Journal of Sound and Vibration 432 (2018) 653–679

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

# Aeroelastic modeling and dynamic analysis of a wind turbine rotor by considering geometric nonlinearities

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ARTICLE INFO

*Article history:*
Received 12 March 2018
Received in revised form 25 June 2018
Accepted 27 June 2018

Handling Editor: H. Ouyang

*Keywords:*
Geometric nonlinearity
Wind turbine rotor
Aeroelastic analysis
Whirling mode
Stability

ABSTRACT

Due to the increased flexibility of modern multi-megawatt wind turbine structures, more advanced analyses are needed to investigate the effects of geometric nonlinearities originating from large blade deformations under operational loads. The main objective of this paper is to study the related dynamics and the aeroelastic effects of these nonlinearities by using a multi-flexible-body aeroelastic model of an entire three-bladed wind turbine assembly instead of a more conventional single-blade model. A geometrically-exact beam formulation is employed to model the rotating blades connected to the wind turbine tower tip via hub and nacelle components; and the revolute joint constraint is applied to model the rotor rotation. The derived governing equations are analyzed by applying a reduced-order approach based on the Galerkin method. After verifying the model by comparing it with an FEM model, it is used in several aeroelastic and dynamic studies. All the performed simulations are based on the specifications of the state-of-the-art 5 MW-NREL wind turbine. Moreover, the time-invariant forms of the governing equations are derived by applying the multi-blade coordinate transformation method. The obtained equations are used to study the whirling characteristics of wind turbine rotor by different models including the model of unloaded blades as well as the linear and nonlinear aeroelastic models. The eigenfrequencies indicate the splitting characteristics according to the gyroscopic effects that originate from the whirling motion in the forward and backward directions. The simulation results reveal that single-blade models are helpful in demonstrating the overall trends of rotor aeroelasticity. However, because single-blade models overestimate the instability limits, an analysis based on a full wind turbine model is crucial. Besides, the geometric nonlinearities significantly alter the eigenfrequency results (especially for the modes dominantly incorporated into flutter instability) as well as the dynamic responses of the system, notably around the flutter speed.


## 1. Introduction

The recent developments and advancements in wind energy technology have led to a steady growth in the capacity and size of modern wind turbines. This trend is expected to continue in the future, especially in offshore applications [1]. In this

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https://doi.org/10.1016/j.jsv.2018.06.063
0022-460X/

regard, some academic research and industrial efforts are underway to develop a 10 MW wind turbine with rotor blades of 140 m diameter [2,3]. Nevertheless, the weight limitation issue has become a great challenge to the enlargement of wind turbines and has forced the engineers to design lighter structures that meet the mandatory strength requirements. These constraints have led to the design of more flexible wind turbine structures and, especially, turbine blades, which are designed for dynamic loading. This greater structural flexibility could result in large deformations under aerodynamic loading, even under nominal operating conditions [4,5]. In these cases, although the strains remain small, special nonlinearities (called geometric nonlinearities) are introduced into the system by the large rotations arisen from elastic structural deformations [6]. Recent research works on the aeroelastic behavior of wind turbines [4,5,7–10] have demonstrated that geometric nonlinearities affect all aspects of these structures including their stiffness and mass characteristics as well as aerodynamic loadings.

In most of the former research works, turbine blades have been structurally analyzed by means of beam models that provide sufficiently accurate results at a fair computational cost. The analytical results may be improved by using higher order beam models such as VABS [11] or beam models developed based on the advanced theories of thin-walled composites [12]. However, because geometric nonlinearities predominantly affect the overall dynamics of a system, the majority of previous research works have used nonlinear Euler-Bernoulli beam models to avoid the extra complexity generally introduced by considering the effects of geometric nonlinearities. Using a reduced-order model (ROM) in the flapwise and edgewise directions, Larsen and Nielsen [7] studied the effects of structural nonlinearities for a rotating wind turbine blade subjected to constant aerodynamic forces. They further used their developed model to explore the role of blade root harmonic motion in the stability characteristics of rotating blades [8]. Wu et al. [13] employed a geometrically-exact beam formulation to study the large deformations of a rotating blade by means of a finite element model (FEM). Rezaei et al. [4] used a similar formula for modeling a 5 MW-NREL wind turbine blade and studied the effects of geometric nonlinearities for different strains and loading conditions. The developed model was further extended to quasi-steady and unsteady aerodynamic analyses considering the nonlinearities associated with aerodynamic loading [5]. The investigations showed the importance of considering the torsion induced by large blade deformations in the lateral direction and the effects of these deformations on the flutter instability of rotating blades.

Although the crucial effects of geometric nonlinearities on the dynamic and aeroelastic characteristics of modern wind turbines have been well demonstrated in recent works, most of the reported results are based on single-blade models that completely ignore the flexibilities of wind turbine tower and the other blades. Therefore, it is essential to investigate the effects of tower flexibility and interactions with rotor blade dynamics on the aeroelastic behavior of entire wind turbine systems. Lee et al. [10] presented a multi-flexible model of a two-bladed wind turbine and employed the FEM to obtain the eigenvalues of the free loaded system. In another work [14], the component mode synthesis method and a linear wind turbine model were used to obtain the transient dynamic responses. Thomsen et al. [15] presented a novel experimental technique for measuring the aerodynamic damping of edgewise blade vibration and demonstrated that the total damping of the system is significantly affected by the whirling motion of rotor. They concluded that it is essential to analyze an entire wind turbine system rather than a single blade, especially when trying to predict turbine stability. Using a linear three-bladed wind turbine model, Hansen et al. [16] derived the time-invariant forms of governing equations by applying the multi-blade coordinate transformation method (also called the Coleman transformation). They analyzed the dynamic behavior of a blade in the forward and backward whirling modes. Bir [17] used the same technique for studying the frequency and damping trends of a 5 MW-NREL wind turbine blade at different rotational speeds. In another work [18] on a wind turbine rotor with anisotropic blades (a rotor with different blades for which the Coleman transformation could not be applied), the more general Lyapunov-Floquet transformation method was employed to obtain the time-invariant forms of governing equations.

Most of the former research works on the dynamics and stability of wind turbine rotors have used simplified aerodynamic models. However, these studies have specifically emphasized the necessity of analyzing the dynamics of entire wind turbine systems; which yield noticeably different results from those predicted by common single-blade models. The observed differences are predominantly due to the flexible blade-tower interactions. Such interactions are intensified under operating conditions in which the aerodynamic loading on blades is directly affected by tower motion. On the other hand, the mentioned influences may be greater in more recent wind turbines in which the large deflections of blades in operation directly affect the angles of attack. This issue definitely has a significant effect on the aeroelastic characteristics of wind turbine systems.

In this paper, the governing equations are developed for the aeroelastic model of a multi-flexible wind turbine system. This model considers the effects of geometric nonlinearities on the structural blade dynamics as well as the aerodynamic loads on blades. The developed ROM is used in the dynamic and aeroelastic simulations of a reference 5 MW-NREL wind turbine. Moreover, the effects of blade-tower interactions on the aeroelastic characteristics of the examined wind turbine are investigated, and the aerodynamic models customarily used in the literature are compared and evaluated.

## 2. Aeroelastic model and structural dynamics

In this section, the governing equations are derived for the aeroelastic model of a multi-flexible 3-bladed wind turbine system under operational loading. The schematic of this wind turbine, including the tower, nacelle, hub and blade components, is illustrated in Fig. 1. The flexibility of this system is mainly due to the flexibilities of tower and blades components. Therefore, similar to most previous studies that have employed full wind turbine models, the nacelle and hub components are