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# Dynamic Response of Flexible Wind Turbine Blade

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***Abstract***

*Aiming at the non-stationary and stall flutter problems of wind turbine blade caused by transient load fluctuations, the dynamic properties of wind turbine were studied, the blade was simplify to a cantilever beam in case of the action of shear deformation and cross section rotating effect were considered in this analysis, equations of the blade were established based on D'Alemberts' principle and the principle of virtual displacement. The dynamic response of the wind turbine was solved by using the finite element method under the transient load environment. A 29.2m rotor blade, previously reported in specialized literature, was chosen as a case study to validate dynamic behaviour predicted by a Timoshenko beam model. It is concluded that despite its simplicity. The cross-sectional shear-deformation has great influence on dynamic response of the blade. Dynamic model is sufficiently accurate to serve as a design tool for the recursive analyses required during design and optimization stages of wind turbines using only readily available computational tools.*

***Keywords:*** *shear deformation, the flexible blade, dynamics, vibration*



## 1. Introduction

An important aspect in wind-turbine technology nowadays is to reduce the uncertainties related to blade dynamics by the improvement of the quality of numerical simulations of the fluid-structure interaction process.The continuing growth of the unit size of commercial wind turbines with current installed capacities of up to 6MW, with rotor diameters of up to 127m. This tendency is driven by economies-of-scale factors that substantially reduce the cost of wind energy. This often leads to contradictory goals, such as the design of stronger and larger yet thinner and lighter rotor blades. In addition to deter-ministic loads because of gravity and centrifugal forces.

The blade of horizontal axis wind turbine is with some of the features such as long span wise, short and flexible, for the time being, It is easy to have the phenomenon of vibration and deformation. Due to the variability of wind on space time, the effect on wind turbine blade crossed by wind is also very completely, and the vibration and deformation will give rise to additional stress and influence it's structural strength. Hence, an important aspect in wind-turbine technology nowa-days is to reduce the uncertainties related to blade dynamics, by the improvement of the quality of numerical simulations of the [1]. The goal is to provide the industry with a tool that helps them to introduce new technological solutions to improve the economics of blade design.

The current state-of-the-art is to solve the aeroelastic equations in a fully nonlinear coupled mode using Bernoulli or Timoshenko beam models [2], where a thorough coverage of the topic is presented. G [3] introduced the finite element method to study the vibration stability of wind turbine blade and discussed the influence on modal of different fiber ply angle. W.C.de Goeij at all [4] used the finite element method makes a study about the bending and torsion coupling model of the blade under aero elastic environment. By applying a beam theory of composite material combined with the finite element method, S.Y.Oh, O.Song, L. Librescu [5-7] predicted the static response of the blade and the dynamic response.

Without damp, the dynamics model of the blade were established in [8] and aerodynamic performance and dynamics of the wind turbine structure were calculated. However, there is still a lack of an integrated simulation model for the time-domain simulation analysis with dynamic conditions of the wind turbine.

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A representative 29.2m rotor blade, typically used in wind turbines rated at about 1200kW, was chosen for the purpose of numerical validation. This paper considered the rotation effect of cross-section and the shear deformation, using the finite element method to solve the dynamic equations of blade, and designed the computer program for calculating the dynamic response of a 1.2MW wind turbine under impact loading, for the time being, the trend of the parameters over time is analyzed.

## 2. Blade Coordinate System

Figure 1 shows a generic Timoshenko beam element of a typical wind turbine blade, The origin of the main coordinate system (CS) x; y; z is placed at the pole p, displacements of the pole p of an arbitrary point located on the blades cross-section the x, y, z coordinates are denoted by x1, y1, z1,and x2, y2, z2 are as the local coordinate system of arbitrary cross-section with deformation [9]. Based on beam small deformation assumptions, in order to simplify the problem and obtain the deformation of any point of the blade, The Timoshenko beam is based on the following assumptions:

(1) Small strains;
(2) The material of blade is homogeneous and isotropic;
(3) All deformation are all slight deformation to ensure the elasticity theory of solid mechanics are still valid.

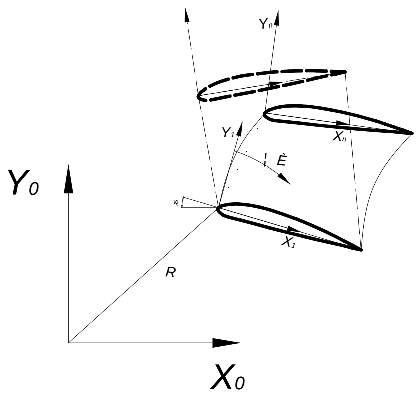


Figure 1. Blade Coordinate System

Based on these assumptions and with the reserves mentioned, the cross-section displacement field can be expressed as:

$$\Delta p = \begin{Bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{Bmatrix} = \begin{Bmatrix} u + z\theta_y - y\theta_z \\ v - z\theta_x \\ w + y\theta_x \end{Bmatrix} \tag{1}$$

$$\Delta p = \begin{bmatrix} 1 & 0 & 0 & 0 & z & -y \\ 0 & 1 & 0 & -z & 0 & 0 \\ 0 & 0 & 1 & y & 0 & 0 \end{bmatrix} \begin{Bmatrix} u \\ v \\ w \\ \theta_x \\ \theta_y \\ \theta_z \end{Bmatrix} = Aq \tag{2}$$

Figure 1 shows the translational any point p in the blade cross-section defined as u, v, w, and the rotation is $\theta_x, \theta_y, \theta_z$, where, A-coefficient matrix corresponds to the vector q, q-a variable vector described .the deformed state of P. of a point of thc deformed beam is defined as:

$$q = \begin{bmatrix} u & v & w & \theta_x & \theta_y & \theta_z \end{bmatrix}^{\mathrm{T}} \tag{3}$$

The expression of the relationship of the point p in the inertial coordinate system is as follows:

$$p = R + T(i\{1 \quad 0 \quad 0\}, \varphi) A \cdot q \tag{4}$$

$$B = T(i\{1 \quad 0 \quad 0\}, \varphi) A \tag{5}$$

And,

$$p = R + Bq \tag{6}$$

Where R-a vector point to an arbitrary cross-sectional coordinates x1, y1, z1 origin at the origin of the inertial coordinate system, $\varphi$ refer the angle of attack of the arbitrary cross section.

## 3. The Governing System

The governing equations and boundary conditions can be systematically derived via the Extended D'Alembert's principle, which is defined as:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial q_i}\right) - \frac{\partial L}{\partial q_i} + \frac{\partial U}{\partial q_i} = Q_i \tag{7}$$

Where U and L denote potential energy and kinetic energy, respectively, while $q_i$ the generalized coordinate, Q is the generalized force of generalized force the system.

### 3.1. The Kinetic Energy of Blade

$$L = \frac{1}{2}\int_m p^{\mathrm{T}} p d_m \tag{8}$$

$$L = \frac{1}{2}\rho_m \int_v (R + Bq)^{\mathrm{T}} p_u^{\mathrm{T}} p_u (R + Bq) d_v \varpi^2 + q^{\mathrm{T}} \frac{1}{2}\rho_m \int_v B^{\mathrm{T}} B dv q + q^{\mathrm{T}} \rho_m \int_v B^{\mathrm{T}} p_u (R + Bq) dv \theta \tag{9}$$

In these equations $\rho_m$ denotes the density of material. The former is due todenote the kinetic energy of the rigid rotation of the blade about the unit vector i with the angular speed θ, the second item denotes the kinetic energy of the blade caused by the deformation; the third term is the kinetic energy coupled by the rigid motion and the deformation of the blade.

### 3.2. The Potential Energy of Blade

According to a modification equation (1) of the blade, the strain of the blades is expressed as:

$$W_T = \int \frac{1}{2} p_a c v_r^2 (C_L \sin(\alpha + \beta) - C_D \cos(\alpha + \beta)) \theta dx \tag{10}$$

And the potential energy is as the follows:

$$V = \frac{1}{2}\int_v E\varepsilon_x{}^2 d_v + \frac{1}{2}\int_v G\gamma_{xz}{}^2 d_v + \frac{1}{2}\int_v G\gamma_{xy}{}^2 dv \quad (11)$$

In which, E denotes the elastic modulus, while G denotes the shear modulus.

### 3.3. Gravity Power

During rotation time, blades always subjected to the action of gravity, the gravity force component in each axis are different with the different blade rotation azimuth, (the azimuth angle is zero when the axis is horizontal), and due to the existence of the axis inclination angle θ, the gravity component of blade surface was also calculated.

Where:

$$dF_g = T(i\{1 \quad 0 \quad 0\}, \beta)$$
$$T(i\{i_x \quad i_y \quad i_z\}, \theta)\begin{Bmatrix} 0 \\ -g \\ 0 \end{Bmatrix}\rho_m \int A d_x \quad (12)$$

Where g is the acceleration of gravity, the work done by gravity on the blade is the blade element acting integrating.

### 3.4. Wind Power

The force acted on the blades of the wind can be represented as follows according to Reference [10].

$$dP = \frac{1}{2}\rho_a c C_l v_r{}^2 dx \quad (13)$$

$$dT = \frac{1}{2}\rho_a c C_d v_r{}^2 dx \quad (14)$$

In which, $v_r$ is relative wind speed give by:

$$v_r{}^2 = \chi\beta + (R\varpi)^2 \quad (15)$$

In the following developments, Where $C_l$ , $C_d$ , $C_d$ and $v_r$ represent the lift coefficient, the drag coefficient, the chord length of the current cross-sectional, and the relative wind speed. $v_r{}^2 = v_\infty{}^2 + (R\varpi)^2$ ( $v_\infty{}^2$ is the absolute wind speed, R, $\varpi$ , $\alpha$ and $\beta$ are the rotation radius of blade element, rotation angular velocity of blade), the twist angle of the blade element and scored the angle of the blade element.

$$dW_a = \frac{1}{2}\rho_a c v_r{}^2 \left[0 \quad C_l\cos\beta + C_d\sin\beta \quad C_l\sin\beta - C_d\cos\beta \quad 0 \quad 0 \quad 0\right] \quad (16)$$

Based on Equations (7)–(16) and using a standard displacement-based Lagrangian formulation, the discrete equations of motion for a generic beam element can be expressed as follows:

$$[M]\{\ddot{q}\} + [C]\{\dot{q}\} + [K]\{q\} = \{F]\} \quad (17)$$

Where $[M]$ and $[K]$ are the element's mass and stiffness matrices $[C]$ is a hysteretic damping matrix, $\{F\}$ is a vector of nodal forces and $\{q\}$ ; $\{\dot{q}\}$ and $\{\ddot{q}\}$ are nodal displacement, velocities and accelerations, respectively.

## 4. Applications

In order to assess the accuracy of the dynamic model ,the dynamic response of a 1.2MW wind turbine blade were calculated and analyzed by programming based on the above theory, the wind turbine is composed by three blades, and the length of each blade is 29.2 meters, the ratio of rotor is 62.5 meters, the hub height is 67 meters. For geometric modelling purposes, the external geometry of the blade was divided in spanwise direction into three clearly defined regions, as shown in Figure 2: the root, a cylindrical-shaped portion located between x=0 (the root end) and x=1.5m with a constant external diameter (or chord) given by(Root= 3.5m; the transitional region, morphing via a non-linear chord variation (given by polynomial Trans.

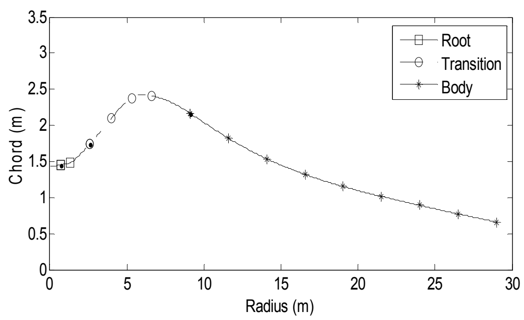


Figure 2. Blade Radius with the Chord Length

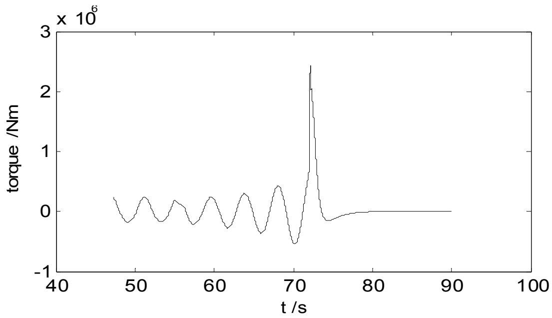


Figure 3. Blade Torque changes with Time

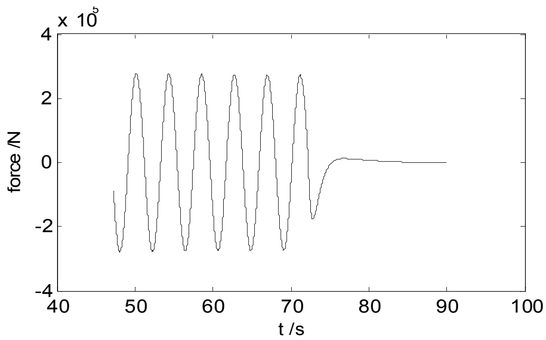


Figure 4. Blade Lift changes with Time

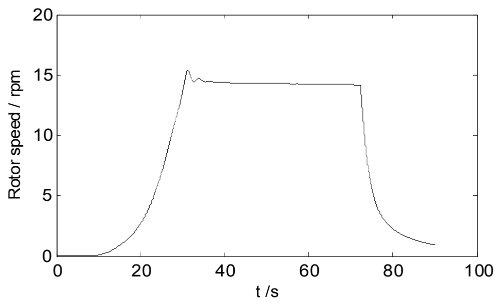


Figure 5. Blade Rotation Speed changes with Time

Figure 3 shows the trend of the thrust and torque of the blade are similar with wind farm trend, However, due to the rotation of rotor, the inducing factor, blade thrust and torque mainly manifest as periodic change. The force starts at a position of t= 45s, when t was increased to 70 seconds, there is a sudden change on wind speed, and the torque increases rapidly, then, the control system starts to adjust the paddle angle to maintain the work of wind turbine in the vicinity of the rated power.

As shown in Figure 4, The torque value is in a certain fixed range due to the presence of the fluctuations of the wind speed and a control system lag, and the rotor speed cannot keep track of the changes in the wind speed.

The wind speed reached start-up requirements of wind turbine, the blades began to work, and wind speed gradually increasing to the rated wind speed(12m/s), When t =10s, wind turbine began generating electricity, When t=25s, the rotation movement of wind turbine blade excite by the coupling of aerodynamic and inertial loads, the load of blade changed a slight vibration load from cyclical changes. When t is in the range of 70～72 s. applying a transient load on wind turbine and the torque increased sharply. After 70 s, wind turbine gradually stops running with the decrease of the wind load.

## 5. Conclusion

(1) A dynamical theory of rotating blades modeled as Timoshenko beam of arbitrary cross-sections obtained via the D'alembert's principle is developed. Finally the kinetic equation may be established using the finite element method, and realized the solving method of the dynamic response under time-varying loads.
(2) Large scale horizontal axis wind turbine bears greater vibration and deformation, it is not only affect the whole stability of wind turbine, but also affect the aerodynamic performance of the blade itself, therefore, dynamic response analysis of the blade should be done in the design process.
(3) The coupling effect of instantaneous load, aerodynamic and inertial force has a greater impact on the response of the blade, It can be more accurately to predict the blade vibration and deformation, if they were taken into account during the simulation.

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