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Numerical and analytical study of aeroelastic characteristics of wind turbine composite blades

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Abstract. Aeroelasticity is the main source of instability in structures which are subjected to aerodynamic forces. One of the major reasons of instability is the coupling of bending and torsional vibration of the flexible bodies, which is known as flutter. The presented investigation aims to study the aeroelastic stability of composite blades of wind turbine. Geometry, layup, and loading of the turbine blades made of laminated composites were calculated and evaluated. To study the flutter phenomenon of the blades, two numerical and analytical methods were selected. The finite element method (FEM), and JAR-23 standard were used to perform the numerical studies. In the analytical method, two degree freedom flutter and Lagrange's equations were employed to study the flutter phenomena analytically and estimate the flutter speed.

Keywords: aeroelasticity; wind turbine; composite blade; flutter; finite element method

1. Introduction

Every structure under the influence of aerodynamic forces has specific type of aerodynamic forces that can change its properties and structure constants such as stiffness coefficient and natural frequencies. Therefore, the structure is faced with strong instabilities that cannot be prevented even by increasing the reliability of the design. This destruction has been created due to a specific force and this value of force is created because of a specific relative velocity of flow that is called flutter phenomenon and the fluid speed destruction is called flutter speed (Fung 2002). Recognizing the flutter speed, we can ensure the safety of structure under aerodynamic forces. In structures such as a plane, flutter speed is considered as the limiting velocity. Limiting velocity is the velocity which must not be reached by an aircraft under any circumstances.

To ensure the safety of aerospace structures against aeroelastic instability, the Joint Aviation Requirements (JAR-23, 1994) standard is used. Based on JAR-23, preventing flutter in the vicinity of fluid velocity can be ensured, if natural frequencies of the bending and torsion are isolated. Shokrieh and Taheri (2001) conducted a numerical and experimental study of aeroelastic stability of composite blades of aircrafts based on this standard.

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Development and application of wind turbines and the related issues such as structural design, aerodynamic design, and material selection as well as manufacturing issues, including fatigue, optimization and aeroelastic stability have attracted researchers' attention. Baumgart (2002) presented a mathematical model for an elastic wind turbine blade and compared analytical and experimental results. Jureczko *et al*. (2005) presented a model for the design and optimization of wind turbine blades and development an ANSYS program that implements a modified genetic algorithm enables optimization of various objective functions subjective to various constraints such as thicknesses and main dimensions of the model blade. Guo (2007) studied weight optimization and aeroelasticity of aircraft wing structure analytically and numerically and compared the results with experimental results. Nonlinear rotor dynamic stimulation of wind turbine by parametric excitation of both linear and nonlinear terms caused by centrifugal and Coriolis forces was investigated by Larsen and Nielsen (2007).

Baxevanou *et al*. (2008) described a new aeroelastic numerical model, which combines a Navier–Stokes CFD solver with an elastic model and two coupling schemes for the study of the aeroelastic behavior of wind turbine blades undergoing classical flutter. Fazelzadeh *et al*. (2009) studied the coupling of bending-torsional flutter of a wing containing an arbitrarily placed mass under a driving force. Results are indicative of the important influence of the location and magnitude of the mass and the driving force on the flutter speed and the frequency of the aircraft wing. The fundamental aspects and the major issues related to the design of offshore wind turbines were outlined by Petrini *et al*. (2010). They considered the decomposition of these structural systems, the required performance, and the acting loads.

Lee *et al*. (2012) investigated the performance and aeroelastic characteristics of wind turbine blades based on flexible multibody dynamics, a new aerodynamic model, and the fluid–structure interaction approach. They proposed a new aerodynamic model based on modified strip theory (MST). Lee *et al*. (2013) numerically investigated the load reduction of large wind turbine blades using active aerodynamic load control devices, namely trailing edge flaps. Tenguria *et al*. (2013) were studied the design and analysis of large horizontal axis wind turbine and NACA airfoil were taken for the blade from root to tip.

This study investigates the structural dynamics of flutter. Numerical and analytical methods were used to study aeroelastic stability of 660 kW composite wind turbine blades. In numerical solution, using finite element method (FEM), and according to JAR-23 (1994) standard, natural frequencies and mode shapes were determined. According to the successive frequency of torsion and bending modes, safety factor of aeroelastic stability was calculated. In analytical solution, a two-dimensional simulated turbine blade with two degrees of freedom was modeled, and the flutter speed was calculated. Given flutter speed and speed performance of turbine, the reliability coefficient can be calculated. Finally, through analytical and numerical methods, the values of safety factor were compared; also the accuracy of composite wind turbine blade design and its performance were evaluated.

2. Numerical study of aeroelastic stability of wind turbine blades

2.1 Finite element modeling

For finite element (FE), analysis of the turbine blade, the ANSYS commercial software was used. The FE model was provided according to dimensions of 660 kW composite wind turbine blades and an airfoil was selected appropriately, as well as most popular design methods (Ghasemi 2000, Tenguria *et al*. 2013). Geometric dimensions of the blade structure are shown in Table 1. To carry aerodynamic forces, the weight of the blade, bending moment in blade and other forces, two beams (main beam and spar) were used in the length of the blade, as shown in Fig. 1.

Table 1 Geometric dimensions of 660 kW wind turbine blades

Length	Attack degree	Chord length (m)		Twist	Distance end section to hub	Airfoil type
(m)	(°)	Root	Tip	(m)	(°)	(NACA)
21	14	2	0.4	15	3.50	$NACA\ 63_2-415$

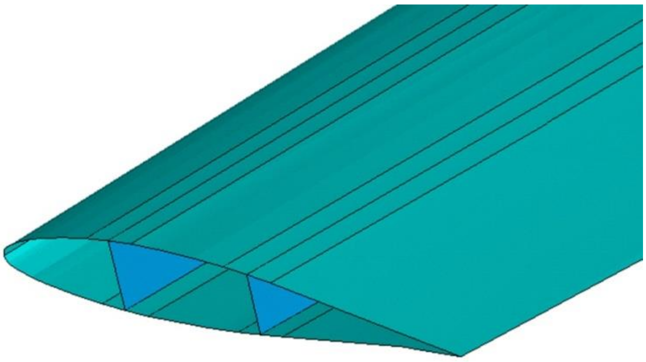


Fig. 1 Section of two beams in the length of blade

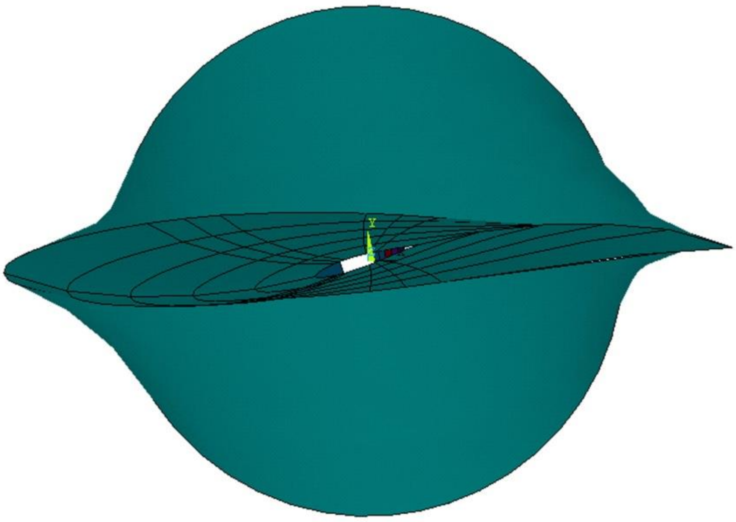


Fig. 2 Twist of the airfoil tip of the blade in relation to its root

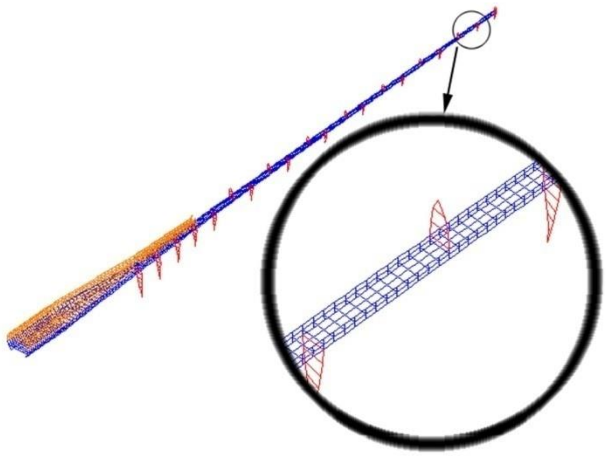


Fig. 3 Three dimensional finite element model of the turbine blade

Section of the blade has taper as well as twist in the length of the blade in which the amount of twist in the tip of the blade as compared to the root is 15 degrees (Fig. 2). According to the physics and geometry of the blade, in order to have the layup ability of the structure, the Shell99 element for meshing was selected. To simulate the structure of the blade, it was divided into five distinct regions, including shell, three parts of the main beam, and the spar, and the special layup was used for each part. The number of extractions of optimal elements carried out for analysis of the blade is known as convergence analysis. The number of optimal element of the structure was about 33200. Three-dimensional finite element model of turbine blade is shown in Fig. 3.

For different parts of the blade according to the applied loads, proper arrangement of the glass/epoxy laminates and foam was used (Tsai 1988). The high stiffness, low density, and good fatigue performance are important for composite wind turbine blades. In the Table 2, ρ is density, E_x and E_y are the stiffness, G_{xy} is the shear stiffness, and ν_{xy} and ν_{yx} are the Poisson's ratios. The thickness of each layer of composite was 0.3 mm and the thickness of the foam was 3 mm.

Table 2 Elastic constants of glass/epoxy uni-directional ply (Tsai 1988)

E_x (GPa)	E_y (GPa)	G_{xy} (GPa)	υ_{xy} (GPa)	$\rho\left({}^{kg}\!/_{m^3}\right)$
76	10.3	7.17	0.28	1.2

Based on the decrease in bending moment from root to tip of the blade, there is no need to have a uniform thickness throughout the length of the beam. Therefore, it is necessary to reduce the thickness by reducing the number of composite ply in order to reduce weight of the structure and to optimize the model.

Since the arrangement of the composite laminates, it should be noted that the flange beam bears the bending forces and the web section transfers the shear stress. Therefore, stacking sequences in the flange in the zero layers and layup in the web section have ± 45 degree angle relative to the longitudinal axis of the blade. The results of the analysis of the metal model confirm this results and the direction of the principle stresses in the metal model indicates the layup of laminate in the composite blade (Ghasemi 2000). Stacking sequences of the shell was $[\pm 54_5 / C / \pm 45_5]$ and its thickness was 6 mm. The main and the secondary beam layup are shown in Table 3.

Table 3 Lay up design of beam and spar for 660 kW turbine blades

Main beam	Stacking sequences in web	Thickness in web	Stacking sequences in flange	Thickness in flange (mm)
Root to 7 m	$[\pm 54_{10} / C / \pm 45_{10}]$	9	$[0]_{46}$	13.8
From 7-14 m	$[\pm 54_9 / C / \pm 45_9]$	8.4	$[0]_{36}$	10.8
From 14-21 m	$[\pm 54_8 / C / \pm 45_8]$	7.8	$[0]_{20}$	6
Spar	$[\pm 54_7 / C / \pm 45_7]$	7.2	$[0]_{20}$	6

2.2 Blade aerodynamic loading

The resultant of the aerodynamic forces into an airfoil section is generally shown as the lift and drag forces. By using lift and drag forces, the force F_Q that causes creation of a useful torque in the direction of rotor's rotation, and the force F_T that applies an axial force to the blades, were calculated. By integration of the moment ΔQ and the thrust ΔT in the length of the blade, bending moment M_T and rotation moment M_Q can be obtained. The value of the torque and thrust axial force for each section from Glauert vortex theory is determined (Eggleston and Stoddard 1987).

$$\begin{aligned} \Delta Q &= 0.5\rho\omega^2 r(C_l \sin\phi - C_d \cos\phi) C\Delta r \\ \Delta T &= 0.5\rho\omega^2 r(C_l \cos\phi + C_d \sin\phi) C\Delta r \end{aligned} \tag{1}$$

$$\begin{aligned} F_Q &= L\sin\phi - D\cos\phi \\ F_T &= L\cos\phi + D\sin\phi \end{aligned} \tag{2}$$

In the above equations the C is chord length and r is radius, ω is angular speed and ρ is air density. The C_l, C_d, L and D indicate the lift and drag coefficients, and lift and drag forces, respectively. The diagram of these forces is shown in Fig. 4. In this figure, W indicates the relative effective wind speed on the blades and the angle ϕ is the angle between the relative wind speed and the axis perpendicular to the rotation axis, which consists of the attack angle (α) and the airfoil torsion (θ) (Eggleston and Stoddard 1987). Using MATLAB software, a computer code was developed which is able to calculate the values of the forces and moments in Eqs. (1) and (2), for the blade 660 kW and are shown in Table 4. The above forces and moments are entered at the center of each section.

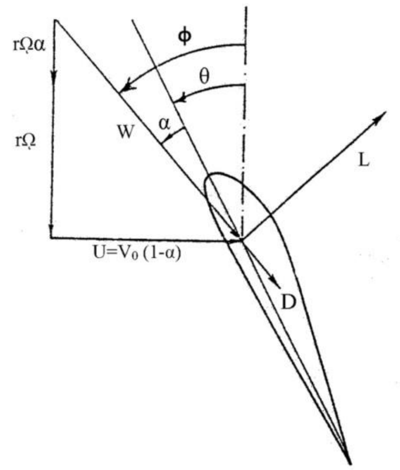


Fig. 4 Aerodynamic forces acting on the turbine blade

Table 4 Total forces and moments on the 660 (kW) turbine blades

Bending Moment (M_T)	Rotation Moment (M_Q)	Axial Forces (F_T)	Rotation Forces (F_Q)
1291914 (N.m)	174015 (N.m)	90177 (N)	13262 (N)

2.3 Centrifugal force loading

The value of centrifugal force caused by rotor rotation with angular speed (ω) that in the plate rotation as tensile load, was calculated using equation $F_{centrifugd} = mr\omega^2$. This force depends on the angular speed of the blade and the radius rotation which is the distance from the axis of rotation to the center of mass. Angular speed of the blade was 4.45 radiations per second and hub radius of 0.8 m was considered.

2.4 Aeroelastic analysis of a section

Flutter analysis was often performed using simple, spring-restrained and rigid-wing models such as the one shown in Fig. 5. In the latter case, the discrete springs would reflect the wing structural bending and torsional stiffnesses, and the reference point would represent the elastic axis (Hodges and Pierce 2002). The points *P*, *C*, *Q*, and *T*, which refer to the reference point, the center of mass, the aerodynamic center, and the three-quarter-chord, respectively. The dimensionless parameters e and a determine the location of the point *C* and *P*, when these parameters are zero, the point lies on the mid chord, and when they are positive/negative, the points lie toward the trailing/leading edge.

The m is mass, b is a reference of semi-chord of the lifting surface and v_C is the velocity of mass center. The degrees of freedom h and θ are easily derived from the work done by the aerodynamic lift, *L*, through a virtual displacement of point *Q* and the aerodynamic pitching moment about *Q* through a virtual rotation of the model.

The chordwise offset of the center of mass from the reference point is defined as follows

$$x_\theta = e - a \tag{3}$$

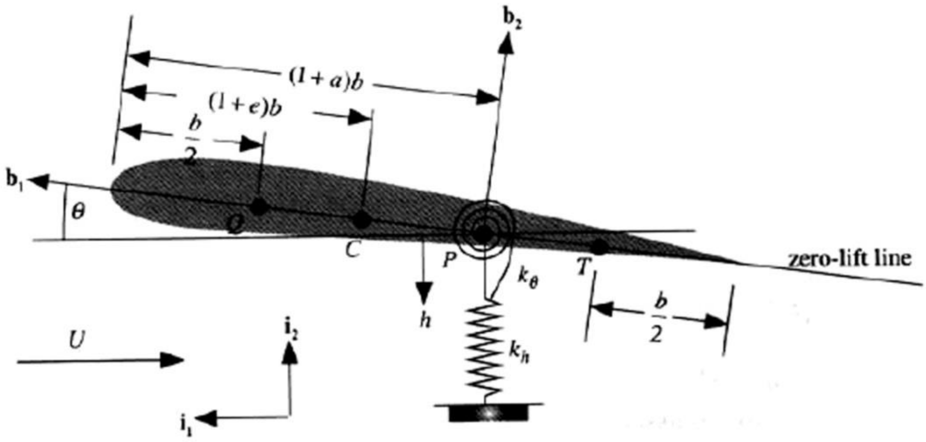


Fig. 5 Two dimensional aeroelastic modeling of airfoil with two degree freedom

The rigid plunging and pitching of the model is restrained by light, linear spring with spring constants k_h and k_θ. It is convenient to formulate the equations of motion from Lagrange's equations. To do this, one needs kinetic and potential energies as well as the generalized forces resulting from aerodynamic loading. The potential and kinetic energies are given by the following formula (Hodges and Pierce 2002)

$$\begin{aligned} P &= \frac{1}{2}k_h h^2 + \frac{1}{2}k_\theta \theta^2 \\ K &= \frac{1}{2}m v_c^2 + \frac{1}{2}I_c \dot{\theta}^2 \end{aligned} \tag{4}$$

Where *C* is the mass center and I_C is the moment of inertia about *C*. Using simplicity in Lagrange's formalism for the aerodynamics equation of motion can be presented as follows (Hodges and Pierce 2002)

$$\begin{aligned} & m(\ddot{h} + b x_\theta \ddot{\theta}) + k_h h = -L \\ & I_P \theta + m b x_\theta \ddot{h} + k_\theta \theta - b(0.5 + a)L \end{aligned} \tag{5}$$

Where $I_P = I_C + m b^2 x_\theta{}^2$. To simplify the formula; we introduce the uncoupled, natural frequencies at zero airspeed, represented by

$$\omega_h = \sqrt{\frac{k_h}{m}}, \qquad \omega_\theta = \sqrt{\frac{k_\theta}{I_P}} \tag{6}$$

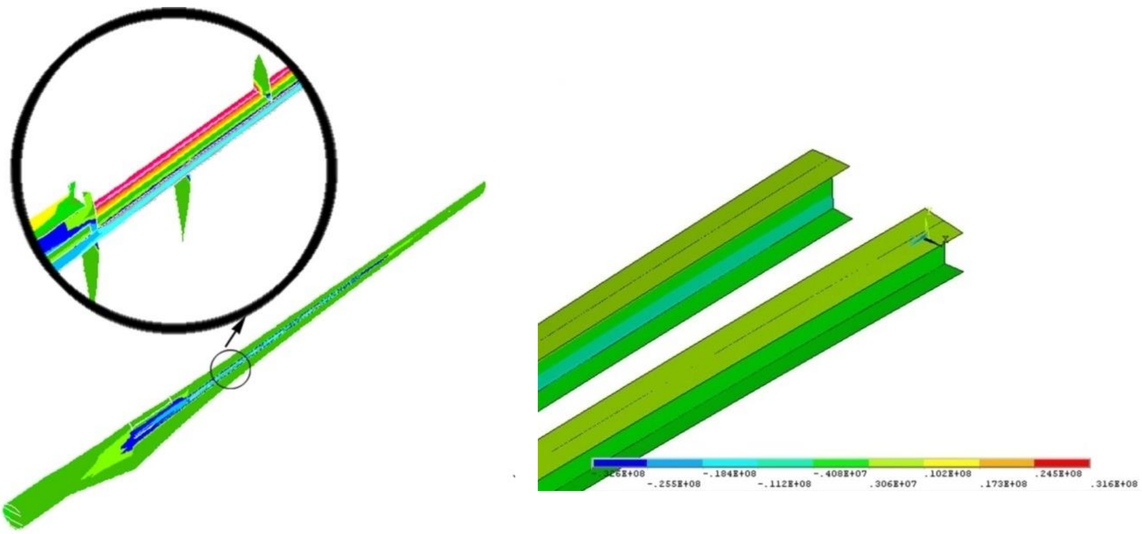
To introduce dimensionless variables to further simplify the problems, we consider the following four parameters

$$\gamma^2 = \frac{I_P}{mb^2} \qquad \sigma = \frac{\omega_h}{\omega_\theta} \qquad \mu = \frac{m}{\rho \pi b^2} \qquad V = \frac{U}{b\omega_\theta} \tag{7}$$

Where r is the dimensionless radius of gyration of the wing about the reference point P with $r^2 \succ x_\theta^2$; σ is the ratio of uncoupled bending to torsional frequencies, μ is the mass ratio parameter reflecting the relative importance of the model mass to the mass of the air affected by the model, and V is the dimensionless free stream speed of the air that is sometimes called the reduced velocity. The equations may be simplified as follows

$$\begin{bmatrix} s^2 + \sigma^2 & s^2 x_\theta + \dfrac{2V^2}{\mu} \\ s^2 x_\theta & s^2\gamma^2 + r^2 - \dfrac{2V^2}{\mu}(\dfrac{1}{2} + a) \end{bmatrix} \begin{Bmatrix} \dfrac{\bar{h}}{b} \\ \bar{\theta} \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \end{Bmatrix} \tag{8}$$

For a nontrivial solution to exist, the determinant of the coefficient matrix must be set equal to zero. There are two complex conjugate pairs of roots, say $s_{1,2} = {(\Gamma_{1,2} \pm i\Omega_{1,2})}/{\omega_\theta}$. For a given configuration and altitude, one must look at the behavior of the complex roots as functions of V and find smallest value of V to give divergent oscillations, whose value is $V_F = \dfrac{U_F}{b\omega_\theta}$, where U_F is the flutter speed.



(a) Stress in fiber direction in beams (b) Stress in transverse direction in beams

Fig. 6 The stress contours in the critical layer of main beam and spar

3. Results and discussion

3.1 Blade static analysis

To control and ensure the safety factor of the structure against applied loads, the stress and strain at different directions must be studied. Using a suitable failure criterion, the static safety factor of structure design can be calculated. From the theoretical point of view, the stress in the area of the blade root which is under the influence of aerodynamic forces, weight force, and maximum bending moment is higher than other parts of the blade.

Furthermore, according to the layer properties of the composites, it is necessary that stress contour in the critical layer in which the possibility of failure is highest in the whole structure be studied. In this study, the critical values were extracted by investigating the stress in fiber direction, perpendicular to fiber (transverse) direction, and the shear stress. The stress contours in the beam and spar critical layer with maximum failure stress number is shown in Fig. 6.

In order to study the safety factor of static design, Tsai-Wu failure criterion was used. Minimum safety factor for destruction in the critical layer was obtained equivalent to 4. Also, during rotor performance, the maximum displacement of the blades was 1.4 meter where the angle of the blade is 3.81 degree deflection at the tip (Ghasemi 2000). This indicates a considerable improvement over similar models. The deflection of composite wind turbine blade is shown in Fig. 7. The minimizing blade tip deflection and the sufficient distance between blade and tower in critical conditions are very important.

Fig. 7 Deflection of the 660 kW turbine blades

3.2 Blade vibration and modal analysis

Dynamic effects in mechanism of the wind turbine due to frequency of aerodynamic loads during normal rotation are significant. In structural engineering, modal analysis uses the overall mass and stiffness of a structure to find the various periods at which it will naturally resonate. The goal of modal analysis in structural mechanics is to determine the natural mode shapes and frequencies of an object or structure during free vibration. It is common to use the FEM to perform this analysis because, like other calculations using the FEM, the object being analyzed can have arbitrary shape and the results of the calculations are acceptable. The types of equations which arise from modal analysis are those seen in eigensystems. The physical interpretation of the eigenvalues and eigenvectors which come from solving the system, that represents the frequencies and corresponding mode shapes. Sometimes, the only desired modes are the lowest frequencies because they can be the most prominent modes at which the object will vibrate, dominating all the higher frequency modes. In order to do aeroelastic analysis and ensure the non-occurrence of flutter phenomenon, modal analysis of composite structures, natural frequencies with their mode shapes are studied. The results of modal analysis of structure using FEM up to 10 natural frequencies are expressed in Table 5. The bending and torsion modes related to these frequencies should be identified and separated by finding the values of natural frequencies.

Table 5 Natural frequencies of the 660 kW composite wind turbine blade

Number Mode	1	2	3	4	5	6	7	8	9	10
Natural Frequency	0.89	2.52	2.98	5.44	8.51	9.41	10.63	14.82	15.72	16.35

According to JAR-23 standard, flutter phenomenon occurs when both bending and torsion sequential modes are overlapped. Therefore, flutter safety factor of blades equals the ratio of two consecutive bending and torsion modes of blades. Structural analysis of composite blade value and safety factor is calculated as follows

$$n_1 = \frac{\omega_b}{\omega_\theta} = \frac{14.82}{10.63} = 1.39 \qquad (9)$$

The torsional and bending modes of composite blade structure are shown in Fig. 8 and Fig. 9. The reason for this choice is the lowest ratio between two successive bending and torsional modes. Obtained minimum safety factor is acceptable. Therefore FEM shows that structural safety and aeroelastic stability are reliable.

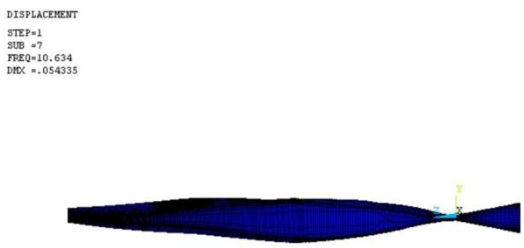


Fig. 8 Torsion mode of the 660 kW composite wind turbine blade

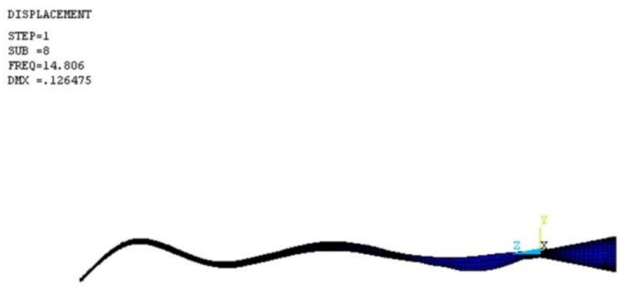


Fig. 9 Bending mode following torsion mode of the 660 (kW) composite wind turbine blade

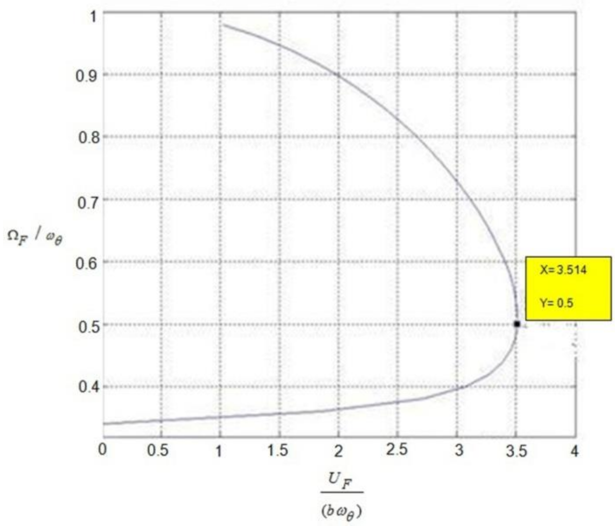


Fig. 10 Modal frequency via V for the first and second modes

3.3 Blade aeroelastic analysis

In this section, the two dimensional analytical study of aeroelastic stability for composite wind turbine blade was carried out with two degrees of freedom.

For looking at flutter, we consider a specific section of a composite blade of wind turbines, defined by $a = 0.2,\ e = 0.1,\ \mu = 20,\ r^2 = 0.24$, and σ is obtained from numerical solution. Plots of the imaginary part of the roots versus V are shown in Figs. 10 and 11. The modal frequency for the first and second modes is shown in Fig. 10. The modal frequency of critical torsional and bending modes is shown in Fig. 11. In Fig. 11, when *V*=0, one expects the two dimensionless frequencies to be close unity and σ represents pitching and plunging oscillations, respectively. Even at $V=0$, these modes are lightly coupled because of the nonzero off-diagram term x_θ in the mass matrix. As V increases, the frequencies start to approach one another, and their respective mode shapes exhibit increasing coupling between plunge and pitch. Flutter occurs when the two modal frequencies come close, at which point the roots become complex conjugate pairs. Under this condition, both modes are highly coupled pitch-plunge oscillations. For this composite blade of wind turbine, the flutter speed is $V_F = \frac{U_F}{b\omega_\theta} = 3.306$, and the flutter frequency is $\frac{\Omega_F}{\omega_\theta} = 0.802$.

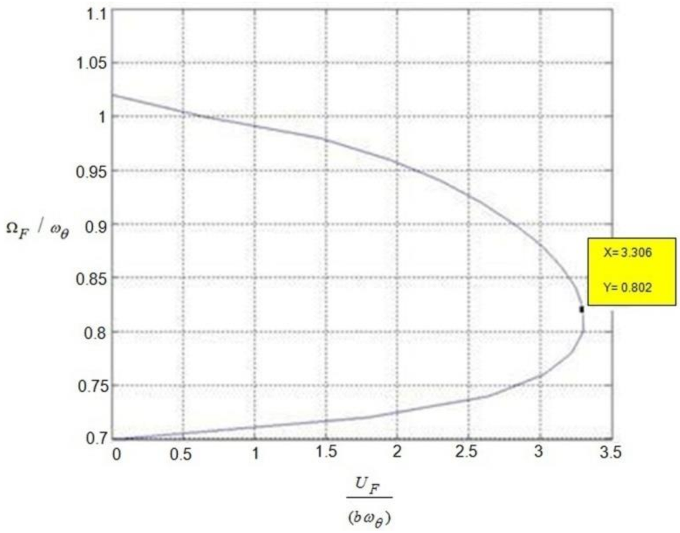


Fig. 11 Modal frequency via V for critical torsional and bending modes

According to the values of modal analysis and natural frequency of the torsion mode, the flutter speed is determined as follow

$$U_F = 3.31 \times b\omega_\theta = 35\, m/s \tag{10}$$

In Eq. (10), b =1 is the half of chord length and $\omega_\theta = 10.63$. The relative real speed of the turbine performance is calculated as follows

$$V = \sqrt{V_{rel}^2} + V_a^2 = 25.3\, m/s \tag{11}$$

Given the flutter speed and the performance speed of the wind turbine, safety factor can be calculated as follows

$$n_2 = \frac{U_F}{V} = 1.38 \tag{12}$$

Obtained safety factor is acceptable and shows the safety and aeroelastic stability of the structure in the performance and design of turbine blades.

4. Conclusions

In this study, the aerodynamic loading, static analysis, dynamic analysis and aeroelastic stability of composite wind turbine blades was considered. Aerodynamic loading with weight and the centrifugal loading to the blade is applied. Safety factor for failure in metal model using Von–Mises criterion and in the composite model using Tsai-Wu failure criterion for the critical layer was obtained. The high stiffness, low density, and good fatigue performance are important and emphasized for composite wind turbine blades. In the finite element model by doing modal analysis and extracting natural frequencies and aeroelastic stability of structure, the safety factor equal 1.39 was calculated. In analytical method the changes in natural frequencies of the system due to free stream speed was studied and flutter speed related to the coupling of bending and torsion was calculated. According to speed performance of turbine, safety factor of aeroelastic stability equivalent to 1.38 was calculated. Obtained safety factor was acceptable in all stages and indicates the stability and safety of composite blades structure in static, dynamic and aeroelastic design.

Acknowledgments

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