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Flexible multibody dynamic modeling of a floating wind turbine

Mohammed Khair Al-Solihat*, Meyer Nahon

Department of Mechanical Engineering, McGill University, Montreal, Canada

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ABSTRACT

This paper presents a modeling approach for the nonlinear flexible dynamics simulation of a floating offshore wind turbine (FOWT). The system consists of a floating platform, the moorings, the wind turbine tower, nacelle and the rotor. The floating platform is modeled as a six-degrees-of-freedom (6-DOF) rigid body subject to buoyancy, hydrodynamic and mooring loads. The wind turbine tower is modeled as a three-dimensional (3D) damped tapered Euler–Bernoulli beam undergoing coupled general rigid body and elastic motions. The beam bending-bending and twist motions are considered. The nacelle is modeled as a rigid body attached to the tower tip. The rotor is also modeled as rigid body spinning around its axis and subject to aerodynamic load. The generator torque control is integrated into the model to capture the rotor spin dynamics. The equations of coupled rigid body and elastic motions are derived using Lagrange's Equation in terms of the generalized flexible coordinates and the platform quasi coordinates. The external loads are formulated and incorporated into the system equations of motion. The dynamic model is extensively validated against the most popular FOWT simulation tools with an excellent agreement. Finally, the influence of the tower flexibility on the FOWT dynamic behavior is investigated.

1. Introduction

The harvesting of ocean wind power could constitute an abundant source of low cost energy. Installing wind turbines on floating platforms far offshore, where the wind is stronger and steadier, maximizes the obtained wind power. Moreover, offshore placement avoids the problems associated with noise and visual impacts. Therefore, several floating offshore wind turbine (FOWT) concepts are increasingly being proposed utilizing the same floating platforms concepts conventionally used for offshore oil and gas industry [1].

Owing to the increasing interest in wind energy, several flexible dynamic models for land-based wind turbines have been proposed in the literature. Wang et al. [2] developed a theoretical nonlinear aeroelastic model validated with experiment for a wind turbine blade with consideration of large blade deflections. Larsen and Nielsen [3] developed a nonlinear dynamic model for a land-based wind turbine structure considering the tower and blades flexibility. The model included geometric nonlinearities caused by the structure deflections. Kessentini et al. [4] conducted a modal analysis using a linear dynamic model considering the flapping deflections of the tower and blades. The effects of pitch angle and blade orientation on the wind turbine natural frequencies and mode shapes were also investigated. Lee et al. [5] presented a multibody dynamics model for the wind turbine considering the coupled dynamics among the rigid body (nacelle and hub) and flexible (tower and blades) subsystems assuming a prescribed rotor speed to determine system natural frequencies and mode shapes. Recently, several studies proposed flexible multibody dynamic models of a blade with consideration of the bending and torsion to investigate the aeroelastic behavior of the NREL 5MW wind turbine [6,7] and predict the blade deflection transient response, and rotor thrust and power performance. Most recently, CFD codes are being coupled with multibody dynamic models of the wind turbine to better predict the unsteady aerodynamic loads e.g. [8,9].

Few theoretical rigid body dynamic models of FOWTs have been presented in literature. Matsukuma and Utsunomiya [10] developed a multibody dynamic model of a 2 MW spar FOWT assuming steady wind and still water. The influence of gyroscopic moment due to the rotor spin was found to be considerable on the system dynamics. Wang and Sweetman [11] developed a rigid multibody dynamic model for a tension leg FOWT. The equations of motion were formulated using a Newton Euler approach. Sandner et al. [12] presented a spar FOWT model based on the OC3 design concept. Simple aerodynamic, hydrodynamic models were integrated to simulate the system response in combined wind and wave loads. None of these works considered the elastic motion of flexible components and the coupling among the flexible and rigid body motions although it can be important.

The flexible coupled dynamic analysis of FOWTs can be performed using design codes such as FAST, HAWC2, and GH Bladed. These codes incorporate aerodynamic, structural dynamics, hydrodynamic, control and cable models to capture the dynamic response to the environmental loads [13,14]. A thorough review for the design codes of FOWTs, their capabilities, and the techniques they adopted to model the system

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* Corresponding author.
E-mail address: solihat@cim.mcgill.ca (M.K. Al-Solihat).

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structural dynamics and the fluid-structure-interactions can be found in [14]. However, the theoretical manuals of these codes [15–18] only present the theory related to the flexible dynamics of the tower and blades, while the coupled dynamics of the platform undergoing general motion is not formulated even though it has a large impact on the system dynamics. Thus, the theoretical approaches presented in these manuals are only sufficient to analyze fixed-bottom wind turbines while the flexible multibody dynamics of FOWTs are far more complex. Moreover, most these codes use simplified linear structural models which could lead to inaccurate results if the structure experiences large deflections [3].

Coupled rigid-flexible multibody dynamics is a topic of importance in the dynamics of aerospace systems and flexible manipulators. Meirovitch and Tuzcu [19] developed a flexible multibody dynamic model of an aircraft. The coupled rigid-flexible dynamic equations of motion were derived using Lagrange's equations in terms of quasi-coordinates. This form of Lagrange's Equations was previously derived by Meirovitch using the Extended Hamilton's Principle [20,21]. Later on, Meirovitch's theory was adopted in many dynamic analyses of flexible aircrafts such as [22,23]. On the other hand, among recent works on flexible manipulators, Zhang et al. [24] investigated the coupled dynamic characteristics of flexible-rigid body motions of a planar parallel manipulator with three flexible intermediate links. Korayem and Shafei [25] presented an analytical dynamic modeling approach for *n*-viscoelastic-link robotic manipulators mounted on a mobile platform. The flexible link motions were modeled using Timoshenko beam theory while considering the longitudinal and torsion elastic motions.

The main objective of this research is to build a high-fidelity structural dynamic model of a FOWT in which the coupling between the rigid body (arising mainly from the platform motion) and the tower elastic motions are considered to formulate the system dynamics. Approximate aerodynamic and hydrodynamic and mooring models are then utilized to predict their corresponding loads. The present study constitutes the first validated theoretical flexible multibody dynamic model for a FOWT in literature. The model is developed for a spar FOWT based on the OC3-Hywind concept [26]. The analysis begins with the formulations of the kinematics of the rigid and flexible bodies. Then, the equations of motion of the coupled rigid body and elastic motions are derived. A nonlinear quasi-static model is utilized for computing the mooring loads. The fluid-structure interaction forces models, including hydrostatic, hydrodynamics and aerodynamics, are incorporated into the system dynamics and eventually simulate the dynamic time response. Unlike most existing codes, the present model considers finite rigid body rotations and large flexible motions. As well, nonlinear beam deformations are utilized to characterize the elastic rotation matrix (considering the tower twist). Finally, the internal structural damping of the tower is formulated, which is essential to predict the elastic motion responses and enhance the simulation's numerical stability.

2. System description

A schematic diagram of the spar FOWT system to be analyzed is shown in Fig. 1. The coupled rigid-flexible multibody dynamic model is comprised of 3 rigid and 1 flexible bodies, ordered as depicted in Fig. 1.

- **Body 1**: the floating platform, with mass m_p, and inertia tensor $\mathbf{I}_p = diag(I_{px}, I_{py}, I_{pz})$. This platform has been proposed to support the NREL 5 MW baseline wind turbine [27].
- **Body 2**: the nacelle, a rigid body, with mass m_{nc}, and inertia tensor $\mathbf{I}_{nc} = diag(I_{ncx}, I_{ncy}, I_{ncz})$.
- **Body 3**: the rotor, a rigid disc spinning around its axis with angular velocity $\Omega(t)$. The mass is m_r, and inertia tensor $\mathbf{I}_r = diag(I_{rx}, I_{ry}, I_{rz})$.
- **Body 4**: the tower, a flexible tapered 3D beam of annular circular section. The beam is of length l, density ρ_t, and variable cross sectional area per length $A_t(z)$. The moments of inertia of the cross section as functions of the tower height around the x_1 and y_1 axes are $I_{t,\,xx}(z)$ and $I_{t,\,yy}(z)$, respectively. The corresponding polar moment of inertial is $J_t(z)$. The material properties of the beam are characterized by Young's modulus E and modulus of rigidity G.

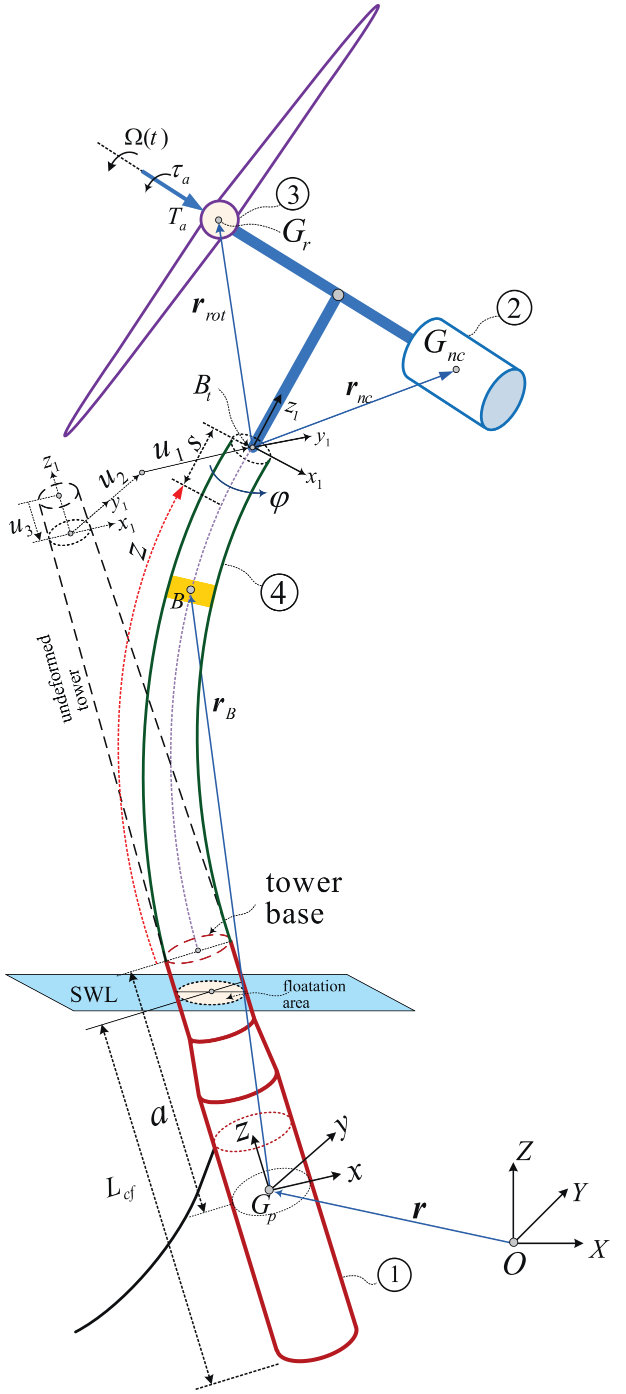

Fig. 1. Schematic diagram of the spar FOWT multibody dynamic model showing the system components and kinematics.

The platform floats in sea water of density ρ and is anchored to the seabed by a catenary mooring system comprised of three lines. The platform, tower, nacelle and rotor related dimensions and mass and inertial properties are available in [26,27]. In this work, the rotor blade flexibility is ignored such that the rotor is modeled as a rigid body and thus the aeroelastic behavior of the turbine blades are not considered. This assumption is expected to have minimal impact on the platform