	-300 C to +400 C
Rated wind speed	12 m/s
Voltage	690 V
Frequency	50/60 Hz
Rotor Diameter	82.5 m
Swept Area	5346 m2

Governing Equations and Boundary Conditions

A. Mathematical Model: Governing Equations

The governing equations are the continuity and Navier-Stokes equations. These equations are written in a frame of reference rotating with the blade. This has the advantage of making our simulation not require a moving mesh to account for the rotation of the blade.

Conservation of mass:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \vec{v}_r = 0$$

Conservation of Momentum (Navier-Stokes):

$$\nabla \cdot (\rho \vec{v}_r \vec{v}_r) + \rho(2\vec{\omega} \times \vec{v}_r + \vec{\omega} \times \vec{\omega} \times \vec{r}) = -\nabla p + \nabla \cdot \overline{\overline{\tau}}_r$$

Where

$\vec{v}_r$ is the relative velocity (the velocity viewed from the moving frame) and $\vec{\omega}$ is the angular velocity.

Note the additional terms for the Coriolis force ($2\vec{\omega} \times \vec{v}_r$) and the centripetal acceleration ($\vec{\omega} \times \vec{\omega} \times \vec{r}$) in the Navier-Stokes equations. In Fluent, we'll turn on the additional terms for a moving frame of reference and input

$$\vec{\omega} = -2.22\hat{\mathbf{k}}$$

We use the Reynolds Averaged form of continuity and momentum and use the SST k-omega turbulence model to close the equation set.

B. Boundary Conditions

We model only 1/3 of the full domain using periodicity assumptions:

$$\vec{v}(r_1, \theta) = \vec{v}(r_1, \theta_1 - 120n)$$

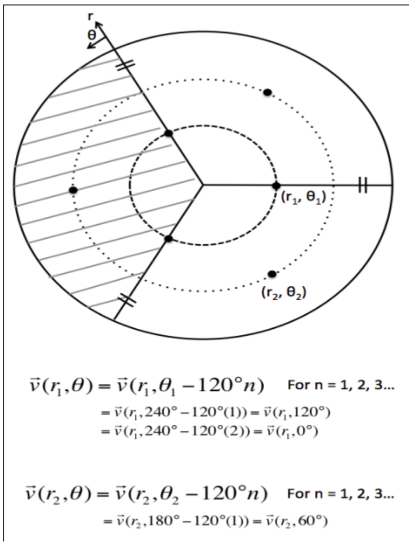

Figure 2. Boundary Conditions

The boundary conditions on the fluid domain are as follow:

Inlet:	Velocity of 12 m/s with turbulent Intensity of 5% and turbulent viscosity ratio of 10
Outlet:	Pressure of 1 atm
Blade:	No-slip
Side Boundaries:	Periodic

III. THEORETICAL STRENGTH CALCULATION

A. Hand-Calculations of Expected blade tip velocity

Theoretical wind velocity at the tip be calculated and compared with CFD results which get from the analysis.

The velocity, v, on the blade should follow the formula

v = r x ω

Plugging in our angular velocity of -2.22 rad/s and using the blade length of 43.2 meters plus 1 meter to account for the distance from the root to the hub,

$$v = -2.22 \text{ rad/s } \hat{\mathbf{k}} \times -44.2 \text{ m } \hat{\mathbf{i}}$$
$$v = 98.12 \text{ m/s } \hat{\mathbf{j}}$$

Additionally, by using the simple one-dimensional momentum theory, we can estimate the power coefficient which is the fraction of harnessed power to total power in the wind for the given turbine swept area. This analysis uses the following assumptions:

- The flow is steady, homogenous and incompressible.
- There is no frictional drag.
- There is uniform thrust over the disc or rotor area.
- The wake is non-rotating.
- The static pressure far upstream and downstream of the rotor is equal to the undisturbed ambient pressure.

Thus, at rated wind speed,

$$C_p = \frac{P_{rated}}{P_{wind}} = \frac{P_{rated}}{0.5\rho A V_{rated}^3} = \frac{P_{rated}}{0.5(1.225\frac{kg}{m^3})(\frac{\pi(82.5m)^2}{4})(11.5\frac{m}{s})^3} = 0.30$$

B. Theoretical value of root Radial Force

The radial force is the outward force that comes from a spinning mass. It is equal and opposite to the reaction force at the root of the blade that keeps the blade connected to the hub. It can also be thought of as the mass times the radial acceleration.

$$F_r = -mr\omega^2$$
$$F_r = -(22,473kg)(-14.232m)(-2.22rad/s)^2$$
$$F_r = 1.5763 * 10^6 N$$
$$F_r = 1576.3kN$$

In this expression, "m" stands for the total mass of the blade and "r" stands for the distance in the radial direction where this mass resides. In this case, "r" will be location of the blade's center of mass in the radial direction. For glass fiber composite, the blade weighs 22,473 kg and its center of mass (X, Y, Z) is located at the coordinate (-14.232 m, -0.213 m, 0.160 m). The blade is oriented so that the x-axis points along the radial direction of the blade.

IV. CFD NUMERICAL RESULTS

A. Mass Flow Rate

Net result value of mass flow rate at inlet and outlet was checked to see if it makes sense, if mass is balanced

Table 1. Mass Flow Rate

Mass Flow Rate	(kg/s)
Inlet	221221.15
Inlet-top	664988.49
Outlet	-886210
Net	-0.3607683

B. Blade Velocity

From plot, it can be seen that local velocity increases with increase in radius from hub. Magnitude of velocity is highest at tip of blade. The blade tip velocity was found to be 98.05 m/s in CFD-Post. This is basically identical to result obtain from hand-calculations which was 98.12 m/s. This validate that CFD model is accurate

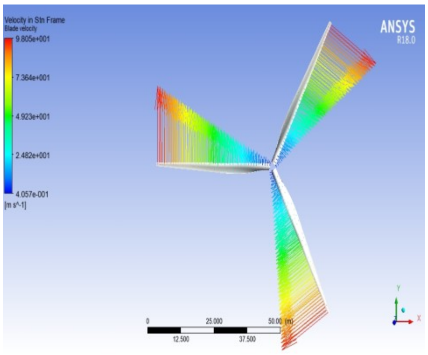

Figure 3. Blade Velocity

C. Pressure Contour

From this plot, it is visible that the pressure is low on back surface of blade as compared to the front surface of blade (realised from colour scheme). Red region shows Positive pressures, green region shows same magnitude but negative in nature, while blue region indicates much higher negative pressure.

So, this pressure difference between front & back surface of blade. As blade is not fully perpendicular to ground, thus there is component of lift in direction of rotation which is in XY Plane. The component of lift in negative Z axis direction has large effect on blade deflection, which we see in FSI analysis

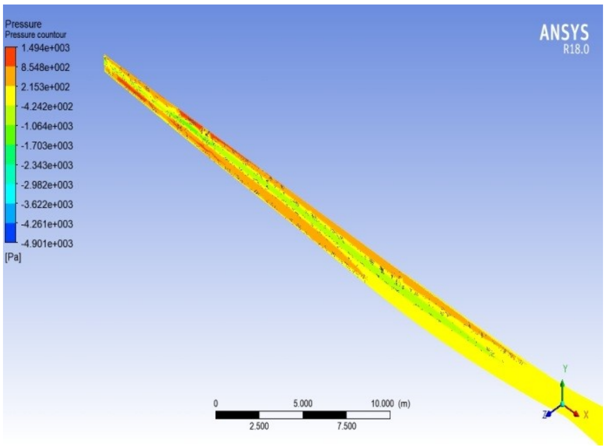

Figure 4. Pressure Contour on Front surface of Blade

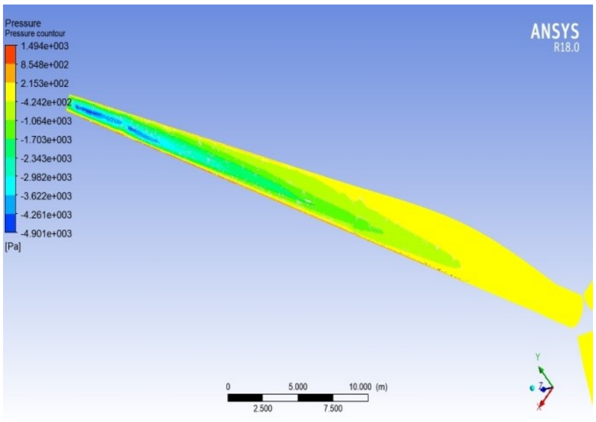

Figure 5. Pressure Contour on Back surface of Blade

V. VERIFICATION OF CFD MODEL

A. Compare blade tip velocity

The blade tip velocity was found to be 98.05 m/s in CFD-Post. This is basically identical to result obtain from hand-calculations which was 98.12 m/s.

B. Compare Power Coefficients

We had predicted the power coefficient to be around 0.3. As seen on the convergence plot below, the numerical results do agree well with this value considering a sufficient number of elements in the mesh.

For example, using a mesh of 2 million cells, the power coefficient becomes 38% as opposed to the 30% from hand-calculations. These match up quite well considering the many assumptions used in the simple 1D momentum theory. At last, we should keep in mind that power coefficient must lie under the Betz limit of 16/27=59.2% for a non-shrouded rotor. Our numerical results correctly fall below this limit.

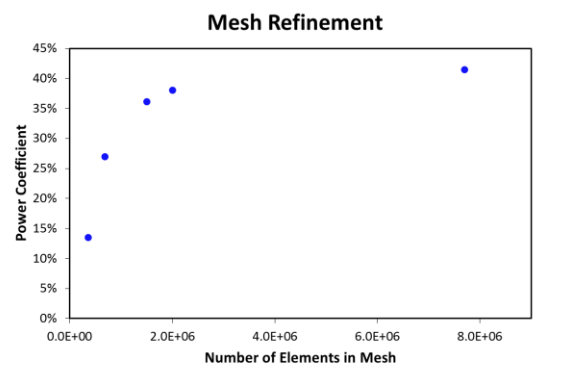

Figure 6. Mesh Refinement

C. FSI Simulation

This section considers the deformation due to aerodynamic loading of a wind turbine blade by performing a steady-state 1-way FSI (Fluid-Structure Interaction) analysis. Previous section of CFD analysis uses ANSYS Fluent to develop the aerodynamics loading on the blade. In this section, the pressures on the wetted areas of the blade are passed as pressure loads to ANSYS Mechanical to determine stresses and deformations on the blade.

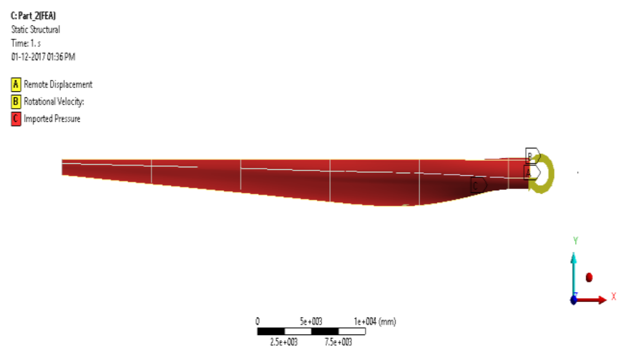

Figure 7. FSI Boundary Conditions

The turbulent wind is flows towards the negative z-direction at 12 m/s which is a typical rated wind speed for a turbine this size. This incoming flow makes the blade rotate at an angular velocity of -2.22 rad/s about the z-axis.

D. Verification of FSI Simulation by Root Radial force

Hand calculated value of root radial force and numerical result are compared, to check validity of FSI model developed. The values are compared in below table, as you can see the results match quit well. Balsa wood has large deviation because in simulation it is considered as isotropic material, while in reality it is anisotropic material. But for simplification of problem, this assumption was considered. Hence large deviation is observed

Table 2. FSI Result (a)

Radial Root Force			
Material	**Theoretical value (kN)**	**ANSYS Value (kN)**	**% difference**
Glass Fiber Composite	1576.28	1579	0.1724
Standard Balsa Wood	1619.49	1683.8	3.8190
Heavy Balsa Wood	2237.27	2123.8	5.3430
Carbon-Carbon Composite	1779.66	1783.2	0.1988
Ceramic Matrix Composite	2776.27	2779.5	0.1162
Polymer matrix composite	1637.26	1640.8	0.2159

Table 3.FSI Result (B)

Sr. no.	**Materials**	**Weight (Kg)**	**Stress (MPa)**	**Deformation (mm)**
1	Glass Fiber Composite	364.74	35.314	489.37
2	Standard Balsa Wood	374.74	8.6498	25339
3	Heavy Balsa Wood	517.69	7.5802	20509
4	Carbon-Carbon Composite	411.8	27.634	1221.3
5	Ceramic	642.41	31.055	678.64

	Matrix Composite			
6	Polymer matrix composite	378.85	16.898	2786.9

VI. CONCLUSION

From results, it can be concluded that Glass fiber based composite material is best suitable replacement from commonly used material viz., wood. It is also noted that weight is optimized with reduction in its lateral deflection Table 1 (b).

Low weight blade can be designed and manufactured with strong load carrying capacity. The FEA results on HAWT Blade shows that, weight of blade can be optimized by almost 30%, using glass composite material. From the results it is also observed that deflection of directional fiber based composite is also reduced. FSI Simulation can also be utilized for optimization of other parts of Wind turbine. Optimized component helps in increasing performance of wind turbine.

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