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Dynamic Characteristics of Wind Turbine Blade

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***Abstract*— this paper presents a review on the dynamic characteristics of Wind Turbine. One of the most important sources of renewable energy is Wind Power. Wind-turbines extract kinetic energy from the wind. The design of a wind turbine structure involves many considerations such as strength, stability, cost and vibration. To design a commercial flexible system, comprehensive understanding of the dynamic characteristics is essential. Reduction of vibration is a good measure for a successful, safe design of the blade structure. Hence to find out the natural frequency of the turbine blade the two different techniques are used, one is Frobenius Method and another is Finite Element Method. It may promote other important design goals, such as low cost and high stability level. A good design for reducing vibration is to separate the natural frequencies of the structure from the harmonics of rotor speed. This would avoid resonance where large amplitudes of vibration could severely damage the structure. Influences of the rotating speed, the pitch angle, the setting angle, and the aerodynamic loads on natural frequencies are discussed in this paper.**

Keywords*— Wind Turbine, Natural frequencies and Mode Shape, Rotating Speed, Blade Pitch Angle, Setting Angle, FEM.

I. INTRODUCTION

A wind turbine consists of several main parts viz. the rotor, generator, driven chain, control system and so on. The rotor is driven by the wind and rotates at predefined speed in terms of the wind speed so that the generator can produce electric energy output under the regulation of the control system.

Growing energy demands require wind turbine manufacturers to design more efficient and higher capacity wind turbines which inevitably results in new models to be put into service which results in flexibility of the structure. However, it has the complicated dynamic interaction between different parts of the turbine as motion of the blades interact with aerodynamic forces, electro-magnetic forces in the generator and the structural dynamics of several turbines components like drive train, nacelle and tower, etc.

Understanding and Identification of the dynamic characteristics of wind turbine blades is essential for optimizing the energy output, safety and reliable operation of the system. As the sizes of modern wind turbine blade increase, their dynamic performance gets more complicated.

Hence it becomes more important to predict the dynamic response characteristics of new designs. Some important system characteristics like stiffness and damping govern the vibration response change which depends on operating conditions like wind speed, rotating speed and blade pitch angle, etc.

II. WIND TURBINES

The performance of Wind Power Station depends on the wind turbine characteristics. This section describes the types of wind turbines and presents their dynamic characteristics.

A. Types of wind turbines

There are two basic types of wind turbines: Vertical Axis and Horizontal Axis Wind Turbine. The Vertical Axis Wind Turbine spins when wind hits the blades perpendicular to the rotating axis. The Horizontal Axis Wind Turbine spins when wind flow that is parallel to the rotating axis hits the blade. A support tower is required in order to avoid the contact of the blades with the ground and to get the maximum energy from the wind. The supporting blade tower is usually two to three times longer than the blade. In both the cases, the wind turbine rotor can be propelled either by drag forces or by aerodynamic lift. The horizontal or vertical based drag designs operate with low speed and high torque, which can be useful mainly for grinding grains and pumping water [1, 2]. On the other hand, the horizontal and vertical based lift designs operate with high speed and low torque used to generate electricity [1].

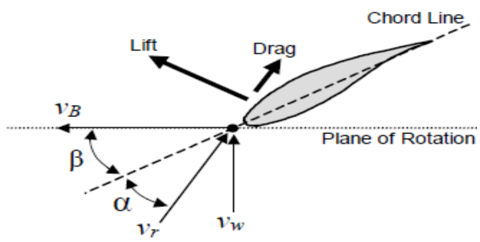

Figure- 2.1. Definitions of lift and drag for 2-D aerodynamics.

In order to understand the basic mechanisms behind of the power generation from a wind turbine it is important to know the forces that act on the blade. The Figure-2.1 represents the cross section of a rotor blade (or airfoil) and shows the forces acting on 2-D aerodynamic blade. The lift force (L) is produced at right angles to the relative wind velocity (v_r) while drag force (D) is aligned relative to it. The relative wind velocity is the vector resulting from the sum of the blade motion (v_B) and the wind velocity (v_w) vectors [1]. This lift force pulls the blades along its rotary path causing thrust. The thrust produces the shaft torque. The lift force increases with the increase in the angle of attack when the airfoil reaches the region of stall behaviour. In the stall region the lift force stays practically constant independent of the angle of attack. In addition, for a precise estimation of the torque generation, it is important to consider the leakage at the tip of the blades. The leakage results in reduction of the angle of attack on the blades and consequently decreases the power extracted from the wind [3]. It is important to note that the local 2-D representation as shown in Figure-2.1 can be used to estimate the power generated by a wind turbine.

III. DYNAMIC CHARACTERISTICS

Certain apparent dynamic characteristics of wind turbine are wind speed, rotor speed and blade pitch angle. On dynamic characteristics of the wind turbine blade, effects of the built-in twist, hub and hydraulic structure. The rotating speed on frequencies was studied by applying the method of matrix analysis in Li et al. [4]. Chortis et al. [5] presented a brief description of composite damping mechanics for blade sections of arbitrary lamination and geometry and investigated composite material coupling effects on blade section stiffness and damping. Li et al.[6–8] studied influences of the rotating speed, pitch angle, wind velocity and the rotational angle on Flapwise natural frequencies of the rotating blade by applying the assumed modes method. They discussed the aero elastic stability of the blade in super-harmonic resonance.

A. Frequency response of the WTS

Generally a complete (offshore) wind turbine system can be modelled as mass-spring-damper systems [9].When a harmonic excitation force F (t) is applied to the mass resulting into magnitude and phase of the resulting displacement (u) strongly depends on the frequency of excitation (ω).

The peak in figure 3.1 corresponds to the natural frequency of the system [11]. The Dynamic Amplification Factor (DAF) and phase angle are determined. Therefore any resonance problem can be counteracted with adequate damping controls. The resonance of the system can experience failure & fatigue behaviour during operating conditions. For analysis of structural dynamics details of the expected frequencies of the excitation and excitation forces are required to be perceived. The normalised amplitude ratio is also known as the Dynamic Amplification Factor commonly used for the design of wind energy. The preliminary design phase accounts for the effect of dynamic loads from static response.

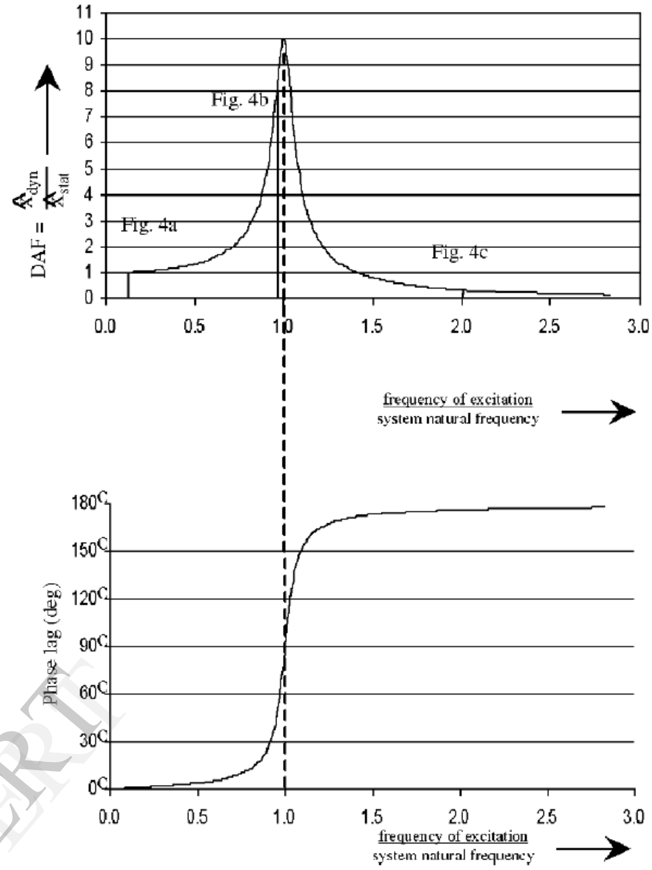

Figure-3.1. Frequency response of WTS
(Magnitude vs. Frequency &Phase lag vs. Frequency)

B. Effects of Rotating Speed on Natural Frequencies

Influence of the rotating speed on the first three frequencies of the blade under unsteady aerodynamic loads are shown in Fig.3.2 where pitch angle is taken as $\beta p = 9^{0.}$ It shows that all three frequencies ascend with the increase in rotating speed. This conclusion is the same with that for flap vibration [6, 7].

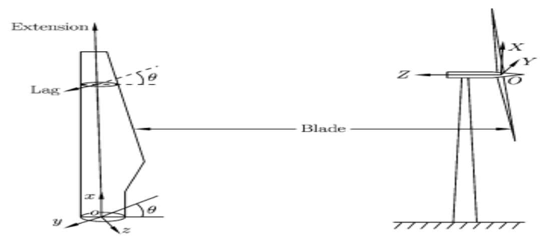

Fig.3.2. Deformation modes and coordinate systems

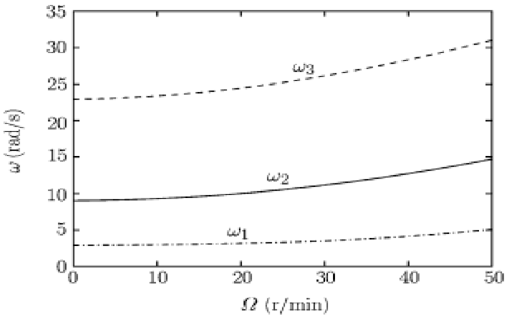

Fig.3.3. Rotating speed vs. natural frequencies

Effects of the pitch angle on first three frequencies are very less by which effect of blade rotational speed is dominant. Natural frequencies are independent of the pitch angle at zero rotating speed. In the range of the normal rotating speed, about 20 RPM~50 RPM, the first frequency increases with increase in pitch angle while the second and third frequencies decrease [10]. The effect of the pitch angle on each frequency becomes prominent with the increase of rotating speed as shown in fig.3.3. It is observed that the first three frequencies are all symmetric about zero pitch angles.

C. Effects of Setting Angle for Natural Frequencies

Influences of the setting angle on the first three frequencies of the blade subjected to aerodynamic loads are given in Fig.3.4, where the pitch angle is taken to be $\beta p = 9^0$[10]. It shows that effects of the setting angle on three frequencies all depend on the rotating speed and these effects are very less at low speed. All three frequencies rise with the setting angle in the normal range of rotating speed. These three frequencies are all asymmetric about zero setting angles which are somewhat different from the effects of the pitch angle.

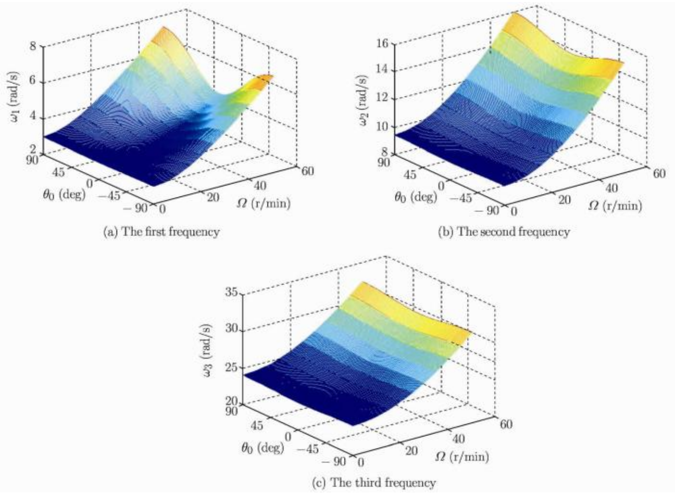

Fig.3.4. setting angle vs. natural frequencies

IV. ANALYSIS OF NATURAL FREQUENCIES

A. Determination of Blade Natural Frequencies Using Frobenius Method:

The governing differential equation for a rotating Euler Bernoulli beam with rigid support under flapwise vibration is

$$\rho A\frac{\partial^2 w}{\partial t^2}+\frac{\partial^2}{\partial x^2}\left(EI\frac{\partial^2 W}{\partial t^2}\right)-\frac{\partial}{\partial x}\left(T\frac{\partial w}{\partial x}\right)=f(x,t) \quad (1)$$

where ρ is the density, *A* is the cross sectional area, *w* is the relative displacement of a point with respect to its static deflected position, *E* is the Young's modulus, *I* is the moment of inertia, *T* is the centrifugal tension force on the beam at a point x with respect to the origin and *f* is the applied force per unit length.
The centrifugal tension T is expressed as

$$T(x)=\int_x^L \rho A\Omega^2(r+x)\,\mathrm{d}x \quad (2)$$

Where L is length, r is the radius of hub and Ω is the angular velocity of rotation, which is assumed to be constant.
The non-dimensional rotational speed parameter and natural frequency parameters are defined as

$$\mu=\bar{\Omega}^2=\frac{\rho A\omega^2 L^4}{EI}, \quad (3)$$

And

$$\nu=\eta^2=\frac{\rho A\Omega^2 L^4}{EI} \quad (4)$$

respectively, where ω is the natural frequency of the beam. Considering ideal clamped-free boundary conditions for a cantilever, the natural frequency equation is obtained to be

$$D^2F(1,2)D^3F(1,3)-D^3F(1,2)D^2F(1,3)=0 \quad (5)$$

After setting f(x, t) = 0 in Equation (1), substituting in the non- dimensional parameters and separating the time- and space-dependant ordinary differential equations, the mode shape equation is obtained in a dimensionless form as

$$\Phi_n(X)=\frac{[D^2F(1,3)F(X,2)-D^2F(1,2)F(X,3)]}{[D^2F(1,3)F(1,2)-D^2F(1,2)F(1,3)]} \quad (6)$$

B. Determination of Blade Natural Frequencies Using Finite Element Method:

The equation of motion for an Euler beam is

$$m(x)\frac{\partial^2 u}{\partial t^2}+\frac{\partial^2}{\partial x^2}\left[EI(x)\frac{\partial^2 u}{\partial x^2}\right]=p(x,t) \quad (7)$$

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where, *m(x)* is the mass density per unit length of the beam, *EI(x)* is its flexural stiffness, *u(x,t)* is its transverse displacement, and *p(x,t)* is the external load.

The displacement *u(x)* can be represented as

$$u(x,t) = \sum_{i=1}^{\infty} \varphi_i(x) q_i(t) \tag{8}$$

where, φ(x) are the mode shapes of the structure and q(t) are known as the modal coordinates.The mode shapes are determined by solving

$$[EI(x)\varphi''(x)]'' - \omega^2 m(x)\varphi(x) = 0 \tag{9}$$

By solving the equation

$$\boldsymbol{M_G}\ddot{q} + \boldsymbol{C_G}\dot{q} + \boldsymbol{K_G}q = \boldsymbol{F_G} \tag{10}$$

The structure may be discretized into multiple beam elements with local mass and stiffness matrices for each element derived using cubic polynomial shape functions. The local matrices are assembled into global mass and stiffness matrices, ***M*** and ***K***, respectively. Solving the eigenvalue problem

$$\boldsymbol{K} - \omega_n^2 \boldsymbol{M} = 0 \tag{11}$$

yields the natural frequencies and mode shapes.

The generalized mass and stiffness matrices can be expressed as

$$\boldsymbol{M_G} = \boldsymbol{\varphi^T M \varphi}$$
$$\boldsymbol{K_G} = \boldsymbol{\varphi^T K \varphi} \tag{12}$$

Where **φ** is a matrix whose columns are the eigen vectors of the structure. The generalized damping matrix can be expressed as

$$\boldsymbol{C_G} = \boldsymbol{\varphi^T C \varphi} \tag{13}$$

Where **C** is a linear combination of **M** and **K**.

The load vector can be expressed as

$$\boldsymbol{F_G} = \boldsymbol{\varphi^T P} \tag{14}$$

Where **P** is a vector of nodal loads.

D. RESULTS AND DISCUSSION

The modal analysis of a Horizontal Axis Wind Turbine Blade is carried to find out the Natural Frequencies of a Blade at various modes in Flapwise and Edgewise direction by using the QBlade v0.8 Software. Also found the deflection & stresses at various wind speeds.

A. Blade Specification:

Length of Blade: - 63m
Maximum cord length: - 5.161 m
Material: - Aluminium
Modulus of Elasticity: - 7.3e+10 pa
Density: - 2900 kg/m^3
Rotating Speed: - 5m/min and 10m/min
Wind Speed: - 5m/min and 10m/min

B. Modal Analysis:

Modal analysis of a Horizontal Axis wind turbine blade is carried out at two different rotating speeds. The rotating speeds are considered as 5m/min and 10m/min. So the value of natural frequency in Flapwise and edgewise directions at various modes obtained is as shown in Fig. 5.1

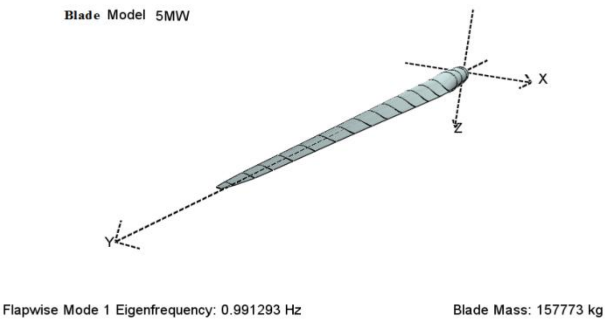


Fig. 5.1 Flapwise Natural Frequency at Rotating Speed 5m/min

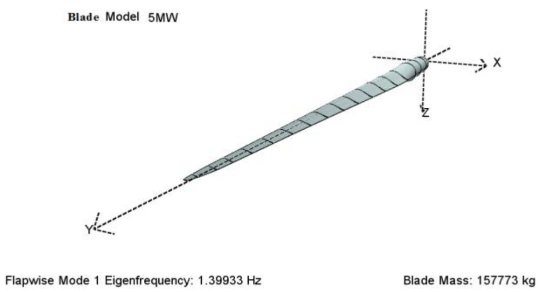


Fig. 5.2 Flapwise Natural Frequency at Rotating Speed 10m/min

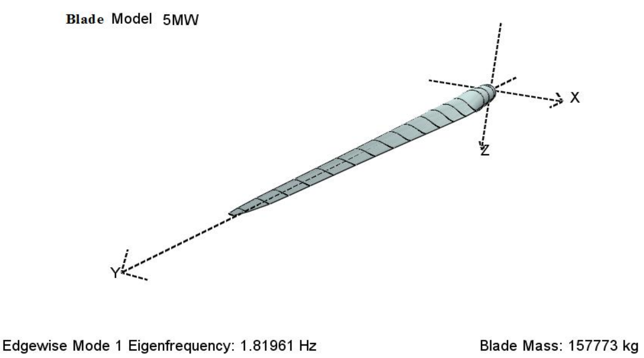


Fig. 5.3 Edgewise Natural Frequency at Rotating Speed

5m/min

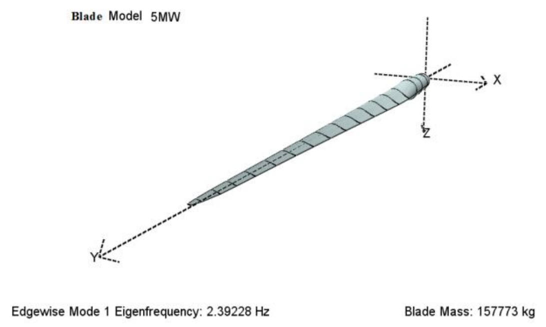


Fig. 5.4 Edgewise Natural Frequency at Rotating Speed 10m/min

C. Stress and Deflection Analysis:

The Stress and Deflection induced in the wind turbine blade subjected to different Wind Speeds are analysed using the QBlade v0.8 Software. Two different Wind Speeds are considered as 5m/min and 10m/min.

Hence the values of Stress and Deflection induced in the wind turbine blade at these Wind Speeds obtained are as follows:

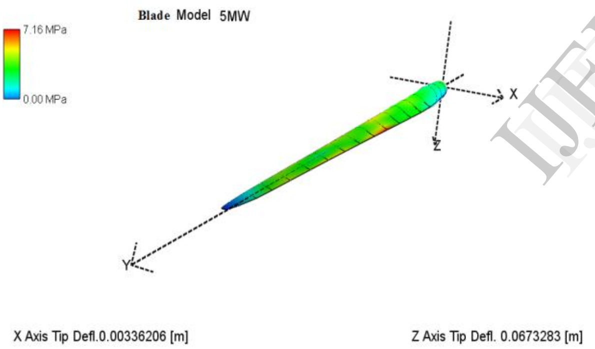


Fig.5.5. Stress and Deflection induced in the wind turbine blade at Wind Speed 5m/min

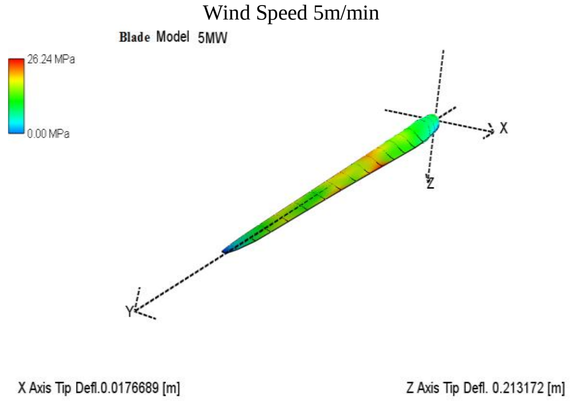


Fig.5.6. Stress and Deflection induced in the wind turbine blade at Wind Speed 10m/min

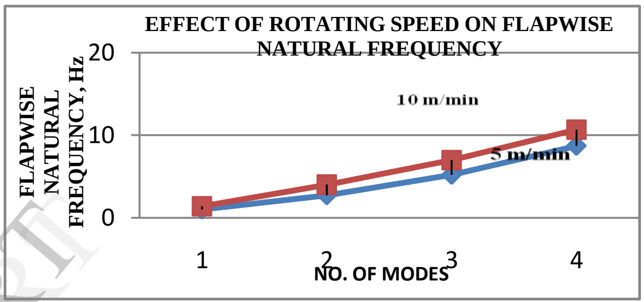
1. Effect of Rotating Speed on Natural Frequencies

Modal analysis of a Horizontal Axis wind turbine blade is carried out at two different rotating speeds as 5m/min and 10m/min. So the value of natural frequency in Flapwise and Edgewise directions at various nodes obtained as shown in Table 5.1 and 5.2.

Table 5.1 Natural frequency of the Wind Turbine Blade at Rotating Speed 5m/min

Natural Frequency in Hz at Rotating Speed 5m/min				
Mode	1	2	3	4
Flapwise	0.991293	2.71857	5.19086	8.6971
Edgewise	1.81961	5.68347	12.9464	23.8461

Table 5.2 Natural frequency of the Wind Turbine Blade at Rotating



Speed 10m/min

Natural Frequency in Hz at Rotating Speed 10m/min				
Mode	1	2	3	4
Flapwise	1.39933	4.01063	6.97655	10.6708
Edgewise	2.39228	6.35212	13.733	24.6181

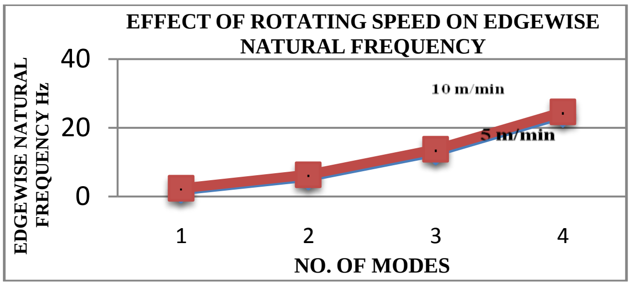


Fig.5.7.Effect of Rotating Speed on Natural Frequencies

Thus as per the results and discussion we can plot a graph as shown in fig.5.7 which shows that Natural frequency of the Wind Turbine Blade in Flap wise and Edgewise direction ascends with increase in rotating speed.

2. Effect of Wind Speed on Stress and Deflection

The Stress and Deflection induced in the wind turbine blade subjected to two different Wind Speeds 5m/min and 10m/min are analysed using the QBlade v0.8 Software and the values obtained as shown in Table 5.3.

Table 5.3 Stress and Deflection induced in the wind turbine blade at Various Wind Speeds

Wind Speed (m/min)	5	10
Stress(MPa)	15.52	26.24
Deflection in X - direction (m)	0.0110024	0.0176689
Deflection in Z- direction (m)	0.121176	0.213172

Thus, we can say that the Stress and Deflection induced in the wind turbine blade increases with increase in Wind Speed.

VI. CONCLUSION

The performance of Wind Power Station depends on the Wind Turbine characteristics like Static and Dynamic. To optimize the vibration of Wind Turbine Blade it is essential to consider the Dynamic Characteristics like Rotational Speed, Wind Speed etc. and their effects on natural frequency of wind turbine blade.

Thus as per the results and discussion we can conclude that

- Natural frequency of the Wind Turbine Blade in Flap wise and Edgewise direction ascends with increase in rotating speed.
- Stress and Deflection induced in the wind turbine blade increases with increase in Wind Speed.
- Natural frequencies are independent of the pitch angle at zero rotating speed. In the range of the normal rotating speed, about 20 RPM~50 RPM, the first frequency increases with increase in pitch angle while the second and third frequencies decreases. It is observed that the first three frequencies are all symmetric about zero pitch angles.
- It shows that effects of the setting angle on three frequencies all depend on the rotating speed and these effects are very less at low speed.

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