A Continuum Based Three-Dimensional Modeling of Wind Turbine Blades

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1 Introduction

In recent years the aerodynamic performance of wind turbine blades has been considerably improved. This has contributed to an overall reduction in the cost of wind power produced electricity. The energy capture is approximately proportional to the square of the blade length while the blade weight is approximately proportional to the cube of its length [1]. To counteract the weight increase, the development of blades goes towards long and relatively flexible structures [1].

The most important aeroelastic components of a wind turbine are the blades. The purpose of the blades is to extract aerodynamic forces from the passing airflow; therefore, they are highly affected by aerodynamic forces. The development of larger wind turbines has resulted in long slender blades with high flexibility. The idea of modeling such blades with non-uniform, and twisted nature, allows for describing the cross-section deformation modes as well as the deformation modes that appear in the existing beam theories (bending, torsion, longitudinal, and shear deformations). In a general continuum mechanics theory, the deformation and rotation (bending, torsion, longitudinal, and shear deformations) can be obtained if the rotating speed reaches the basic natural frequency of the flexible blade [4]. To overcome the geometric stiffness effect, the internal elastic coupling between different forms of motion should be taken into consideration. Furthermore, real wind turbine blades are made of composite materials, making them anisotropic which increase the internal elastic coupling effect of blade motion. This cannot be described by the moving frame of reference, especially with high rotating speeds. The modeling computation problem increases as the rotor blade diameter increases. For instance, the Enercon E-126 is the largest wind turbine model built to date, manufactured by the German wind turbine producer Enercon. With a hub height of (135 m), rotor diameter of (126 m) and a total height of (198 m), this large model can generate up to 7.58 Megawatts of power per turbine [5].

The recently developed ANCF had been used in the analysis of large deformation of flexible multibody systems including belt drives [6–8], rotor blade [9], large deformation piezo-electric laminated plates [10], flexible robotic manipulators [4], and cable applications [11]. The important advantage of using this formulation in multibody computer simulations is the constant mass matrix that can be obtained for fully nonlinear dynamic problems. Therefore, this nonlinear finite element formulation can be implemented using nonincremental solution procedures in a general framework of multibody computer algorithms. The elastic forces; in contrast, are calculated using a general continuum mechanics approach. This allows for describing the cross-section deformation modes as well as the deformation modes that appear in the existing beam theories (bending, torsion, longitudinal, and shear deformations). In a general continuum mechanics theory, the deformation and rotation fields within an infinitesimal volume can be uniquely defined using nine components of the displacement gradients in the three-dimensional applications. For this reason, the nine independent gradient coordinates are used in the ANCF to describe the large rotational motion defined using the three independent rotational parameters as well as the deformation defined using the six strain components [3,12]. Using such gradient coordinates leads to simpler expressions of the generalized inertia forces and the exact modeling of the rigid body motion [12–14].

Recent advances in the ANCF, involving the method of calculating the strain energy [15], illuminating high frequency modes [16,17] and development of stiff integrators [18,19]; help in reducing the calculation time and enhance the sensitivity of the system equations. Also the formulation of 3D joint constraints is well established and verified [20], which enable constructing the
model of complete wind turbine blades structure. Further advances in the ANCF were carried out including the modeling of internal damping [21] and nonlinear viscoelasticity [22].

In this paper, a mapping procedure to construct ANCF model of NACA airfoils of large wind turbine blades is established. The variation of the cross sectional layouts across the blade are manipulated and the corresponding mapping equations are derived. Because of the special cross-sectional geometric features/parameters of wind turbine blades; the use of ANCF and the computational tools that provide fast and accurate results, opens opportunities to improve the design of flexible blades. The obtained results are necessary for improving the dynamics for design (DFD) process concerning large-rotation, large-deformation wind turbine blades.

2 Airfoil Shape Parameters

Wind turbines on the propeller blades possess various blade profiles such as NACA, LS and LM profiles standards [23]. In horizontal axis wind turbines NACA profiles standards of National Advisory Committee for Aeronautics is applied in Ref. [24]. The NACA 44 series profiles were used on older wind turbines (up to 95 KW models). This profile was developed during the 1930s, and has good all-round properties, giving a good power curve and a good stall. The shape of the airfoil can be chosen in the famous NACA 4 digits library [24]. This simple library is interesting because the shape is analytically expressed as a function of only three parameters, which control the maximum camber, maximum camber location, and maximum thickness of the airfoil, see Fig. 1. A wide variety of airfoils can be obtained by varying these three parameters, as shown in Fig. 2. A numbering system is used to define NACA wing sections by 4-digits: the first digit indicates the maximum value of the mean-line ordinate in percent of the chord. The second digit indicates the distance from the leading edge to the location of the maximum camber in tens of the chord. The last two digits indicate the section thickness as a percentage of the chord. Thus, the NACA 4512 has 4% camber located at 50% of the chord from the leading edge, and is 12% thick. It is noted that these digits do not really have to be integers.

By extension of the notation, a NACA 4.23 2.21 17.2 would have 4.23% camber located at 22.1% of the chord from the leading edge, and be 17.2% thick.

One of the significant factors of a blade profile is the chord length which is the distance between leading edge and trailing edge. Chord length may have various values at the square and end points on the blade.

The camber line can be expressed in the $xz$ plane, as:

$$
\frac{z_c}{c} = \frac{m}{p^2} (2p\xi - \xi^2), \quad \cdot \cdot \cdot \xi \leq p
$$

$$
= \frac{m}{(1-p)} (1 - 2p + 2p\xi - \xi^2), \quad \xi \geq p
$$

In these expressions, $c$ is the airfoil chord length, $m$ is the maximum camber, $p$ is the maximum camber location, and $\xi = (x/c)$ is the parametric position. The thickness distribution for the NACA 4-digits sections is given by:

$$
z_{th} = 5ch \left(0.2969\xi^{3/2} - 0.1260\xi - 0.3516\xi^2 + 0.2843\xi^3 - 0.1015\xi^4\right)
$$

where $h$ is the maximum thickness expressed as a fraction of the chord.
The wing section is obtained by combining the camber line and the thickness distribution as shown on the Fig. 2.

\[ x_u = x - z_{th} \sin(\theta) \]  
\[ z_u = z_{th} + z_{th} \cos(\theta) \]
\[ x_i = x + z_{th} \sin(\theta) \]  
\[ z_i = z_{th} - z_{th} \cos(\theta) \]

where \((x_u, z_u)\) and \((x_i, z_i)\) are the coordinates of the upper and lower airfoil surfaces, respectively. Here, \(\theta\) is the slope of the camber line, and can be calculated using the following equation:

\[ \frac{dz_c}{dx} = \frac{d(z_c/\xi)}{d\xi} = \frac{2m}{p^2} (p - \xi), \quad \cdots \quad \xi \leq p \]  
\[ \frac{d(z_c/\xi)}{d\xi} = \frac{2m}{(1-p)^2} (p - \xi), \quad \xi \geq p \]

3 Absolute Nodal Coordinates Formulation (ANCF)

In the absolute nodal coordinate formulation, the nodal coordinates of the elements are defined in a fixed inertial coordinate system, and consequently no coordinate transformation is required. The element nodal coordinates represent global displacements and gradients (slopes) at node 1. The nodal coordinates of one element can then be given by the vector \(e\):

\[ e = [e^{1T} \quad e^{2T} \quad e^{3T} \quad e^{4T}]^T \]

3.1 Thin Plate Element. For thin plates, the deformation of the element along the thickness direction can be neglected. This leads to reduced set of deformation modes since the displacement field of the element becomes dependent on the spatial coordinates \(x\) and \(y\) only. In this case, the position vector gradients obtained by differentiation with respect to \(z\) are not considered as nodal coordinates, leading to a reduced order element with 36 degrees of freedom. The normal vector \(n\) of the mid surface of the plate can always be defined using cross product of the vectors \(r_x\) and \(r_y\), with subscript \(x\) and \(y\) refer to partial derivatives with respect to these coordinates; see Fig. 4. The shape functions of the thin plate element can be directly obtained from the shape function matrix of the plate element by omitting the components that depend on the \(z\) coordinate [6]. For the reduced order element, the element nodal coordinate vector at node (1) is defined as follows:

\[ e^1 = [r_x^{1T} \quad r_y^{1T} \quad r_z^{1T}]^T \]
\[ r = S(x,y) e \]

3.2 ANCF of Airfoil Geometry. The blade profile is a hollow profile usually formed by two (shell) structures glued together, one upper shell on the suction side, and one lower shell on the pressure side. It is required to construct the wind turbine blade with specific NACA code, and therefore, the NACA profile equations should be used to estimate the node position and gradients. In this section, two ANCF thin plate element should be used to construct the wind turbine blade and the resulting error should be mentioned. One plate on the upper and the other on the lower side of the wind turbine blade.

The thickness distribution of the airfoil can be described by the slope in \(xz\) direction of the first and last nodes, i.e., nodes number (1, 4), which have the same slope in \(x\)-direction. For the upper element, the gradient can be estimated as:

\[ r_x^k = \left[ \frac{dx_u}{dx} \quad 0 \quad \frac{dz_u}{dx} \right]^T, \quad \cdots \quad k = 1, 2, 3, 4 \]
\[ r_y^k = [0 \quad 1 \quad 0]^T, \quad \cdots \quad k = 1, 2, 3, 4 \]

where \(r_x^k\) is the gradient at node \(k\), with respect to \(x\). For nodes number (1) and number (4), Eq. (8) should be used at start point \(x \neq 0\), and Eq. (9) is used for nodes (2) and (3) at the \(x = c\). For the lower element, the gradient can be estimated as:

\[ r_x^k = \left[ \frac{dx_i}{dx} \quad 0 \quad \frac{dz_i}{dx} \right]^T, \quad \cdots \quad k = 5, 8 \]
4 Blade Tapering

It is important that the blade sections near the hub are able to resist forces and stresses from the rest of the blade. Therefore, the blade profile near the root is both thick and wide. Further, along the blade, the blade profile becomes thinner so as to obtain acceptable aerodynamic properties. Therefore, the effect of tapering the blade is obvious; it tends to decrease the stresses. Also, as the blade speed increases towards the tip, the lift force will increase towards the tip. Decreasing the chord width towards the tip will contribute to counteract this effect. From aerodynamical point of view, it improves the wind rotor performance, although it increases the manufacturing cost. In other words, the blade tapers from a point somewhere near the root towards the tip. In general, the blade profile constitutes a compromise between the desire for strength and the desire for good aerodynamic properties. At the root, the blade profile is usually narrower and tubular to fit the hub. In this section, a method of constructing the ANCF model of tapered (nonuniform) blade is introduced using the lofted surface geometry [25].

4.1 Lofted Surfaces. Lofted surfaces are defined as those surfaces that through every point on it, there is a straight line that lies completely on the surface. In the previous section it was shown the possibility of modeling a uniform wind turbine blade with the ANCF, with its derived shape functions, $S$ [12]. In the case of obtaining the global position vector for the nonuniform wind turbine blade, the global position, $r$, should be linearly interpolated between the blade starting chord and the ending chord. This bounded curves can be denoted by $r(\xi, 0)$ and $r(\xi, 1)$ and by two straight segments $r(0, \eta)$ and $r(1, \eta)$ connecting them. Surface lines in $\eta$ direction are therefore straight, i.e., lofted surfaces, whereas each line in the $\xi$ direction is a blend of $r(\xi, 0)$ and $r(\xi, 1)$ this blend constitutes the following surface expression:

$$ r(\xi, \eta) = (1 - \eta)r(\xi, 0) + \eta r(\xi, 1) $$

where $\eta$ and $\xi$ are parametric domains such that $\xi, \eta \in [0, 1]$ and can be estimated as $\xi = x/a$, $\eta = y/b$, with $a$, and $b$ are the plate element length and width, respectively. It should be mentioned here that this kind of surface is fully defined by specifying the two boundary curves. The four corner points of the plate elements are implicit in these curves. These surfaces are sometimes called “ruled,” because straight lines are an important part of their description.

4.2 Tapering of Blade. Tapering is connecting two cross sections along the span length, $L_s$, within the blade surface, with
chord length, \( d \) is the chord length, and \( c_1, c_2 \) are the chord length at the “start” and “end” cross sections, respectively. Depending on \( c_1 \) and \( c_2 \), the boundary curves can be obtained as:

\[
r(\xi; 0) = r' = S(x; 0)e \quad \ldots \quad x \in [0, c_1]
\]

where \( e \) is the nodal coordinates of the starting cross section \( i \); see Fig. 9. Thus, the ending cross section can be concluded as:

\[
r(\xi; 1) = r' = \begin{bmatrix} [0] & [0] \end{bmatrix} + \begin{bmatrix} c_2/c_1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & c_2/c_1 \end{bmatrix} \begin{bmatrix} 0 \\
1 \\
0 \end{bmatrix}
\]

By substituting Eqs. (23) and (24) into Eq. (20) gives the curves of cross sections between \( r' \) and \( r' \). Then, Eq. (20) can be solved for the nodal coordinates \( e \) of the ending cross section, i.e., the nodal coordinates of nodes number 3, 4, 6, and 14, on the upper surface and the nodal coordinates of nodes number 9, 10, 12, and 16 on the lower surface; see Sec. 3.3. If the upper and lower surfaces should be divided into more than one element along the span length, Eq. (20) should be used to calculate the corresponding nodal coordinates.

Figure 10 shows a tapered wind turbine blade according to NACA 4412 with tapering angle \( \alpha = 5 \) deg, span length \( L_s = 5 \) m, and plate thickness \( t = 0.006 \) m; while Fig. 11 shows a tapered wind turbine blade according to NACA 8812 with tapering angle \( \alpha = 8 \) deg with the same span length and plate thickness.

### 4.3 Blade Twist

The blade is twisted along its axis so as to enable it to follow the change in the direction of the resulting wind along the blade, which the blade will experience when it rotates. Hence, the pitch will vary along the blade. The pitch is the

\[
\Delta \alpha = L_s \tan \alpha
\]

where \( \alpha \) is the taper angle, \( \alpha \); see Fig. 9 to achieve the required strength properties for the wind turbine blade. The change in the chord length, \( \Delta \alpha \), can be obtained as:

\[
\begin{array}{l}
 c_2 = c_1 \Delta \alpha \\
 c_2 = c_1 - \Delta c \\
\end{array}
\]
angle between the chord of the blade profile and the rotor plane. In order to construct the wind turbine blade with certain twist angle \( \beta \). The lofted surface described in the previous section is modified such that the end cross section of the wind turbine blade is twisted by the angle \( \beta \); see Fig. 12. This can be done by multiplying the global position vector matrix of the end section, \( \mathbf{r}^j \), i.e., \( \mathbf{r}(\xi, 1) \), by a rotation matrix around \( y \)-axis with the twist angle \( \beta \). Thus, the global position vector equations of the end cross section can be calculated as:

\[
\mathbf{r}(\xi, 1) = \begin{bmatrix} \cos(\beta) & 0 & -\sin(\beta) \\ 0 & 1 & 0 \\ \sin(\beta) & 0 & \cos(\beta) \end{bmatrix} \mathbf{r}(\xi, 0)
\]

(25)

where \( \mathbf{r}(\xi, 0) \) can be estimated using Eq. (23), the lofted surface, Eq. (20) can be used in the case of dividing the wind turbine blade into more than one element along the span length.

Figures 13 and 14 show a tapered/twisted wind turbine blade according to NACA 4412 with tapering angle \( \alpha = 5 \) deg, and twist angle of \( \beta = 30 \) deg, span length \( L_s = 5 \) m, and thickness \( h = 0.006 \) m. While Figs. 15 and 16 show a tapered/twisted wind turbine blade according to NACA 8812 with tapering angle \( \alpha = 8 \) deg twist angle of \( \beta = 30 \) deg, with the same span length and thickness.

Twisting the wind turbine blade is vital key for achieving the acceptable aerodynamic properties. The twisting of the blade tip increases the strength of the blade as the stiffness increases. Also, it is found that by increasing the twist angle and decreasing the eigenvalue, this results in twisting decreases the probability of reaching the resonant frequency of the blade [26].

5 Equations of Motion

The general dynamic equations of the flexible multibody systems can be written as:

\[
\mathbf{M} \ddot{\mathbf{e}} = \mathbf{Q}
\]

(26)

where \( \mathbf{M} \) is the mass matrix associated with the ANCF [27], and the vector \( \mathbf{Q} \) includes the generalized forces associated with nodal coordinates, which can be written as:

\[
\mathbf{Q} = \mathbf{Q}_e + \mathbf{Q}_x
\]

(27)

\( \mathbf{Q}_e \) is the vector of elastic forces, and \( \mathbf{Q}_x \) is the vector of the external forces (gravity and aerodynamic forces).

5.1 Mass Matrix. The total kinetic energy \( T \) is described by:

\[
T = \frac{1}{2} \int_{V_0} \rho \mathbf{e}^T \mathbf{e} dV_0 = \frac{1}{2} \rho \mathbf{e}^T \left[ \int_{V_0} \mathbf{S}^T \mathbf{S} dV_0 \right] \dot{\mathbf{e}}
\]

(28)

Fig. 8 ANCF models of NACA airfoils, red lines represent NACA code profile

Fig. 9 Nonuniform wind turbine blade

Fig. 10 WTB NACA 4412, \( \alpha = 5 \) (deg)
where \( \mathbf{r} \) is the velocity vector of an arbitrary point on the plate, \( \rho \) is the material density and \( V_0 \) is the element initial volume. In the case of wind turbine blade model, the plate elements are initially curved; otherwise, the integration should be estimated with respect to the straight reference configuration. The relation between volumes in the un-curved reference and initially curved configuration can be defined using the gradient transformation matrix \( \mathbf{J} \), and can be expressed as follows [6,28]:

\[
V_0 = |\mathbf{J}|V
\]

where \( V_0 \) is the volume of the element in initial curved configuration and \( V \) is volume in the un-curved configuration. Therefore, the mass matrix can be written as:

\[
\mathbf{M} = \int_V \rho \mathbf{S}^T \mathbf{J}^T \mathbf{J} dV 
\]

5.2 Elastic Forces. The elastic force vector \( \mathbf{Q}_k \) is obtained by differentiating the strain energy \( U \) with respect to the nodal coordinate vector \( \mathbf{e} \), as:

\[
\mathbf{Q}_k = -\left( \frac{\partial U}{\partial \mathbf{e}} \right)^T
\]

The thin-plate element is based on Kirchhoff’s plate theory. Accordingly, the strain energy can be written as the sum of two terms: one term is due to membrane and shear deformations at the plate mid-surface, whereas the other term is due to the plate...
bending and twist. The strain energy can then be written for a thin plate as follows [6,12]:

$$U_e = U_m^e + U_j^e = \frac{1}{2} \int_{V_0} \epsilon^e : \epsilon^e \, dV + \frac{1}{2} \int_{V_0} \eta^e : \eta^e \, dV$$  \hspace{1cm} (32)

where $\epsilon^e$ is the strain energy for homogeneous isotropic material [10]. The membrane and shear strain vector $\epsilon^m$ is defined as:

$$\epsilon^m = [\epsilon_{xx}, \epsilon_{yy}, 2\epsilon_{xy}]^T$$  \hspace{1cm} (33)

where $\epsilon_{xx}$ and $\epsilon_{yy}$ are the normal strain components in $x$ and $y$ direction and $\epsilon_{xy}$ is the shear strain. The curvature strain vector $\epsilon^c$ is given by:

$$\epsilon^c = \kappa n$$  \hspace{1cm} (34)

The curvature vector $\kappa = [\kappa_{xx} \kappa_{yy} 2\kappa_{xy}]^T$ can be expressed in terms of the gradient vectors as the following relations [10]:

$$\kappa_{xx} = \frac{n^T r_{xx}}{||n||^3}, \quad \kappa_{yy} = \frac{n^T r_{yy}}{||n||^3}, \quad \kappa_{xy} = \frac{n^T r_{xy}}{||n||^3}$$  \hspace{1cm} (35)

where $n$ is the normal to the element mid surface such that: $n = r_x \times r_y$, and its norm is defined as $||n|| = \sqrt{n^T n}$.

It is important to note that the reference configuration defined by $|J|$ remains constant in the ANCF since nonincremental procedures are used, which do not require updating reference configuration. Using the gradient transformation, the strains of the curved configuration are expressed with respect to those defined in the element coordinate system. The effect of strains at the initially curved configuration is eliminated using Almansi strain [29].
5.3 Gravitational and Aerodynamic Forces. The generalized forces of an external force vector \( \mathbf{F} \) can be expressed as:

\[
Q = \int_{V_0} S^t \mathbf{F} dV_0
\]  (36)

The gravity force per unit volume of plate can be expressed as \( q_g \), where \( q \) is the density of the material, \( g = [0 \quad 0 \quad g]^T \) is the gravity acceleration vector. Hence, the generalized gravity forces can be written as:

\[
Q_g = \rho \int_{V_0} S^t g dV_0
\]  (37)

For free stream wind velocity \( V \), the aerodynamic loads are expressed in the following forms [30,31]:

\[
F_L = \frac{1}{2} \rho_a \cdot V^2 \cdot c \cdot C_L
\]  (38)

\[
F_D = \frac{1}{2} \rho_a \cdot V^2 \cdot c \cdot C_D
\]  (39)

where \( F_L \) and \( F_D \) are the lift and drag forces, \( \rho_a \) is density of air. The aerodynamics characteristics of the blade are determined through the lift and drag coefficients, \( C_L \), \( C_D \), respectively. The coefficients mainly depend on the flow angle of attack, \( \phi \); see Fig. 17. The angle of flow is measured from the inlet tangent to the mean camber line of the airfoil. The generalized forces due to aerodynamics load can be established by substituting the resultant force \( \mathbf{F}_R \) into Eq. (36). \( \mathbf{F}_R \) are distributed over a mid-line of the blade.

6 Dynamic Simulation

The dynamic simulation of a fixed cantilevered wind turbine blade is carried out using multibody system computer code, systematic analysis of multibody systems (SAMS2000) [32]. Three examples are carried out in order to demonstrate the use of the developed procedure for modeling large-size wind turbine blades. The numerical integration is carried out by using the sparse HHT integrator [19], with the following parameters: relative error: \( 1 \times 10^{-6} \), absolute error: \( 1 \times 10^{-6} \), and constraint tolerance: \( 1 \times 10^{-9} \).

The first example concerns fixed cantilevered blade with the following data: NACA 4412, chord length of \( c_1 = 2 \) m, span length \( L_s = 10 \) m, taper angle \( \alpha = 0 \) deg, twist angle \( \beta = 25 \) deg, plate thickness \( t = 15 \) mm. The Polyethylene which is isoparametric plastic material is chosen with modulus of elasticity \( E = 1 \) GPa, Poisson ratio \( \nu = 0.4 \), and density \( \rho = 1200 \) Kg/m³. The external force is considered to be the standard gravitational forces of the blade. In order to compare the results with other FEM codes, the ANCF model is converted to 2D sections and then to 3D parasolid models. This 3D model is used to construct the FEM model using the ANSYS code [33]; see Fig. 18. The FEM model of the blade is constructed using tetrahedrons meshing and consists of 4208 elements, 8359 nodes. It is observed that the numerical results of the ANCF model and ANSYS-FEM model are in good agreement; see Fig. 19. The difference between transverse deflection curves is due to the oscillatory nature of the ANCF model. This nature is the direct effect of the coupled deformation modes of the ANCF model [17] comparing with the smooth results of the ANSYS solution. It is found that, in the case of a very flexible structure, as in the case of large-size wind turbine blade, the inclusion of the ANCF-coupled deformation modes becomes necessary to obtain an accurate solution. Therefore, in this case, the use of the general continuum mechanics approach leads to an efficient solution algorithm and to more accurate numerical results.

The second example concerns fixed cantilevered tapered-blade with the following data: NACA 4412, chord length of \( c_1 = 3 \) m, span length \( L_s = 10 \) m, taper angle \( \alpha = 3 \) deg, twist angle \( \beta = 25 \) deg with the same material used in the first example. The ANSYS-FEM model is shown in Fig. 20. The transient solution...
Fig. 18  FEM blade model with ANSYS (nontapered blade)

Fig. 19  Transverse deflection of tip edge point

Fig. 20  FEM blade model with ANSYS (tapered blade)
due to gravity force is illustrated in Fig. 21. It is observed that, tapering the blade increases the difference between the transverse deflection curves of the two models, not only in the amplitude of the deflection but also in the periodic time (frequency) of the two models. To obtain good results, the authors believe that the non-conforming plate elements [34] produced due to the tapering property of the blade should be manipulated carefully. A modified mass matrix and elastic force vector should be estimated to take into account the nonconforming structure of the reference configuration of the plate elements. Other suggestion is increasing the number of elements along the span length of the tapered blade, which can decrease the error significantly. The results obtained in this section, encourage the authors to extend the work to formalize optimal design process for large-size wind turbine blades.

In the third example, the blade of the second example is subjected to air stream with velocity of 3 m/s. It is shown by Ref. [31] that the aerodynamics characteristics of NACA 4412 are as follows: mid-blade lift coefficient is \( C_L = 1.35 \) at flow angle of \( \phi = 12.5 \) deg, and drag coefficient of \( C_D = 0.03 \). Other values of the coefficients along the mid-line of the blade are obtained from Refs. 35 and 36. In order to compare the ANCF results with ANSYS, advanced coupled numerical method of computational fluid dynamics (CFD) module and computational flexible multi-body dynamics (CFMBD) module has been developed in order to investigate the aero elastic response of this example. The meshing domains of both the blade wall and fluid are shown in Fig. 22, while the ANSYS solution is shown in Fig. 23. The comparison between the transient responses of the ANCF and ANSYS-FEM models is shown in Fig. 24, the numerical results are in good agreement.
agreement with the same noticeable errors due to the nonconforming structure of the reference configuration of the plate elements.

7 Comments and Discussion

The numerical examples in the last section are addressed for six-elements blade model, i.e., only one section is considered along the span length of the wind turbine blade. In order to improve the dynamic simulation results, it is suggested to increase the number of elements along span length. Figure 25 shows different blade models with 1, 2 and 4 sections along the span length within 6, 12 and 24 elements, respectively. It is found that, as the number of degree of freedoms increases, the calculation time increases dramatically.

In the first numerical example, a reduced order dynamic model is obtained by excluding some gradients from the integration process. Several attempts of excluding gradients are carried out to maintain the correct results of the model with the remaining gradients at the nodal points. It is identified that the gradients of \( \partial r_1 / \partial x \), \( \partial r_2 / \partial x \), \( \partial r_1 / \partial y \), and \( \partial r_2 / \partial y \), introduce very high frequencies to the blade motion. If those frequencies are excluded, the numerical results expected to coincide with ANSYS simulation results. This is because the position vector \( r_1, r_2, r_3 \), and the gradients of \( \partial r_1 / \partial x \) and \( \partial r_3 / \partial y \) are “only” included in the numerical integration.

The dynamic simulation of the blade model of first example, in which, \( c = 2 \text{ m}, L_s = 10 \text{ m}, \beta = 25 \text{ deg} \) and \( x = 0 \text{ deg} \) is shown in Fig. 26. It shown that the transverse deflection of the 2- and
In this paper, an efficient procedure is developed for mapping NACA airfoil wind turbine blades into absolute nodal coordinate formulation (ANCF) models. The procedure concerned the wind turbine blade with the nonuniform, twisted nature. The variations of the cross sectional layouts across the blade is manipulated and the corresponding mapping equations are derived. Several examples of mapping various NACA airfoils are illustrated over the paper with good agreements.

The ANCF models of large-size wind turbine blades are solved using the IHT integrator implemented in SAMS2000 code, which is used for dynamic simulation of the developed blade models. The ANCF blade model is converted to 3D parasolid, which can be invoked by ANSYS code for comparisons. Regardless, the oscillatory nature of the ANCF response, the numerical results show a very good agreement in transient solution of straight (Nontapered) blade due to gravitational forces. Noticeable difference is in the case of tapered blades due to the nonconforming structure of the plate element in the reference configuration. It is found that, in the case of a very flexible structure, as in the case of large-size wind turbine blade, the inclusion of the ANCF-coupled deformation modes becomes necessary in order to obtain an accurate solution. In conclusion, the simulation results show a numerical convergence and good accuracy. Since the ANCF is suited for rate solution. In conclusion, the simulation results show a numerical convergence and good accuracy. Since the ANCF is suited for rate solution.

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Nomenclature

\[ \begin{align*}
C_p & = \text{drag force coefficient} \\
C_l & = \text{left force coefficient} \\
e & = \text{vector of absolute nodal coordinates} \\
E & = \text{Young's modulus of elasticity} \\
e & = \text{stream vector} \\
F & = \text{external force vector} \\
g & = \text{gravity acceleration constant} \\
g & = \text{gravity acceleration vector} \\
h & = \text{maximum thickness of airfoil (parametric)} \\
\eta & = \text{parametric position along y-axis} \\
J & = \text{initial position gradient matrix} \\
\kappa & = \text{curvature vector} \\
L_0 & = \text{span length of wind turbine blade (m)} \\
m & = \text{maximum camber (parametric)} \\
M & = \text{mass matrix} \\
n & = \text{normal vector of the midplane of the plate} \\
\nu & = \text{Poisson ratio} \\
p & = \text{mass density} \\
Q & = \text{generalized force vector} \\
Q_e & = \text{generalized external force vector} \\
Q_g & = \text{generalized gravity force vector} \\
Q_e & = \text{generalized elastic force vector} \\
r & = \text{position vector in the global coordinate system} \\
r_L & = \text{longitudinal gradient vector} \\
S & = \text{shape function matrix} \\
t & = \text{thickness of plate element (m)} \\
T & = \text{kinetic energy} \\
U & = \text{potential energy} \\
V & = \text{volume of plate element} \\
x & = \text{vector of local coordinates (x, y, z)} \\
z_c & = \text{camber line position coordinates z-axis (parametric)} \\
z_{th} & = \text{thickness distribution of the NACA airfoil (parametric)} \\
\phi & = \text{flow angle} \\
\xi & = \text{parametric position along x-axis}
\end{align*} \]

References


