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A coupled finite difference mooring dynamics model for floating offshore wind turbine analysis

Lin Chen[a], Biswajit Basu[a,*], Søren R.K. Nielsen[b]

[a] School of Engineering, Trinity College Dublin, Dublin 2, Ireland
[b] Department of Civil Engineering, Aalborg University, 9000 Aalborg, Denmark

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ABSTRACT

This study develops a coupled nonlinear hydrodynamic model of a mooring system consisting of multiple cables for analyses of floating offshore wind turbines (FOWTs). The model is based on a finite difference model of submerged cables which considers cable-seabed interaction, current effect, cable bending and torsional stiffness. The implementation of the model proposes a parallelization scheme for solving the cable responses to improve the computational efficiency. The developed program is then coupled with a spar type FOWT and verified using an experimentally validated open source mooring simulation program. Furthermore, the model is used to study the impact of nonlinear dynamics of the mooring system on FOWT responses in the presence of current. Both static responses of a spar FOWT under current load and dynamic responses of the spar FOWT under wind, wave and current loads are investigated. Responses are compared where varied mooring models are used including the linear model, quasi-static model and nonlinear mooring models without and with current effect on cables considered. The results show that the current effect on cables can have a considerable impact on the restoring effect of the mooring system and hence the spar and cable responses. The current effect on mooring cables needs to be properly considered in the FOWT analysis.

1. Introduction

Offshore wind energy is one of the most promising renewable energy solutions (EWEA Business Intelligence, 2015). Modeling floating offshore wind turbines (FOWTs) is the key for commercializing current concepts at water depth beyond 45 m (James and Ros, 2015). The nonlinear mooring dynamics is one of the challenging tasks in modeling offshore floating structures (Butterfield et al., 2005; Matha et al., 2011).

Mooring cables have been modeled as linear or nonlinear springs in earlier dynamic analysis of offshore moored structures (Jain, 1980; Sannasiraj et al., 1998). The linear or nonlinear stiffness is determined based on the initial cable profile or from the cable profiles for a number of prescribed platform displacements (Jonkman, 2007). Quasi-static models have been also widely used, which solve a new static problem for each updated cable fairlead position. The linear and quasi-static models are mainly based on the analytical catenary solution (Irvine, 1981). The classic catenary soltuion has also been extended to include seabed friction (Jonkman, 2007; Jonkman et al., 2009) and to deal with multi-segment mooring cables (Masciola et al., 2013). The improved quasi-static model has been implemented in the widely used offshore wind turbine analysis tool FAST (Jonkman, 2007; Jonkman and Matha, 2011; Masciola et al., 2014).

The quasi-static model can account for part of the nonlinear cable behavior compared to the linear model. However, it still lacks in the description of the hydrodynamic effect in particular the damping effect owing to the hydrodynamic drag forces while the damping was found to have considerable impact on cable responses (Johanning et al., 2007). A nonlinear dynamic model can additionally include the cable inertia effect and current load which can not be considered in the aforementioned two methods. It can also account for the coupling effect of in-plane and out-of-plane cable motions. Nonlinear models generally require more computational effort while with the advancement of computational techniques they are gaining more attention recently for offshore renewable energy. Some recent comparison studies have demonstrated the importance of nonlinear cable dynamics in numerical analysis of offshore renewable applications (Fitzgerald and Bergdahl, 2008; Kim et al., 2013; Karimirad and Moan, 2012; Jeon et al., 2013; Masciola et al., 2013; Hall et al., 2014; Azcona et al., 2017b).

There are mainly four different models for nonlinear mooring dynamics, i.e. lumped mass model which dates back to Walton and Polachek (1960), finite element model based on rod theory (Garrett, 1982), finite difference model and multi-body dynamics model

* Corresponding author.
E-mail addresses: l.chen.tj@gmail.com (L. Chen), basub@tcd.ie (B. Basu), srkn@civil.aau.dk (S.R.K. Nielsen).

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(Kreuzer and Wilke, 2003). In fact, a number of finite element models are available, for instance, the typical model ignoring cable bending stiffness (Aamo and Fossen, 2000) and the comprehensive one including both bending and torsion effects (Buckham et al., 2004), to name but a few. The most widely used finite difference model is based on a Lagrangian formulation of the cable motion (Bliek, 1984; Tjavaras, 1996). However, mooring cable modeling is still a topical research area due to the complexity of this problem, even though these fundamental investigations have been carried out decades ago. Recent studies have focused on extending and validating these models, and the use of them in coupled analysis. For example, Hall and Goupee (2015) and Azcona et al. (2017a) have validated two lumped mass models respectively, Palm et al. (2013, 2017) improved the finite element model for handling snap loading in cables, and Antonutti et al. (2018) has modeled the mooring cables using an open source finite element modeling library. In particular, two open source mooring codes have been developed and coupled to FAST for offshore wind turbine analysis, the lumped mass model by (Hall and Goupee, 2015) and the finite element model by (Bae, 2014).

However, in the dynamic mooring models, the current effect on cables has not received adequate attention. For example, to the best knowledge of the authors, the two dynamic models used in the present version of FAST have not provided the capability to include the current load on cables. Therefore, this study aims at developing a dynamic mooring system model considering the current load and further to study the impact of nonlinear mooring dynamics on the FOWT responses in the presence of underlying current. The finite difference model developed by (Bliek, 1984; Tjavaras, 1996) is adopted for describing the cable mechanics, which is comprehensive as it is able to consider the cable bending and torsional effects, the nonlinear strain and stress relationship and drag and inertia effects of the surrounding flow. It is also relatively simple to implement. The issue of numerical drift for computing cable displacement using this model has been recently tackled by Gobat and Grosenbaugh (2006), making it further robust. This model has been widely used for modeling riser dynamics (Chatjigeorgiou et al., 2008; Katifeoglou and Chatjigeorgiou, 2012) while it has not been coupled with FOWTs.

The rest of this paper is organized as follows. Section 2 introduces the single cable mechanics and develops the coupled mooring system model. The model is then coupled to a simplified spar type FOWT model in Section 3 and verification of the developed mooring model is provided in Section 4. The numerical study on the impact of nonlinear mooring dynamics in the presence of current based on the developed models is conducted in Section 5. The paper is closed with concluding remarks in Section 6.

2. Coupled mooring system model

2.1. Problem description

As illustrated in Fig. 1 is a typical mooring system consisting of several cables attached to a platform at the fairleads. The platform and the cables are subjected to wave and current loads. To describe their motions, a fixed global coordinate system is defined as (o, x, y, z). Generally, the platform can be modeled as a rigid body of six degrees of freedom (6DOF) and its motion can be described by the three translational displacements (ξ_1, ξ_2, ξ_3) and three rotations (ξ_4, ξ_5, ξ_6) of a reference point.

Although cables in a mooring system often have identical properties and the horizontal layout of the cables is axisymmetric and symmetric with respect to horizontal axes, the cable static and dynamic responses are coupled when the mean wind and current effects are considered. They induce static offsets of the platform and hence the cable responses need to be analyzed simultaneously. For each cable, solving its static and dynamic responses is a two-point boundary-valued problem while the boundary conditions at the fairleads of all the cables are coupled by the platform motion.

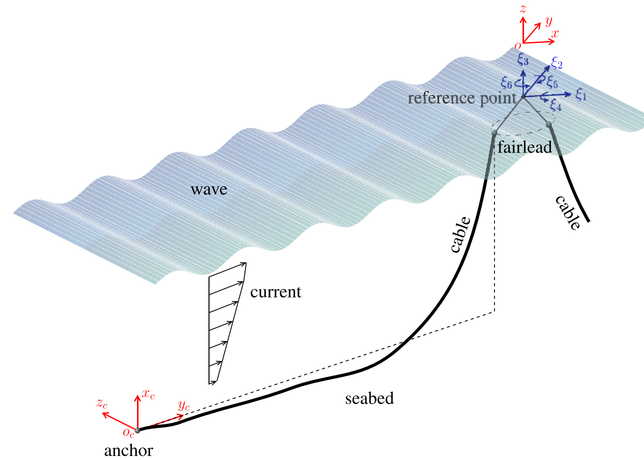

Fig. 1. A typical mooring system and the coordinate systems.

2.2. Single cable mechanics

For solving the two-point boundary-valued problem of each cable, the cable model developed by (Tjavaras, 1996; Tjavaras et al., 1998; Gobat and Grosenbaugh, 2006) is used herein. The cable is assumed to have a uniform circular cross-section with diameter d, mass per unit length m, bending stiffness EI, and torsional stiffness GJ. For describing the cable motion, a fixed Cartesian coordinate system (x_c, y_c, z_c) is defined for each cable, as shown in Figs. 1 and 2. The origin of the cable Cartesian coordinate is placed at the cable seabed anchor with x_c pointing upwards and the $x_c - y_c$ plane is in the vertical plane defined by the cable anchor and the initial fairlead location. The horizontal and vertical distances between the cable anchor and the initial fairlead are denoted as l_c and h_c, respectively. In deriving the equations of motion, the force and moment balances are established in a moving Lagrangian coordinate system attached to the unstretched cable at an arc length of s with (e_1, e_2, e_3) corresponding to the local tangential, normal and binormal directions. The Lagrangian coordinate system is parametrized by s and two angles φ and θ. The cable position in the Cartesian coordinate system at the arc length s can be determined from s, φ, θ and the cable strain ε after solving the equations in the Lagrangian coordinate system (Gobat, 2000). Note that in the model formulation the Poisson ratio is assumed to be 0.5.

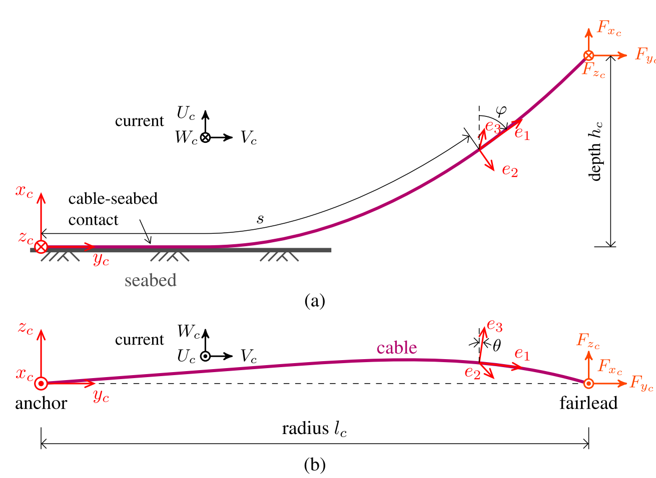

Fig. 2. Cable motion description and the coordinate systems: (a) vertical plane; (b) horizontal plane.