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Design and Dynamic Analysis of Wind Turbine Blade

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ABSTRACT: Wind turbine blade is one of the important components requiring more attention at the design stage. These blades are made up of fibrous material and sometimes hollow composite web sections may be employed in its construction. The main focus in its design is to achieve a desired strength to withstand various loads as per the power requirements. In view of this, modelling & dynamic analysis of blades is an essential requirement not only to avoid resonant vibrations but also to understand the stability of operation during various operating conditions.

In this project work mainly focusing on dynamics of horizontal- axis wind turbine blade with NACA 63415 profiles subjected to aerodynamic, centrifugal and gravity loads. The basic geometrical parameters of the blade are to be designed by using blade element moment method & the blade is modelled as a ruled 3D surface. By computing element wise cross sectional details from 3D model, a 1D beam finite element modelling is developing and modal characteristics are to be calculated. These models are further validated with 3D finite element model result. After that, the effects of the tip speed ratio and rotational speed on the natural frequencies are also to be studied. Further, finite element model have 10 elements with 6 degrees of freedom per node is used to obtain the dynamic response of the blade subjected to various loading conditions. The effect of aerodynamic, centrifugal and gravity parameters on the frequency response, edge-wise and flap-wise beating at the tip of blade are to be studying.

I. INTRODUCTION

Wind turbines can be classified into Horizontal Axis Wind Turbines (HAWT), and Vertical Axis Wind Turbines (VAWT). Horizontal type turbines have the blades rotating in a plane which is perpendicular to the axis of rotation. The HAWTs are most widely used type of wind turbines and come in varied sizes and shapes. The primary type of force acting on the blades of HAWT are the drag forces. The Horizontal type are commercially applicable type due to its varied sizes and storage capacities. In Vertical Axis Wind Turbine blades, the rotation axis coincides with the axis of generation of power. Advantages of Vertical Axis wind turbine is the placement of generator at the base of the turbine. But these type are nearer to ground which makes it difficult to capture the power at higher altitudes. While the HAWTs require yaw mechanism to orient themselves in the direction of wind, the VAWTs do not have such problem. But disadvantage with VAWTs is the low starting torque, lesser installation height and dynamic stability issues.

II. LITERATURE REVIEW

Designing a blade by using well known Blade Element Momentum (BEM) Theory is a fascination to many researchers who are interested to get better geometrical parameters to maximize the power output of the blades. Using the airfoil profile, knowing the angle of attack of the wind and the proposed length of the blade, researchers such as Tenguria et al. [1] have used BEM theory to optimize the coefficient of power, lift and drag characteristics with various tip speed ratio, lift and drag coefficients. It is observed that at a power coefficient 0.46 and lift to drag coefficient is 124.47, the power absorption is maximum. John McCosker [2], developed an optimized code for a discretized 9 element wind turbine blade having a length of 0.95 m. He obtained optimal speed ratio, angle of wind, the pitch angle and relative chord lengths for each element. Anjali et al [3], in which they described an ant colony optimization method by varying the composite material of the blade and conducting stress analysis. Thumthae and Chitsomboon [4] investigated an untwisted blade for obtaining optimal pitch to get maximum power for wind turbine using steady flow wind conditions.

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Greiner [5], for a test turbine having 19m rotor diameter and 100 KW nominal power. Similar works have been done [6-9] where observations state that optimizing the blade shape parameters is mostly to maximize the output power generation of the blade. Ingram [8] derived equations relating to the Blade Element Theory in order to find the axial force, Lift and drag characteristics, considering the tip loss correction to calculate the rotor performance. An iterative procedure is used to refine the obtained results. Vasjaliya et al [9], evaluated multidisciplinary optimization process to minimize cost, weight and maximize power output by considering a fluid structure interaction and structural robustness to enhance performance of a QBlade / Xfoil airfoil blade. Finally Performance of wind turbine blade models with NACA 63415 profile, airfoil blade section analysis with taper and twist, in stationary and rotating conditions, modal data & forced vibration analysis, using analytical and FE Modelling. Based on the exhaustive literature review it was found that the affect of subsequent on dynamics of horizontal- axis wind turbine blade with NACA 63415 profiles subjected to aerodynamic, centrifugal and gravity loads.

III. MODELLING OF THE BLADE

The values of coordinates of top and bottom surfaces of airfoil as stored in excel format are called in commercial solid model software CATIA V5. The macro after pasting the coordinates prompts an option either to generate only points, or points & spline, or loft the splines. The inserted spline in the CATIA part file is either scaled to the required size or rotated to give the amount of twist to the wind turbine blade. After getting the two splines, the surface modelling feature is activated and a loft surface is formed by multi section solids option from CATIA toolbox. After getting the loft surfaces, upper and lower surfaces are joined so that we get a solid model ready for analysis as shown in Fig.3.1. The solid model obtained is saved in either .parasolid or .IGS format and is exported to ANSYS for further analysis as seen in Fig.3.2. The first few natural frequencies of the system can be found out using ANSYS workbench which will serve as a base for transient and vibrational analysis of the system. In this analysis, the wind turbine blade is simplified to be a cantilever problem where the blade is fixed at the hub portion.

The .igs file is opened in ANSYS workbench for modal analysis. The modal analysis tool is invoked, the materials are given and the geometry is imported into the workbench. The total deformation and first five natural frequencies are obtained and their mode shapes are recorded.

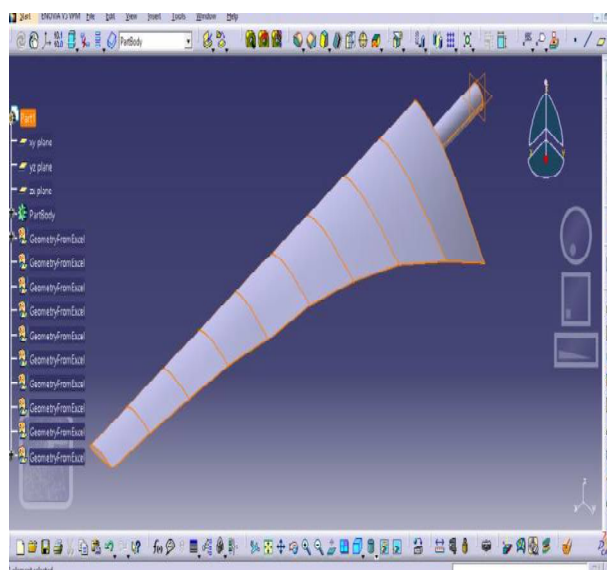


Fig 3.1 Solid model of the twisted blade

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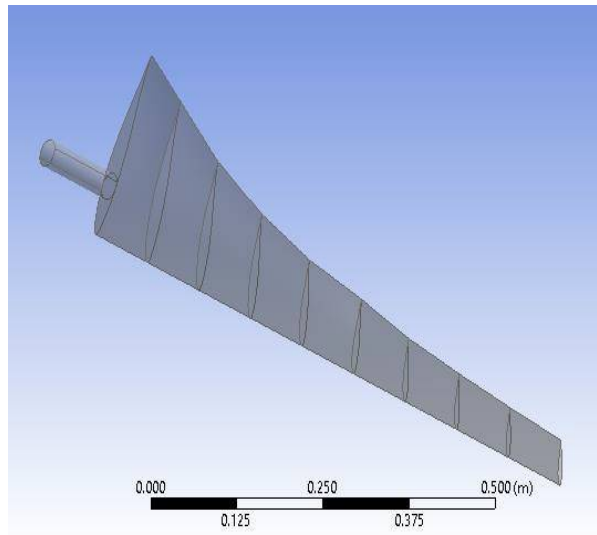


Fig 3.2 Imported solid model

IV. RESULTS & DISCUSSION

Dynamic analysis of such coupled fluid-structure problem required several considerations. First step is to generate the blade geometry. Then CAD model is formulated in 3-D, followed by its frequency analysis. 1-D beam formulation is then presented with the generated force system. The dynamic equations are solved by New mark's time integration with zero initial conditions. Details are explained one after the other as follows.

4.1 Blade Data Selection Procedure

An important factor to consider in generation of power of wind turbine is the blade design. The following procedure is to be adopted in determining the blade dimensional properties.

Step 1: Determine the radius of the blade $R = 1.02\text{m}$

Step 2: Choose a tip speed ratio $\lambda=6$

Step 3: The number of blades $B=3$

Step 4: Select an airfoil: NACA 63415

Step 5: Choose a chord distribution of the aerofoil $c = \frac{8\Pi r}{BC_L} (1 - \cos \phi_r)$

Step 6: Discretize the blade into n elements $n=10$

Step 7: Choose an angle of attack α in such a way that its value is constant throughout the blade: $\alpha=6^\circ$

Step 8: Examine the lift C_L & drag coefficient C_D curves for the airfoil by considering Reynolds Number of 100,000.

Step 9: Obtain the lift, drag, moment coefficients for the specified angle of attack of the blade: $C_m=-0.0597, C_L=0.8765, C_D=0.0258$

Step 10: Obtain the angle of relative wind $\phi_r = \frac{2}{3} \tan^{-1} \frac{1}{\lambda_e}$

Step 11: Calculate the angle of blade twist θ_T , from the angle of attack and angle of relative wind. $\theta = \phi - \alpha$

4.2 Input Parameters

The parameters of the wind turbine blade considered in the present analysis are depicted in Table 4.1. The geometrical properties of the blade elements are tabulated in Tables A1 in the Appendix II and Inertial properties can be tabulated as shown in Table 4.2.

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Table 4.1 Properties of the blade

Material	Glass Fiber Reinforced Plastic
Mass density of the blade	1400 kg/m ³
Elastic Modulus of the blade	6 GPa
Poisson's Ratio	0.18
No. of Elements	10
No. of Elements at the root section	1
No. of Elements in the working region	9
Length of the blade	1.02m
Radius of the hub	0.06m

Table 4.2 Inertial Properties of the Blade at tip-speed ratio $\lambda=6$

Element	dr	A, cm ²	Twist θ	I_{xx} , cm ⁴	I_{yy} , cm ⁴	I_{zz} , cm ⁴	I_{yz} , cm ⁴
1	0.12	8.365	0	11.137	5.568	5.568	0
2	0.1	42.394	29.825	934.172	196.041	738.131	339.058
3	0.1	30.701	15.891	504.374	53.747	450.626	130.524
4	0.1	20.193	10.671	217.006	13.286	203.719	38.015
5	0.1	13.745	7.379	99.700	4.206	95.493	11.849
6	0.1	9.815	5.145	50.477	1.944	48.533	5.248
7	0.1	7.311	3.539	27.863	1.071	26.792	2.661
8	0.1	5.637	2.332	16.501	0.457	16.044	0.519
9	0.1	4.470	1.393	10.349	0.278	10.071	0.159
10	0.1	3.627	0.643	6.800	0.181	6.619	0.0178

4.2 1-D Beam Finite Element Analysis Outputs

The blade under consideration has a variable cross section and 10 elements are taken, one near the root and nine along the blade working zone. By arresting the first node, 66×66 matrices reduce to 60×60 matrices. The computational work is carried out using MATLAB to find out the Global Mass and Global Stiffness matrices, giving boundary conditions, and Eigen value analysis is conducted.

4.3 Modal Characteristics of the blade from ANSYS 15.0

Using ANSYS 15.0 workbench, the modal analysis tool is invoked, the material properties are given, and the geometry is imported into the workbench. Fig 4.3 shows the mesh details for 3-D model using Tetrahedral beam elements. The total deformation and first five natural frequencies are obtained and their mode shapes are recorded.

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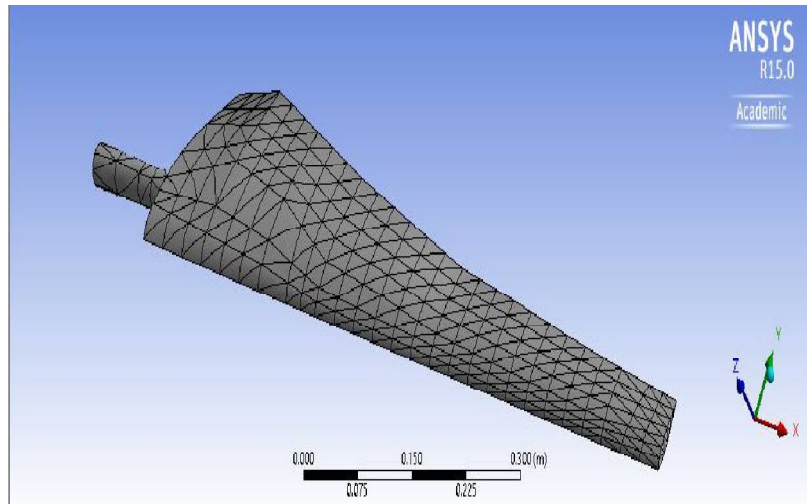


Fig 4.3 Mapped Mesh of the blade

Modal analysis is conducted and the first five natural frequencies are shown in Table 4.3 in comparison with 1-D model. The results are found to be in close comparison by both methods.

Table 4.3 Modal Characteristics of the Blade

Mode	1-D Beam Element, Hz	3D Solid Model, Hz
1	11.63185	11.344
2	15.39532	15.335
3	31.5512	31.202
4	77.95628	75.913
5	124.99	124.79

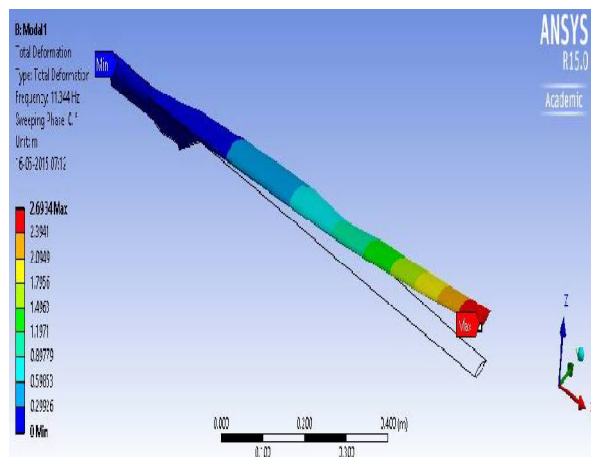


Fig. 4.7a 1st Flap wise Bending Mode shape

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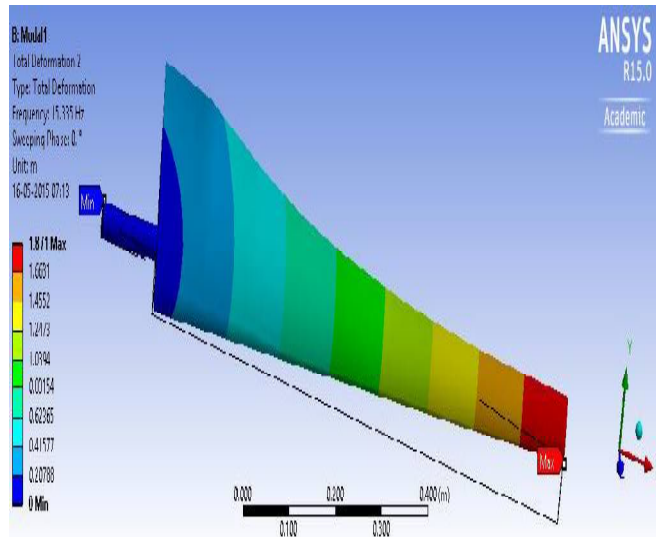


Fig 4.7b 1st Edgewise Bending Mode shape

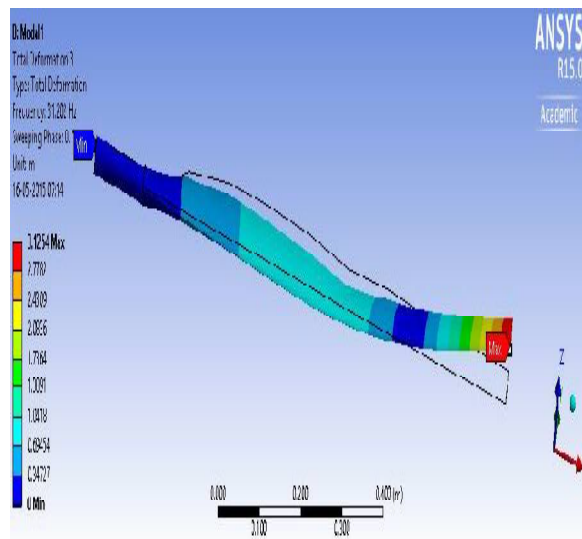


Fig 4.7c Combined Bending Mode shape

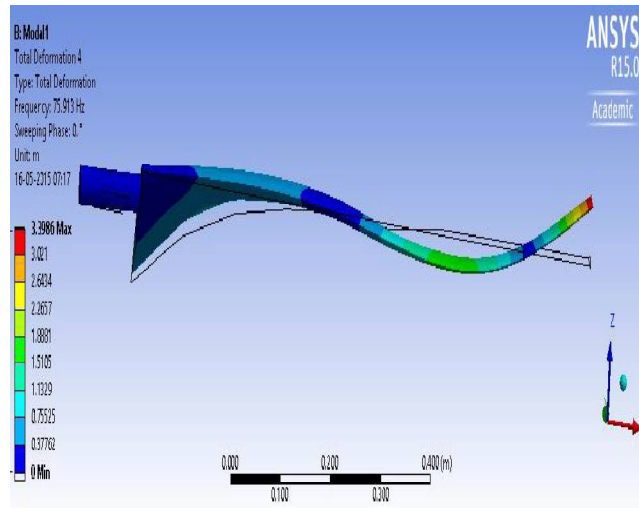


Fig 4.7d 2nd Flapwise Mode shape

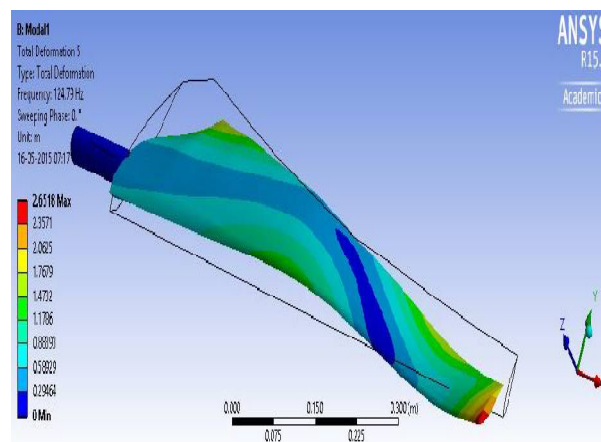


Fig 4.7e Torsional Mode shape

Aerodynamic and elastic forces occurring cause aero-elastic vibrations, and these vibrations arise around all three axes. First, the rotor blades generally vibrates across the plane in which rotor rotates in flap-wise direction (1st mode, Fig 4.7a). Further, rotor blades vibrate in the plane edge wise (1st mode, Fig 4.7b). Further in mode shapes Fig 4.7c and Fig 4.7d, the blades simultaneously vibrate along 2 directions (sway). The mode shape in Fig 4.7e shows additional torsional vibration along the x axis.

4.4 Effect of Rotational Speed on Natural Frequencies

Constant speed Analysis is helpful to examine the effect of system parameters on the natural frequencies of undamped free vibrations of a tapered wind turbine blade rotating at various speeds from 0rpm to 50 rpm. Graphs are plotted as shown in Figures 4.8 to 4.10 between the frequency of flap-wise bending, Edge-wise bending and torsional bending modes with increase in the rotational speed of the blade.

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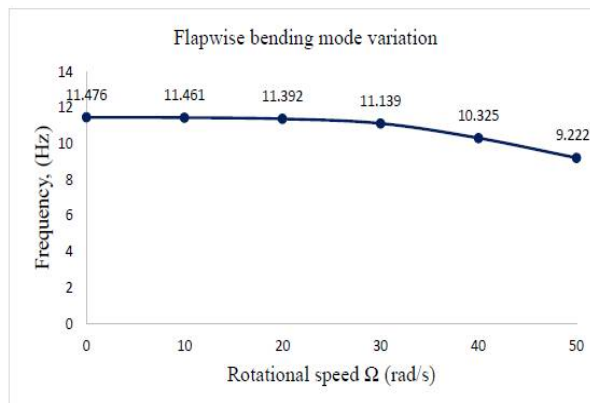


Fig 4.8 Variation of Flap wise bending mode with respect to rotational speed

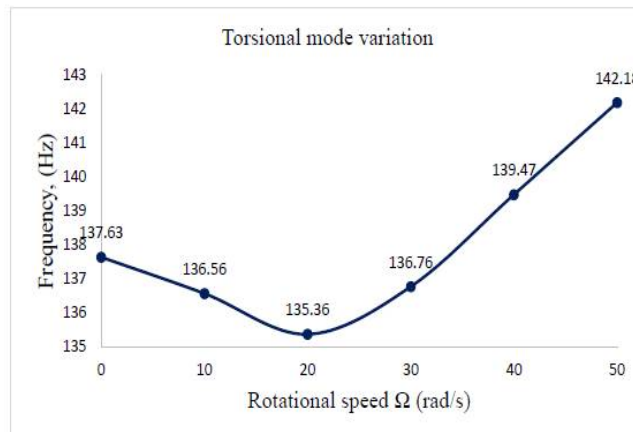


Fig 4.9 Variation of Torsional bending mode with respect to rotational speed

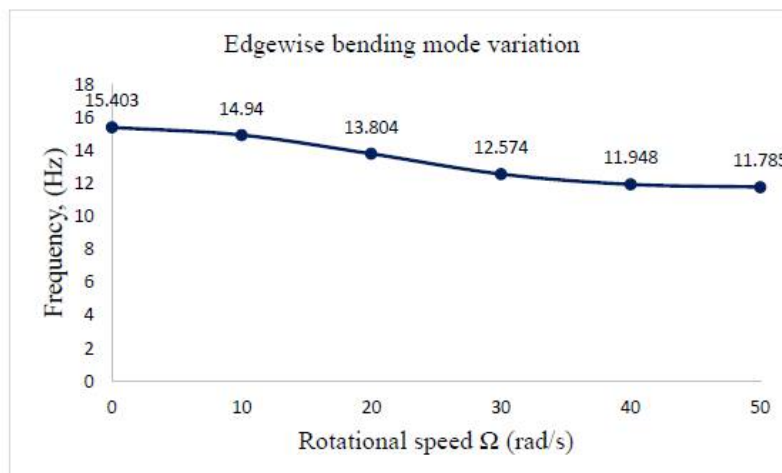


Fig 4.10 Variation of edgewise bending mode with respect to rotational speed

It is observed from the figures 4.8 to 4.10 the value of natural frequencies are more in torsional bending mode compared to the flap-wise bending mode and edge-wise bending mode. It is also seen that in the torsional mode, the

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trend of natural frequencies are seen to decrease until 20 rpm and then increase. This can be noted that optimal speed of the wind turbine operation must be more than 20 rpm in order to ensure safety of the component.

4.5 Effect of tip speed ratio on the chord & Twist distributions of the blade

Graphs are plotted between the distances from the root to the chord length as shown (Figure 4.11) and twist distributions (Figure 4.12) for different values of tip speed ratios.

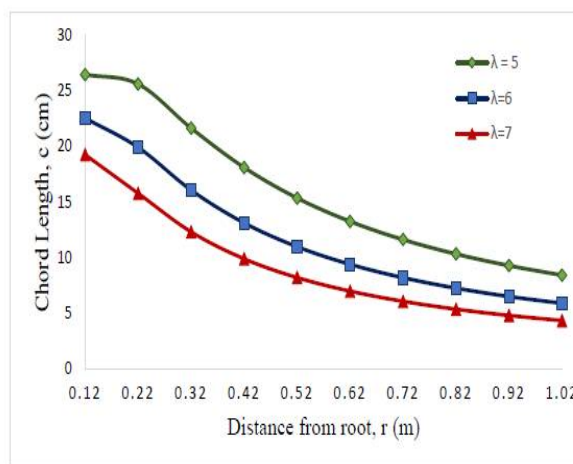


Fig 4.11 Chord distribution variation for different taper ratios.

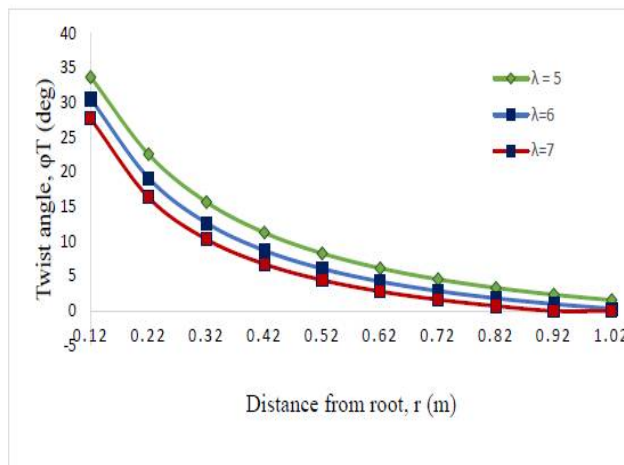


Fig 4.12 Twist distribution variation for different taper ratios

From the figure 4.11 it is observed that whenever the tip speed ratio (λ) increases the chord length also increases. From the figure 4.12 it is observed that whenever the tip speed ratio (λ) is increases the twisting angle is decreasing. This corresponds to the fact that larger tip speed ratio blades must have lesser chord length to ensure that they rotate faster reducing the overall centrifugal forces of the blade.

4.6 Effect of tip speed ratio on the modal characteristics of the blade

Graph is plotted between the first five natural frequencies and mode shapes for different tip speed ratios of 5,6 and 7 from the results of modal analysis.

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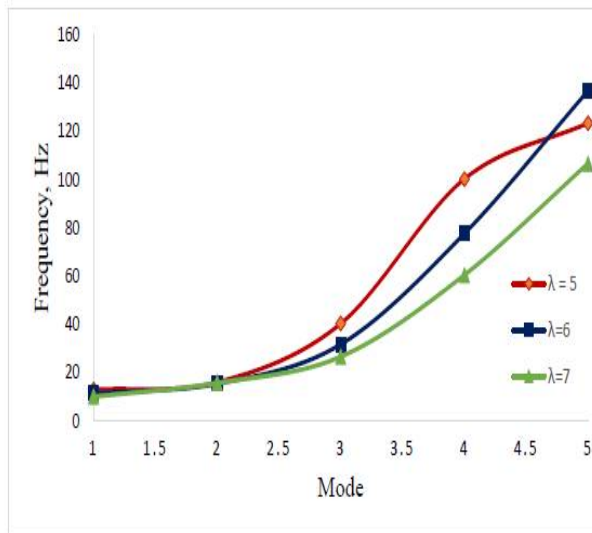


Fig 4.13 Modal Variation for different taper ratios

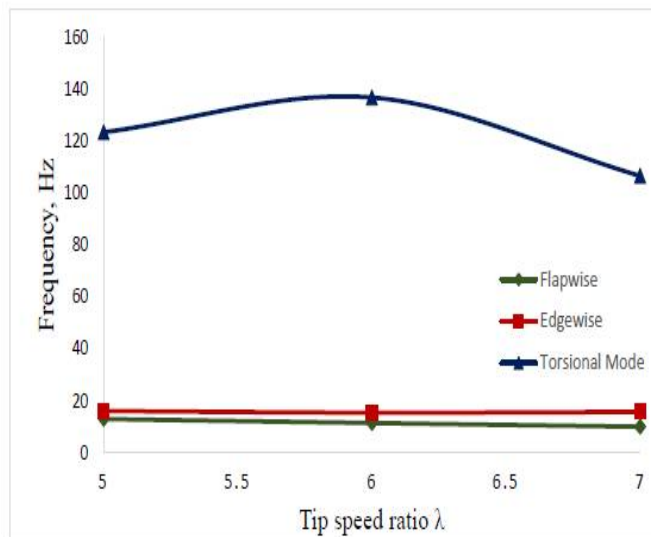


Fig 4.14 Variation of flap wise, edgewise and torsional modes for different taper ratios.

From the figure 4.13 it is observed that lower tip speed ratios have higher values of modal frequencies. Compared to $\lambda=6$ & 7, where the trend of modal frequencies are gradually increasing, the frequencies are found to be increasing at gradual mode until 4th natural frequency for $\lambda=5$ and then slope of the curve is observed to decrease.

For the plot drawn (Figure 4.14) to observe the pattern of flap-wise, edge-wise and Torsional modes at different taper ratios, it is seen that the natural frequency values for the torsional mode the frequency are high and the curve reaches a peak of 136Hz at $\lambda=6$ and then decreases. The effect of edge-wise modes with increase of taper ratio is found to be negligible and the flap-wise modes are found to gradually decrease from 13Hz to 9Hz.

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V. CONCLUSION

High speed rotating wind turbine blade dynamic analysis has been conducted in this work. From the available literature, various forces acting on the blade are accounted and the tapered-twisted aerofoil profile of the blade was generated as a 3D model. By computing element wise cross sectional details from 3D model, a one dimensional finite element beam modelling was considered to discretize the blade from the hub center. Also, a method proposed in literature for the blade dimensions selection was adopted to get the optimum chord and twist angle when the blade tip speed ratio, airfoil type & length of the blade are specified as inputs. The entire work concentrates on the beam finite element modelling of the blade. The modal and transient analysis studies are conducted using 10 beam elements with 6 degrees of freedom per node. It was considered that the blade is fixed at the hub rigidly with five degrees of freedom constrained. The effect of rotational speed on variations of the natural frequencies with the system parameters are given and it is found that with increase in speed, torsional modes vary at larger extent compared to flap-wise and edge-wise modes. Three blade models having tip speed ratios of $\lambda=5$, 6 and 7 are considered and the effect of tip speed ratio on the chord & twist distributions and on the modal characteristics are studied. The results show that at tip-speed ratio ($\lambda=6$), the torsional frequencies are more. Dynamic response by considering various loading conditions of blade displacement, and edge-wise, flap-wise beating responses are obtained and studied. Results are very interesting indicating the effects of aerodynamic load, centrifugal loads and gravity on the tip response. These results are helpful for the design of blades to avoid resonant conditions.

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