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Modal Analysis of A Small Wind Turbine Blade Made of Different Materials

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Abstract— A wind turbine is a mechanical device that uses wind energy to generate power by converting the kinetic energy of the rotor blade, Small wind turbines need to be installed with affordable cost, and it should be reliable and maintenance free small-scale wind turbines produces useful electrical energy in developing countries. And also in developed countries for autonomous applications in locations that are far away from the grid power.

In the present, work the dynamic parameters of small wind turbine blade are determined by carrying modal analysis on different materials. Modal analysis of wind turbine blade made up of Aluminium PVC and composite materials is carried out to obtain Natural frequencies and corresponding mode shapes by the finite element analysis software ANASYS 14.5. Wind turbine blade is modelled by using modelling software and the model meshes with tetrahedral elements. Modal analysis of wind turbine blade is carried out by applying the fixed supports at the one end of the blade and other end left free. Five natural frequencies and five mode shapes are extracted for wind turbine blades of different materials

Index Terms—*Wind Turbine Blade, Natural frequency, Mode shape, PVC, Al, Composite Material, ANSYS*

I. INTRODUCTION

Wind energy is one of the renewable energy sources and it is growing effectively to generate electricity in affordable cost. The most common and reliable type of wind turbine is horizontal axis wind turbine (HAWT), among the different types and designs, are available. To extract the maximum possible energy available in the wind, the wind turbine blade design is to be improved and need to reduce the weight of wind turbine by using different materials for the wind turbine blade. Before using different materials for the blade, the static and dynamic analysis of the blade materials to carried out to check the static and dynamic stability of the blade

A wind turbine is a mechanical device that uses wind energy to generate power by converting the kinetic energy of the rotor blade, Small wind turbines need to be installed with affordable cost, and it should be reliable and maintenance free small-scale wind turbines produces useful electrical energy in developing countries. Moreover, in developed countries for autonomous applications in locations those are far away from the grid power. Small-scale wind turbines are becoming an increasingly promising way to supply electricity in developing countries.

Horizontal Axis Wind Turbines (HAWTs) are very advanced, reliable, and economically viable. The different sizes and shapes are available but they are all from old wind mills used to pump water and to grind grains. Today these machines are used in the world to produce the clean, affordable, and sufficient amount of electricity.

Wind turbines are classified based on the wind turbine size, or capacity to produce electricity. A wind turbine can be small which produce less than 100 kW of power and intermediate wind turbine produces the power of about 100-500 kW, and large wind turbine produces the power of about 500 kW - 5 MW. Small wind turbines are used for domestic purpose, and in companies, and n remote areas, where the supply of electricity is difficult.

II. WIND TURBINE BLADE MATERIALS AND GEOMETRY

A wind turbine blade is a key component in wind power generation systems. It's rotating motion is converted in to electricity and its shape affects the efficiency of the wind power generation system. The wind turbine blade is the main component for converting wind power to rotatory motion, and there is a demand for the blade to have lightweight and it should be durable.

The wind turbine blade resemble like a cantilever beam and it is assembled into the main body of the wind turbine through a hub, and it should support high bending stress due to bending moment and it is maximum at the root of the blade and shear stress due to torsional load. Wind turbine blades are also subject to the external loading, which includes the flap wise and edgewise gravitational loads, inertia forces, and loads due to pitch acceleration. The flap wise load is caused by the wind pressure, while the edge wise load is caused by gravitational forces and torque load.

In general, blade materials should meet the following requirements.

1. Wide availability and easy processing to reduce cost and maintenance
2. Low weight or density to reduce gravitational forces
3. High strength to withstand strong loading of wind and gravitational force of the blade itself
4. High fatigue resistance to withstand cyclic loading
5. High stiffness to ensure stability of the optimal

shape and orientation of the blade and clearance with the tower

6. High fracture toughness
7. The ability to withstand environmental impacts such as lightning strikes, humidity. a few are certified, as being inaudible even a few feet (about a meter) under the turbine

PVC blades: PVC blades have the lightweight and easy to install but it is only used in small wind turbines.
Aluminum alloy blades: It is not an unusual blade material for small wind turbines. In some countries, aluminum alloy blades are used for 1kw-5kw wind turbines.
Fiber Glass blades: It is the popular wind turbine blade material for both small wind turbines and large wind turbines. The problem is that it is difficult to make for home or small factory

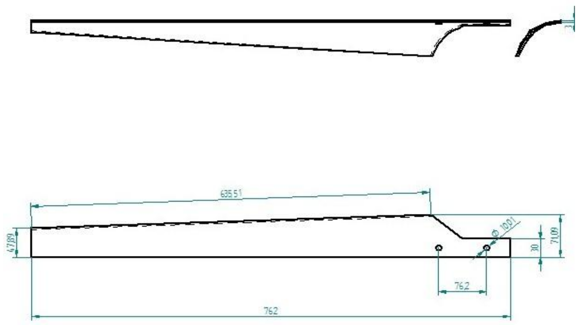

Figure 1. 2D model of wind turbine blade

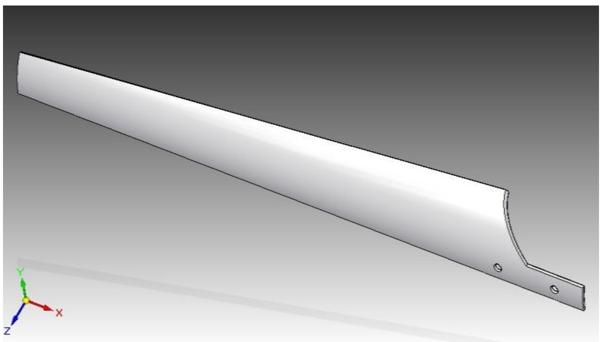

Figure2. 3D model of wind turbine blade

III. Modal Analysis Of Wind Turbine Blade By Finite Element Method

The aim of modal analysis in structural mechanics is to determine the natural frequencies and mode shapes of a component or structure when it is subjected to free vibration. It is common to use the finite element method (FEM) to perform modal analysis because using the FEM, the component or structure being analyzed can have a complex shape and the obtained approximate results are acceptable. The physical model of the problem can be defined by using differential equations and by solving these results in Eigen values and Eigenvectors and they represent the natural frequencies and corresponding mode shapes. Sometimes, only desired lower mode shapes and corresponding natural frequencies are used to design the model and the lowest frequencies are considered because at these frequencies the component vibrate more compare to the higher natural frequencies

The Basic differential equation used for modal analysis and the calculation of natural frequency for a discretized system is given by.

$$M\ddot{x} + C\dot{x} + Kx = F(t) \qquad (1)$$

Eq (1) shows the set of equations of motion in matrix form for a random discretized structure. M, C and K are the mass, damping and stiffness matrices, respectively. The vector F(t) is a time-dependent load vector.

For calculating the natural frequencies, the free vibration of the system is considered; damping coefficient and external forces are taken to be zero. Thus Eq (1) becomes.

$$M\ddot{x} + Kx = 0$$

The general eigenvalue problem can be formulated.

$$(K - \omega^2 M)x = 0 \qquad (2)$$

Assuming the existence of the vector x meaningly a non-trivial solution of this set of equations, the system's determinant has to vanish. This leads to the characteristically equation displayed in

$$|K - \lambda M| = 0 \qquad (3)$$

The solutions of this equation are the n eigen values for a system of n degrees of freedom, where each eigen value λ corresponds to a natural angular frequency ω_i as stated in

$$\lambda_i = \omega_i^2 \text{ with } i=1,2, . n. \qquad (4)$$

The amplitude vector corresponding to an eigenvalue is the eigenvector or mode shape vector Ψ_i. The combinations of natural frequencies and mode shape vectors describe preferred states of vibration of the structure.

Modal analysis is carried out for wind turbine blade made up of aluminium, PVC, and composite materials. The mechanical properties of aluminium, PVC, and composite materials are shown in table 1

TABLE I
THE MECHANICAL PROPERTIES OF ALUMINIUM, PVC, AND COMPOSITE MATERIALS

Material properties	Al	PVC	CM
Density kg/m^3	2700	1467	1200
Modulus of elasticity (Pa)	7.e+010	3.3e+009	2.e+009
Poisson's Ratio	0.35	0.4	0.3
Bulk Modulus Pa	7.7778e+010	5.5e+009	1.6667e+009
Shear Modulus Pa	2.5926e+010	1.1786e+009	7.6923e+008
Coefficient of Thermal Expansion / C^0	2.4e-005	7.e-005	1.5e-005

The blade model is created by using modeling software shown in figure1 & 2. The created model is exported to

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ANSYS software to perform the modal analysis. The model meshes with tetrahedral elements and around 7329 elements are created as shown in figure4. Analysis is carried out by applying fixed support to the base of the blade and another end is left free to vibrate as shown in figure5.

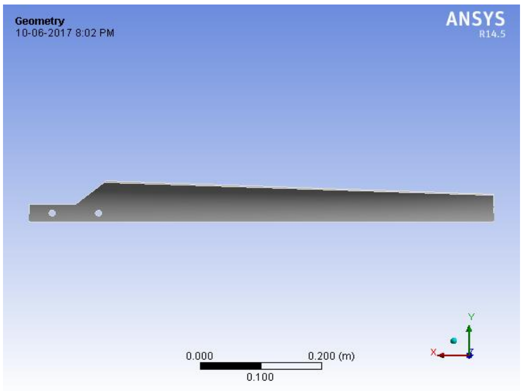


Figure 3. CAD model of blade

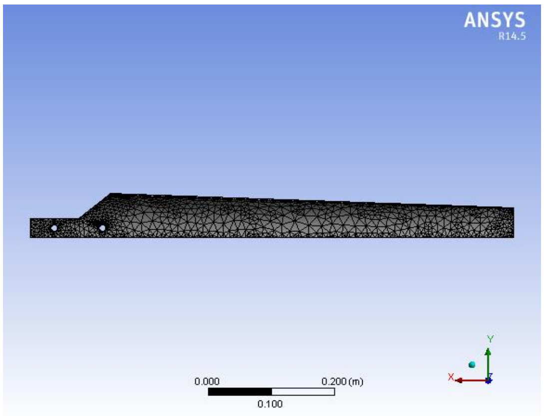


Figure 4. FEA Meshed model of blade

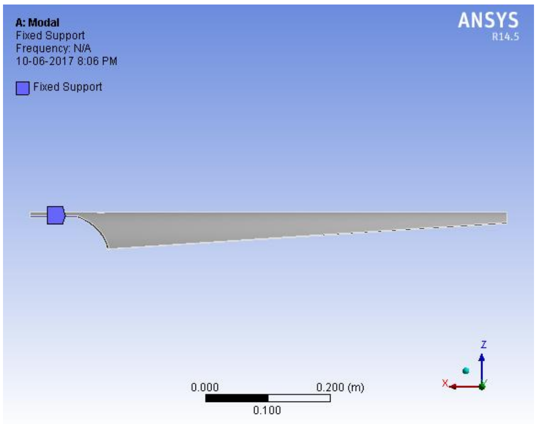


Figure5. Boundary conditions for wind turbine blade

IV. Results And Discussions

The Modal analysis is carried out for a blade with constant element thickness by applying cantilever boundary condition that is the root of the blade fixed completely with zero degrees of freedom and tip of the blade is left free for vibration. Table 2 shows natural frequencies and maximum displacement for different modes of vibration of PVC wind turbine blade. Figure 6, 7, 8 and 9 shows the mode shapes for different natural frequencies and maximum displacements of PVC blade.

TABLE II
NATURAL FREQUENCIES FOR DIFFERENT MODES OF VIBRATION OF PVC WIND TURBINE BLADE

Mode	Frequency [Hz]	Maximum Displacement (m)
1.	6.2883	4.6925
2.	27.625	5.5843
3.	32.509	5.9684
4.	41.659	7.1622
5.	83.16	7.2187

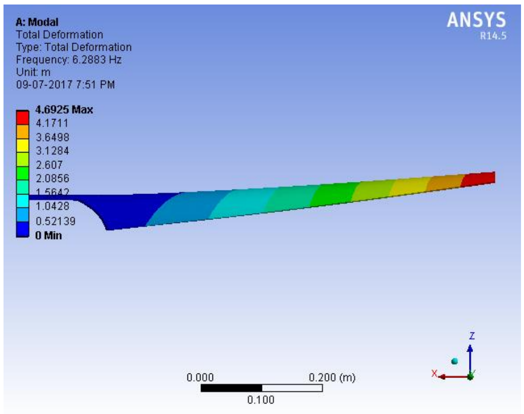


Figure 6. First mode shape of free vibration for PVC blade

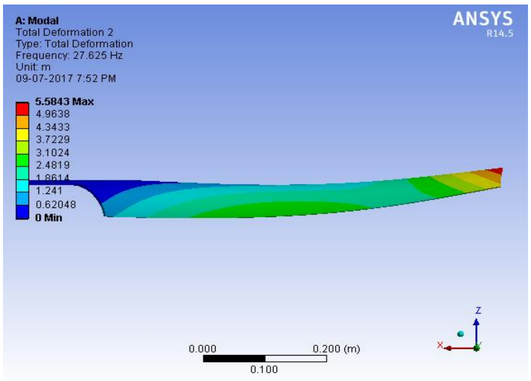


Figure 7. Second mode shape of free vibration for PVC blade

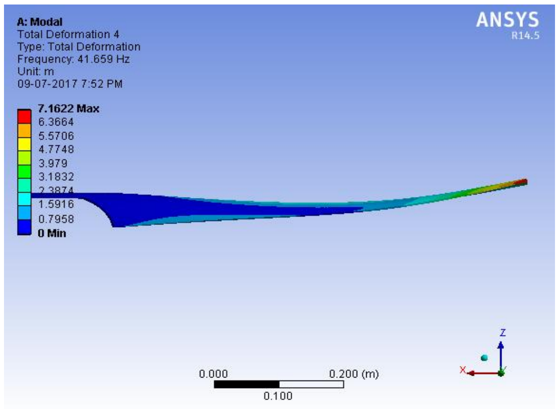


Figure 8. Fourth mode shape of free vibration for PVC blade

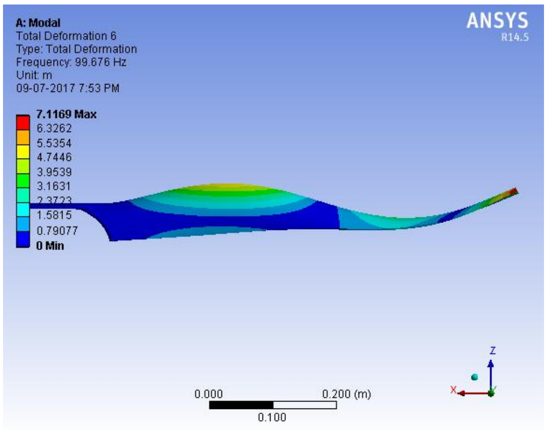


Figure 9. Sixth mode shape of free vibration for PVC blade

Table 3 shows natural frequencies and maximum displacement for different modes of vibrations of Aluminium wind turbine blade. Figure 10, 11, 12, and 13 shows the mode shapes for different natural frequencies and maximum displacements of Al blade.

TABLE III
NATURAL FREQUENCIES FOR DIFFERENT MODES OF VIBRATION OF AL BLADE

Mode	Frequency [Hz]	Maximum displacement (m)
1.	23.963	3.1893
2.	103.1	3.3803
3.	142.64	4.3058
4.	244.24	3.7502
5.	388.36	5.1121

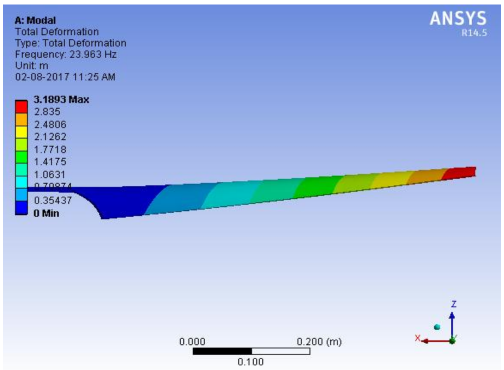
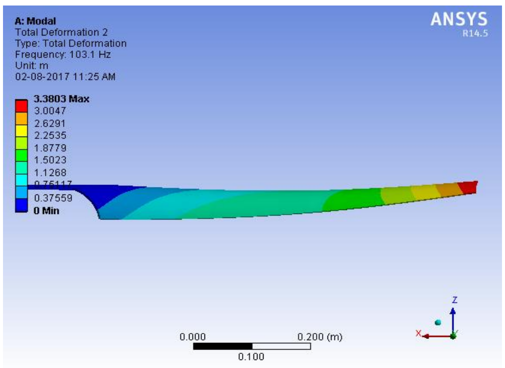


Figure10: First mode shape of free vibration for Al blade



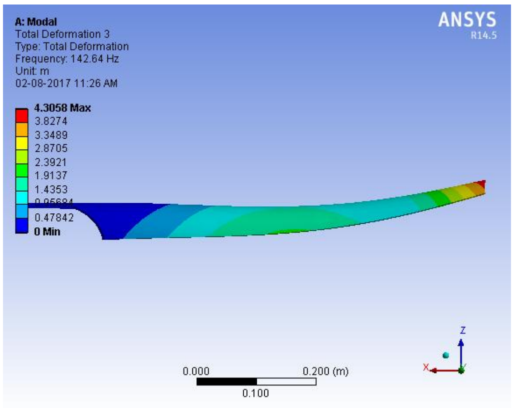


Figure12. Fourth mode shape of free vibration for Al blade

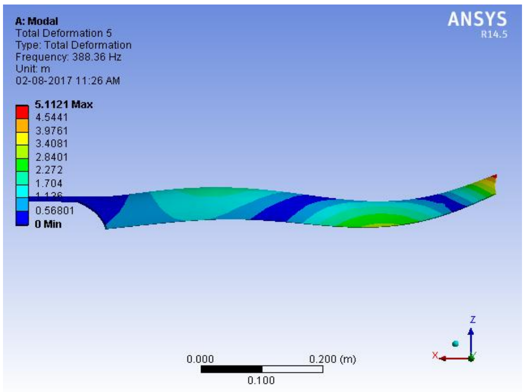


Figure 13. Fifth mode shape of free vibration for Al blade

Table 4 shows natural frequencies and maximum displacement for different modes of vibration of the composite material wind turbine blade. Figure 14, 15, 16 and 17 shows the mode shapes for different natural frequencies and maximum displacements of composite material blade

TABLE 4
NATURAL FREQUENCIES FOR DIFFERENT MODES OF VIBRATION OF COMPOSITE MATERIAL WTB

Mode	Frequency(Hz)	Maximum displacement(m)
1	6.0301	4.7801
2	26.001	5.085
3	36.063	6.4357
4	61.692	5.5965
5	97.914	7.6542

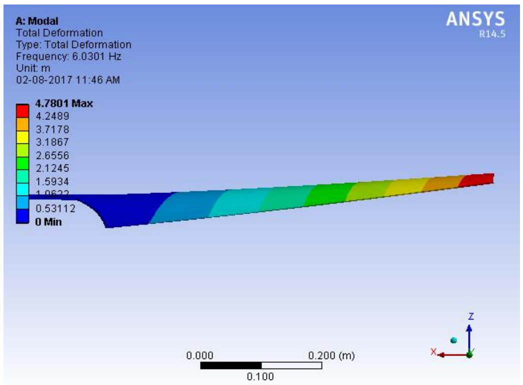


Figure14: First mode shape of free vibration for CM blade

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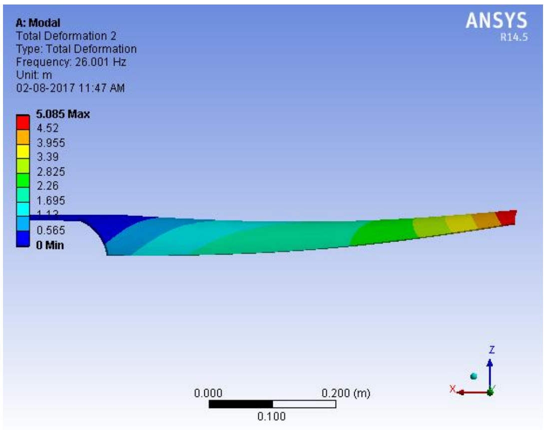

Figure 15. Second mode shape of free vibration for CM blade

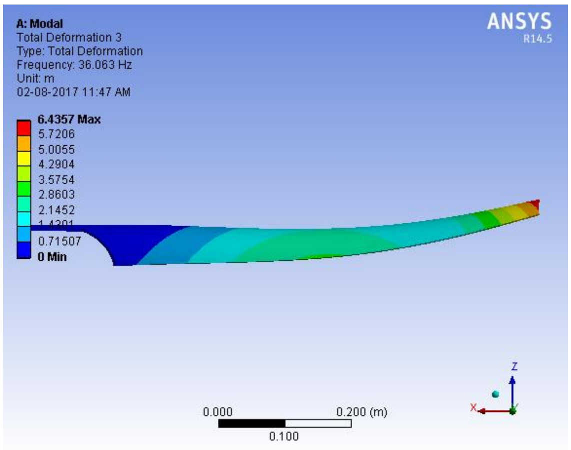

Figure16: Fourth mode shape of free vibration for CM blade

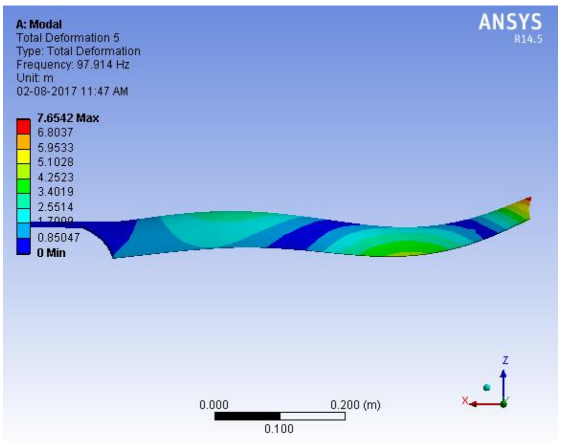

Figure 17. Fifth mode shape of free vibration for CM blade

Table 5 shows the results of modal parameters like natural frequencies and maximum displacement for different materials. The natural frequencies of PVC blade and CM blade are nearly same for different modes of vibration and natural frequencies of Al blade values are higher for same modes of vibration.

TABLE 5
NATURAL FREQUENCIES FOR DIFFERENT MODES OF VIBRATIONS FOR AL, PVC, CM BLADE

Mode shapes	PVC blade		Aluminium blade		CM blade	
	Frequencies (Hz)	Maximum displacement (m)	Frequencies (Hz)	Maximum displacement (m)	Frequencies (Hz)	Maximum displacement (m)
1	6.288	4.692	23.96	3.189	6.030	4.780
2	27.62	5.584	103.1	3.380	26.00	5.085
3	32.50	5.968	142.6	4.305	36.06	6.435
4	41.65	7.162	244.2	3.750	61.69	5.596
5	83.16	7.218	388.3	5.112	97.91	7.654

V. CONCLUSIONS

The blade is the most important part in a wind turbine, which is made of composite material, PVC, and Al with an aerodynamic profile, twisted tip and varying cross sectional area along its length. The geometry of the blade is modeled utilizing modeling software. Initially, the finite element model is created by using tetrahedral elements for modal analysis to determine natural frequencies and corresponding mode of vibration. Modal analysis of wind turbine blade is carried out by applying the fixed supports at the one end of the blade and other end left free. Five natural frequencies and five mode shapes are extracted for wind turbine blades of different materials

The present investigation shows that the structural integrity of a structure can be monitored by using modal parameters, like natural frequencies, and mode shapes. Operational Modal analysis is performed and results are compared with different material blades and good correlation between PVC blade and CM blade has been found. Furthermore, these modal parameters are used for harmonic analysis to check the stability of materials for the dynamic loads. The natural frequencies are compared with excitation frequencies to avoid resonance condition and violent vibration.

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