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Horizontal Axis Wind Turbine Blade Finite Element Design Modeling with Structure and Vibration Modal Analyses to Optimize Wind Power for Offshore Applications

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Abstract:

Offshore wind farms are subject to complex stresses with respect to the wind influence on the turbine blades. When air flows through the airfoil surface of a wind turbine blade's element profile, the relative wind velocity causes the aerodynamic forces (axial and tangential) to act upon blade-element. This article presents a novel factor of axial induction factor "a" and the tangential induction factor "b" of the Wilson design, depending on the blade element momentum theory to deduce the blade's spanwise force distribution. The aerodynamic analysis has been performed at the blade with wind having a velocity of 12 m/s. The pressure produced at the blade surface is evaluated. Structural analysis is presented from imported CFD pressure load at a rotational speed of 21 rpm. In contrast, the blade's finite element model analysis was performed combined with aerodynamic force to obtain the vibration pattern. It is concluded that the blade's axial force increased linearly with the increase of the "r" radius, which mainly affects the wave vibration. The blade's tangential force increases initially and decreases with the rise of the "r" radius, which primarily affects the shimmy vibration. The analysis upon aerodynamics forces, pressure distributions along with structural vibration analysis provides an absolute reference for the subsequent design optimization of the wind turbine blade and its power.

Keywords: *Wind turbine blade; Finite element method; Wilson design model; Aerodynamic force; Modal analysis; Numerical simulation; Structural vibration analysis*

1. Introduction and literature review

The wind is an inexhaustible and clean, renewable energy source [1]. Wind energy can overcome energy sustainability and climate change. It has gained considerable attention from the people, policymakers, and the energy industry over the past few decade [2]. According to statistics, wind energy storage capacity is tremendous. The wind energy used for development is about 2×107 MW, which is ten times larger than the total amount of hydropower exploited and used on the earth [3]. The largest component of renewable generation capacity is wind power [4]. However, wind power generators that are directly related to wind energy are near associated with our lives. [5] provided insights into the design optimization of wind power conversion technology, incorporating a variety optimization technique and the vital role of

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design modelling with blade materials and the working environment. [6] investigated the consequences of orthotropic materials on wind turbine blade flutter mitigation. Using the iFEM technique, [7] mentioned a shape-detecting method for wind turbine blades. Small wind turbines were the concentration of optimization research by [8] that studied how design factors affected performance. [9] considered wind turbine blades aerodynamic, structural, and aeroelastic design. The design and optimization of wind turbines for better performance and dependability can improve considerably from these results. The importance of incorporating consideration aspects like rotor dynamics, structural dynamics, and aerodynamics in wind turbine design and analysis was emphasized in addition the implications of aerodynamic loads, and vibration characteristics were all carried out as factors in [10,11] in-depth studies of the coupled interactions between fluid flow and the blade structure.

The research gap reveals the need for even more research into leading to improved approaches that incorporate aerodynamic forces with FEM analysis to determine more precise and reliable wind turbine blade vibration patterns. Scholars have successfully established a series of blade design optimization methods by studying the airflow field's characteristics when air flows through the blade's surface, dependent on Blade-element Momentum's theory and leads to the blade profile development. However, each point's force distribution along the wind turbine blade's spanwise segment while the air flows through the wind turbine blades requires the combination of various design theories to derive the law of force distribution on the wind turbine's blade surface. The corresponding research used mainstream 750 KW wind turbine blades to obtain the axial and tangential force components of the wind turbine blade along its span. The axial force and tangential force can be obtained at a different blade's radius.

By analyzing how tangential force changes with respect to the radius along the blade, this study aims to provide valuable insights for designing wind turbine blades with improved stability and reduced vibration in ocean wind farms. The aerodynamic thrust generated by the normal component perpendicular to the rotation plane is essential for designing components such as the transmission chain and the tower, which influences the blade's flapping vibration. The tangential component parallel to the rotation plane produces the torque to drive the power generation system to work typically and affects the blades' oscillation. The force acting on the blade's surface can be related to the blade's vibration to absolute reference the blade's optimal design through the modal analysis.

2. Methodology

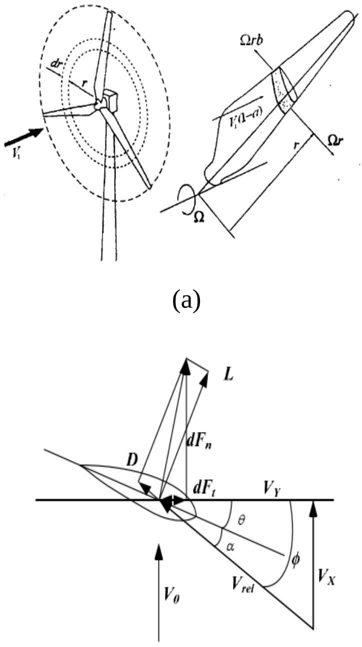
2.1 Blade modelling

This article focuses on approach to analyze the impact of wind loads on airfoil stability in ocean environments, offering valuable data for ocean engineering applications

2.2 Blade-element Theory

Blade Element Theory is mainly applied to the general aerodynamics principle. This theory divides the wind turbine blade into many micro-segments along the spanwise section. These micro-segments are termed blade elements [12]. The elements are considered to have an infinitesimal thickness in the blade element theory and aerodynamically separate and do not interfere with each other [13]. However, each blade element's influence at different radii of the blade is often neglected in practice. The force applied to a single blade element only depends on the lift-drag characteristics of the airfoil. The blade is simplified to finite blade elements that are superimposed in the radial direction. The rotor's three-dimensional aerodynamic features can be achieved by integrating the blade elements' aerodynamic characteristics along the radial direction, such as force and torque [14].

A blade element with a "dr" length is taken at a distance "r" from the wind turbine blade's rotation centre. Figure 1 (a) shows the blade element rotates clockwise as a concentric ring under wind forces.



(a)

(b)

Figure 1. (a) Blade element theory model; (b) Blade element forces and relative wind velocity [15].

2.3 Geometric Modeling and Numerical Analysis

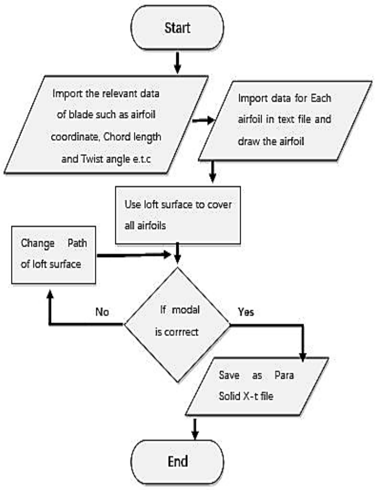
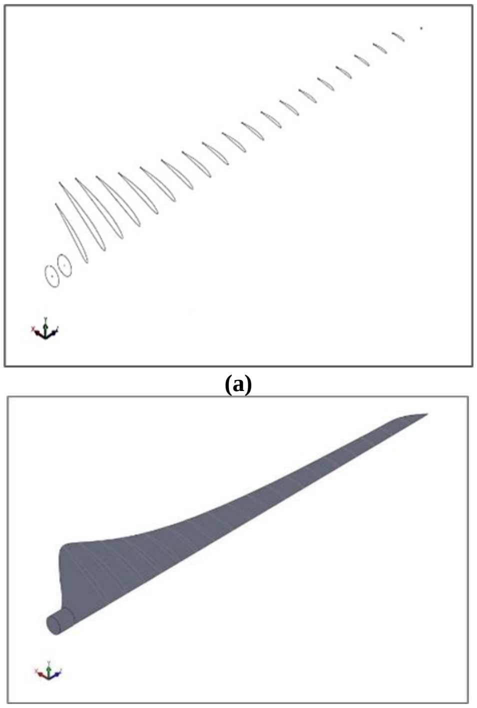


Figure 2. SolidWorks flow chart process of wind turbine blade

To design a wind turbine blade, a commercial CAD package, Solidworks 2021, has been used. Then the blade geometry file is imported in the ANSYS Workbench 2020 R2. ANSYS FLUENT was used for CFD simulation to verify the pressure impact at the wind turbine blade surface. Then, Static Structural analysis conducting with this output pressure load from CFD and the wind turbine rotor's rotational speed used to calculate the structural properties, i.e., von-mises stress and total deformation. Additionally, a Modal analysis has been performed to obtain the vibration mode shape.

In this paper, the blade element's twist angle and chord length at different cross-sections spanwise radii of the wind turbine blade are determined. Then Profili tool is used to generate the airfoil coordinates of NACA4412.



(a)

(b)

Figure 3. (a) Blade Skeleton**;** (b) Lofted Surface Geometry from SolidWorks.

The blade development for the FEA model is done after defining the full geometry. It is modelled as a loft surface in SolidWorks CAD suite to achieve maximum flexibility and computational efficiency within ANSYS. The Surface Loft Feature enables SolidWorks to automatically produce the intermediate blade shape to connect multiple sketches into a single body. The airfoil leading edge is selected as the loft guide point to curtail unnecessary complexity in every section's geometry. The schematic diagram of the turbine blade is shown in Figure 3.

2.4 Structural analysis

2.4.1 Finite element framework

The Mathematical model was established by the formulation of the finite element analysis described in this section. This mathematical model analyses and solves problems of steady-state and vibration [16]. A mechanical tool of ANSYS evaluates the wind turbine blade surface's stresses related to the rotation and vibration.

The main focus of this work is to evaluate the wind turbine blade's response under varying conditions. The blade was presumed to operate at the critical condition when maximum rotational speed at 21 rpm.

The differential equation of discrete motion at a time (t) for the rotating wind turbine blades relate to a structural domain model, defined as [17,18];

$$[M]\{\ddot{u}\}_t + [C]\{\dot{u}\}_t + [K]\{u\}_t = \{F(z,t)\} \quad (1)$$

Where mass matrix is "[M]"; damping matrix is "[C]"; displacement at a time (t) represent by "$\{u\}_t$"; "$\{\dot{u}\}_t$" is velocity vector; "$\{\ddot{u}\}_t$" is acceleration; The matrix of stiffness with the nonlinear geometric characteristics of the rotating blade is "[K]", and "$F(z,t)$" is the wind load vector.

$$[K] = [K_0] + [K_d] + [K_g] \quad (2)$$

The matrix of normal stiffness is because of the small blade deformation defined by "$[K_0]$". "$[K_d]$"is the dynamic matrix of stiffness formed by the correlation of elastic deformation and rigid motion, and due to deformation through centrifugal force, the stiffness matrix of geometric is denoted by "$[K_g]$".

The flexible structure can vibrate harmonically, and the frequency at vibration movement appears identified as natural frequency. It develops deformation patterns defined as mode shapes [19]. The structure's mass and stiffness are correlated to the mode shape and vibration [20]. The damping effect is neglected [C]=0 when computing the blade structure's natural frequency and assumed external load vector $F(z,t)$=0 . Free vibration equation (19) can be written as follows:

$$[M]\{\ddot{u}\}_t + [K]\{u\}_t = 0 \quad (3)$$

And the harmonic displacement is,

$$u_i = \emptyset_i \sin(\omega_i t + \theta_i) \quad i = 1,2, \ldots..DOF \quad (4)$$

Where, ω_i, $\emptyset_i$ represents ith modes shape angular frequency and vector of structure's vibration respectively and phase angle denoted by θ_i. And the acceleration form is as follows,

$$\ddot{u}_i = -\omega_i^2 \emptyset_i \sin(\omega_i t + \theta_i) \quad (5)$$

Replace equation (3) with (4), (5) and the expression $\sin(\omega_i t + \theta_i)$ was eliminated to get the following structure undamped vibration type equation,

$$[K]\{\phi_i\} = \omega_i^2 [M]\{\phi_i\} \quad (6)$$

The equation for the blade's structural vibration (Eigenvalue problem) is (6), the symmetric as follows [21],

$$([S] - \lambda_i [T])R_i = 0 \quad (7)$$

In this equation [S] is a dynamic matrix (symmetric matrix), λ_i indicates the ith eigenvalue, Identity matrix defined as [T] and the eigenvector according to this homogeneous equation's current scheme denoted by R_i. Transform equation (6) as a formula of equation (7) by applying the Cholesky square root method with adding matrix [K] or matrix [M]. It is a fundametal technique to solve the linear systems assigned as products of the lower and upper triangular matrixes due to the use of any matrix is square matrix [S] [16,21].

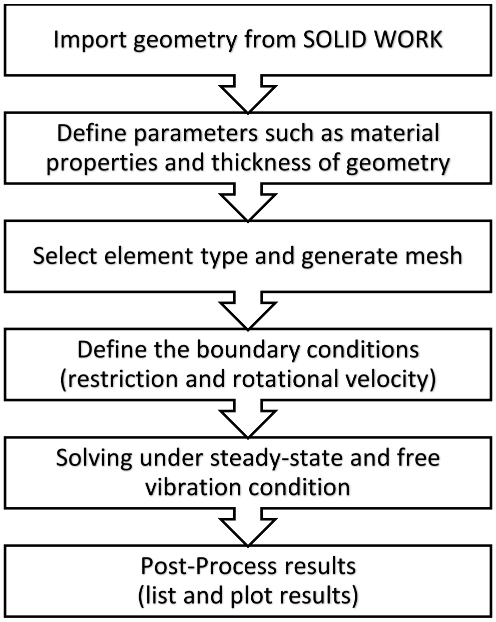


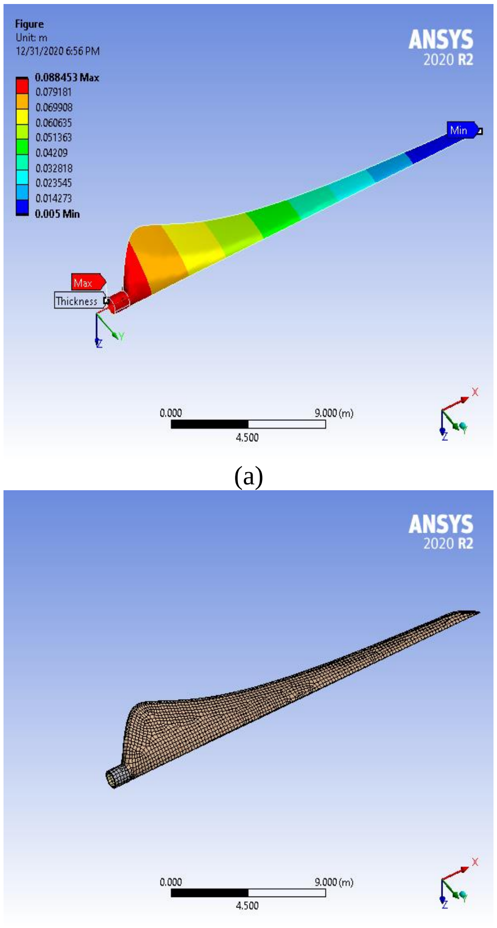
Figure 4. The main steps of finite elements analysis.

2.4.2 Material Properties and Mesh Generation

The wind turbine blade Parasolid x-t file exported to the ANSYS workbench. The material of the blade is the "E-glass LY556 epoxy resin lamina". Low mass and high stiffness strength are the bases for selecting composites material. The mechanical characteristics of "E-glass LY556 epoxy resin lamina" are as follows **T** [22,23];

TABLE I. Mechanical Properties of Material.

E-glass LY556 Epoxy Resin Lamina			
Properties	**Value**	**Properties**	**Value**
Density (kg/m^3)	2000	Poisson's Ratio-YZ	0.336
Young's Modulus-X (Pa)	3.4412 x10^{10}	Poisson's Ratio-XZ	0.217
Young's Modulus-Y (Pa)	6.531 10^{9}	xShear Modulus-XY (Pa)	2.43 x10^{9}
Young's Modulus-Z (Pa)	6.531 x10^{9}	Shear Modulus-YZ (Pa)	1.698 x10^{9}
Poisson's Ratio-XY	0.217	Shear Modulus-XZ (Pa)	2.43 x10^{9}

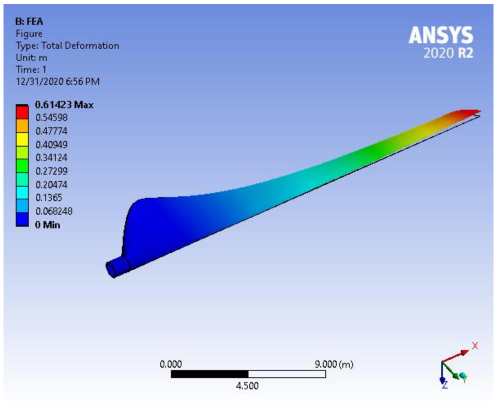


(a)

(b)

Figure 5. (a) Thickness distribution along with blade; (b) FEA blade meshed model.

The blade surface has adequately meshed as it may reflect the calculation's accuracy. Quadrilateral surface computational mesh with 2607 nodes and 3018 elements is used for the blade, as shown in following **Figure** . the said nodes and elements were selected to keep the computational limitations and accuracy of the results.



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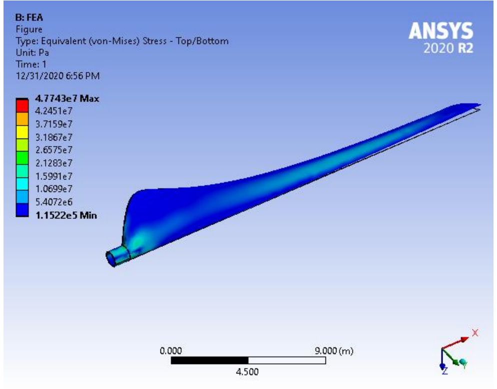

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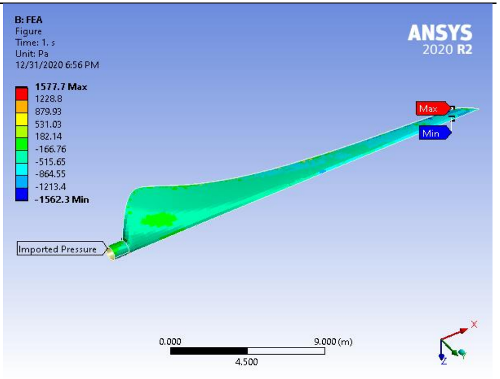


(c)

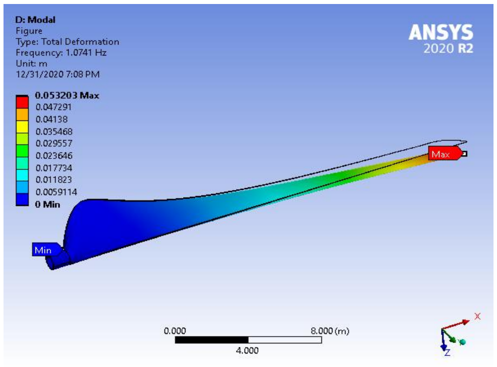
Figure 6. Structural analysis results as: (a) Total deformation; (b) Equivalent Stress; (c) Imported CFD pressure load into FEA blade surface.

2.4.3 Vibration Modal Shapes Analysis

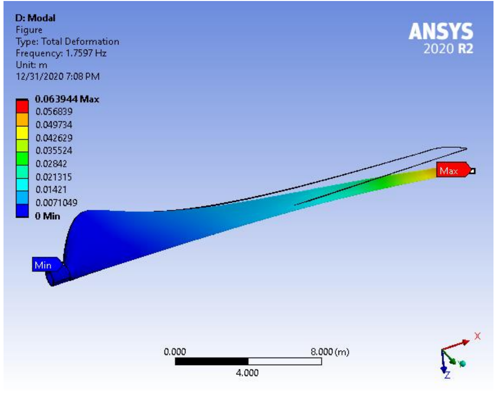
The constraints need to be imposed on the mesh model. In the simplified calculations of a single blade, the entire blade root interface needs to be constrained entirely, and the blade tip is a free end. After the analyses are completed, the first 06 order modes shape of vibration are extracted. The deformation result modes shape of vibration are shown in **Figure 7** (a~f), and various vibration frequencies are presented in **T**

TABLE II. Natural Frequencies of the Blade (Hz).

Mode order	**1**	**2**	**3**	**4**	**5**	**6**
Natural Frequency (Hz)	1.07	1.7	.92	4.76	6.86	8.62



(a)



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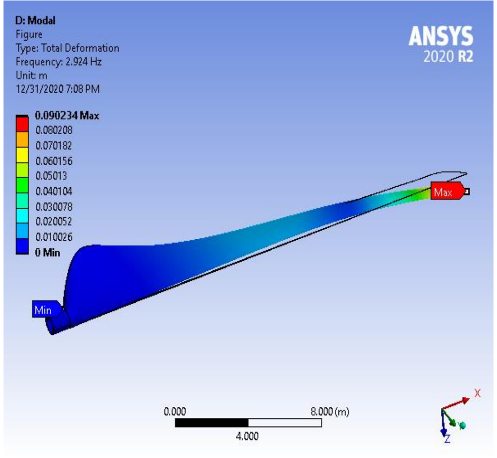

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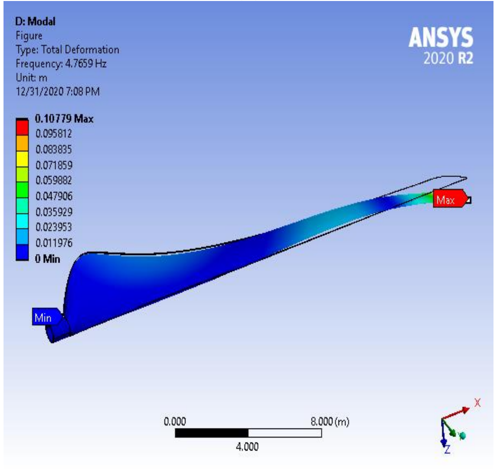

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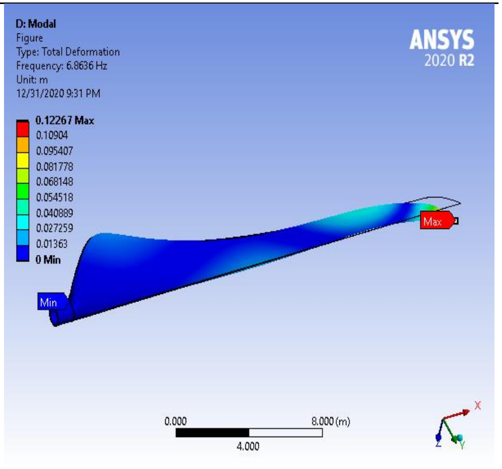

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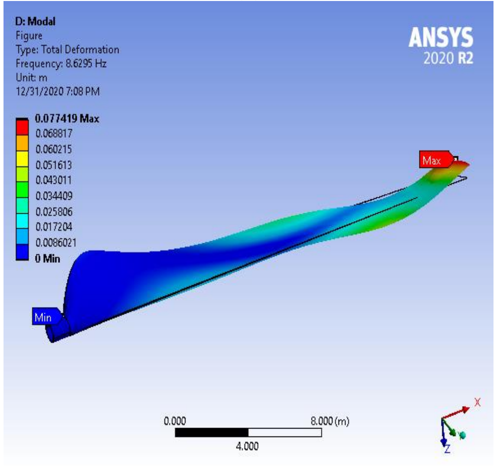

(f)

Figure 7. Vibration pattern of the blade as: (a) First-order; (b) Second-order; (c) Third-order; (d) Fourth-order; (e) Fifth-order; (f) Sixth-order.

3. Results and discussion

It can be seen from the above Figure 7 that the wind turbine blades exhibit wave vibration for the tip of the blade at the first-order natural frequency of 1.074 Hz. A slight wave accompanies the second-order natural frequency exhibit as shimmy vibration. The third-order natural frequency mainly wave vibration. At the fourth-order natural frequency, the wave vibration became intense, manifesting as a mixed vibration of wave vibration and shimmy. The fifth-order natural frequency was mainly displayed as wave vibration and accompanied by slight torsional vibration.

The near proximity of 1st order frequency is alligned with offshore excitation loads . This poses resonance risks demanding design of the blade to be more stiff to enhance the fatigue life.

Moreover, lastly, sixth-order shows complex vibration of the combination of torsional vibration with shimmy vibration. It can be seen that the wave and shimmy vibration are mainly the blade's vibration patterns. From the force analysis of the blade, the blade rotation plane's normal axial force causes a particular blade effect. As a result of the impact, the blade swings in the axial direction, and the vibration from the blade root to the tip gradually strengthens. The tangential force causes the blade to swing from side to side in the rotation plane's radial direction. The Coriolis inertia force causes the wave vibration and the shimmy to be coupled due to the change of the microelements on the blade, such as the fourth-order natural frequency. The main reason for the blade's vibration may be related to the gravity of the blade itself or a specific impact on the blade caused by changes in wind speed and wind direction.

4. Conclusion

The wind turbine blade's structural performance is determined by the resulting pressure on the blade's surface from CFD analysis was taken as an input pressure load. This pressure load with rotational speed was applied to evaluate the total deformation and the von mises stress produced in the blade. "E-glass LY556 epoxy resin lamina" was selected as the blade's material.

Finite element modal and aerodynamics force analysis on the surface of wind turbine blades showed that when the air flows through the blades, there are mainly axial and tangential forces via the decomposition of the combined forces lift to drag. Combining the blade-element theory and the Wilson design model to solve the forces at different radii in the spanwise direction of the blade, and then carrying out the finite element modal analysis combined with the blade's forces, the following findings were made:

The axial force from the blade root to the blade's tip has increased with the increase of radius r, showing a linear growth.

The tangential force from the blade's root to mid increases and then decreases. The blade tip's driving force is less than the root of the blade. It is because the blade tip's relative wind angle and chord length are the smallest.

The normal axial force of the blade rotation plane causes a particular impact on the blade. As a result of the effect, the blade swings in the axial direction. The vibration also gradually strengthens as the axial force from the blade root to the tip increases. The tangential force causes the blade to oscillate from side to side in the rotating plane's radial direction, where the degree of the crook of the blade tip is greater.

After analysis of the blade response under ocean/offshore wind action, which can be carried out on the blade follow-up optimization design, it reduces force overload or uneven force and unstable vibration of the blade.

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