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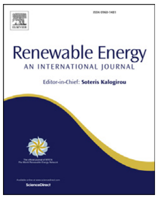

Coupled aero-hydro-servo-elastic methods for floating wind turbines

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ABSTRACT

To meet the demand of the development of floating wind turbines, coupled aero-hydro-servo-elastic methods were developed and then were programmed as an integrated code DARwind (short for Dynamic Analysis for Response of Wind Turbines) for simulating floating wind turbines. This paper first presents the theoretical background, including Kane's dynamical equations in combination with the Cardan angles method, the hybrid coordinate dynamic analysis method, and the adjacent array approach for kinematics and kinetics. The blade element/momentum method with aerodynamic corrections was used for aerodynamic simulation. Potential-flow theory, the second-order wave forces and the Morison formula with the strip theory were used for hydrodynamics, and a quasi-static mooring modelling approach was developed for the catenary mooring system. A generator-torque controller and a full-span rotor-collective blade-pitch controller were adopted for control strategies. The code was then verified by a series of code-to-experiment comparisons, including the mooring system, the structural elasticity, the aerodynamic performance, the hydrodynamic performance and the control strategy. The comparisons demonstrated that the coupled aero-hydro-servo-elastic methods have a satisfactory ability to perform fully coupled simulations for floating wind turbines.

1. Introduction

In recent years, the rapid development of the offshore wind industry has been attracting increasing worldwide attention [1]. Currently, offshore wind turbines can be classified into two categories [2]: bottom-mounted offshore wind turbines and floating offshore wind turbines (FOWTs). Compared with the bottom-mounted turbines, which are limited to water depths of 30 m, FOWTs can take advantage of abundant wind resources in deeper water regions [3].

To demonstrate the technical feasibility of the proposed FOWTs, three methods are generally applied, including onsite measurements, scaled model tests and numerical analysis. The first full-scale FOWT demonstration of the onsite measurement method was conducted off the coast of Norway in 2009 using the Hywind turbine (a spar-type FOWT) [4]. In 2011, a semi-submersible FOWT, WindFloat, was deployed 5 km off Portugal's coast [5]. From 2013 to 2015, the Fukushima floating offshore wind farm demonstration project was conducted with three different FOWTs and one floating power sub-station [6]. The first offshore grid-connected wind turbine in the Americas, VolturnUS, was tested for 18 months from 2013 to 2014 off Castine in eastern Maine, USA [7]. With respect to scaled model tests, the Hydro Oil & Energy Company supported a 1/47th scale 5-MW spar-type FOWT model test at the MARINTEK (Norwegian Marine Technology Research Institute) in 2006 [8]. In 2012, 1/50th scale model tests were conducted at the Maritime Research Institute Netherlands (MARIN) with a tension-leg FOWT, a spar-type FOWT, and a semi-submersible FOWT [9]. The public details of the MARIN's experiments greatly promoted the worldwide development of the FOWT model tests. In 2013, a 1/50th scale model test using a spar-type FOWT and a semi-submersible FOWT was conducted at the Deepwater Offshore Basin of Shanghai Jiao Tong University [10,11]. In 2014, a 1/50th scale combined wind and wave power generation system model, STC, was conducted at the towing tank of the MARINTEK [12]. However, onsite measurements and scaled model tests have generally required great amounts of money and time. Moreover, most of these experimental projects relied quite heavily on industrial investments, which make the valuable measured data unavailable to normal researchers. In contrast, the numerical analysis method for FOWTs is cheaper, faster and more convenient. Therefore, more and more efforts are being devoted to the development of reliable numerical tools for FOWTs. Currently, there are two popular numerical analysis

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methods for FOWTs: the frequency-domain analysis method and the time-domain analysis method [13].

Learning from the technologies of offshore O&G industries in the field, some researchers have studied the dynamical characteristics of FOWTs using frequency-domain analysis tools. For example, Lee et al. [14] carried out preliminary investigations on a TLP FOWT by the linear frequency-domain analysis method. Wayman et al. [15] analysed the shallow-drafted barge FOWT and the MIT/NREL TLP FOWT using frequency-domain analysis technology. However, there are some limitations in the frequency-domain analysis method. For example, it is not capable of modelling nonlinear dynamic behaviours, transient events and controllers, which are generally important for FOWTs.

By comparison, the time-domain analysis method is more appropriate for FOWTs. In the time-domain analysis, a FOWT can be considered as a fully coupled aero-hydro-servo-elastic model by solving the dynamical equations of numerous degrees of freedom. For instance, Madjid et al. [16] studied extreme structural response and fatigue loads of a spar-type FOWT in the time-domain. Bachynski et al. [17] conducted investigation on transient events for FOWTs, e.g., pitch actuator fault, grid loss, and shutdown in the time-domain. More and more efforts are devoted to the development of time-domain analysis tools currently.

Nonetheless, fully coupled time-domain numerical tools for FOWTs remain limited. Some are developed from the commercially available general-purpose multibody-system (MBS, for short) codes combined with aerodynamic, mooring and hydrodynamic subroutines. For example, Withee et al. [18] conducted research on FOWTs using ADAMS (a commercial general-purpose MBS code for the aerospace and robotics industries) in combination with additional aerodynamic and hydrodynamic subroutines. Similarly, Matha et al. [19] made use of another commercial general-purpose MBS code, SIMPACK, with an aerodynamic subroutine package AeroDyn, a hydrodynamic subroutine package HydroDyn, and a developed mooring-lines subroutine. On the other hand, some time-domain numerical tools are developed from codes originally for onshore bottom-mounted wind turbines; for example, Jonkman [20,21] recoded the land-based horizontal-axis wind turbine simulation code FAST and developed its capacity for calculating hydrodynamic loads and mooring loads on FOWTs. Some time-domain simulation tools have been developed from the field of offshore structures in the O&G industries; for instance, Fylling et al. [22] conducted research on FOWTs using SIMO/RIFLEX combined with a separate aerodynamic subroutine; SIMO is used to simulate structural dynamics and hydrodynamics, and RIFLEX is used to model mooring lines with FEM technology. In recent years, some researchers have attempted to make use of computational fluid dynamics (CFD) tools to model FOWTs. Wan et al. [23,24] conducted a series of investigations on dynamical characteristics of FOWTs using their CFD tool NAOE-FOAM-SJTU. Nematbakhsh et al. [25] conducted a series of comparisons of wave load effects on a TLP FOWT using CFD and potential flow theory approaches. Up to now, the development of adequate fully coupled time-domain FOWT simulation tools is in progress, and is still important for the research of FOWTs.

The Offshore Code Comparison Collaboration (OC3) project [26] and the Offshore Code Comparison Collaboration Continuation (OC4) project [27] performed a successive series of code-to-code comparisons to verify the technical feasibility of the FOWTs numerical tools. Nonetheless, detailed code-to-experiment comparisons are still relatively few because of the scarcity of the FOWT test data being openly available to the public.

In view of the above-mentioned facts, an integrated code DARwind (short for Dynamic Analysis for Response of Wind Turbines) based on fully coupled aero-hydro-servo-elastic methods was developed for simulating FOWTs in this paper. For kinematics and kinetics, Kane's dynamical method [28] in combination with the Cardan angles method [29], the hybrid coordinate dynamical method [30], the nonlinear deformations model and the adjacent array approach [31] were applied to establish the fully coupled multi-body dynamic model for FOWTs. For aerodynamics, the blade element/momentum method [32] with aerodynamic corrections [33] was used to calculate aerodynamic loads. For hydrodynamics [34], the linear potential-flow theory, the second-order wave forces theory and the Morison formula with the strip theory were applied to account for hydrodynamic loads. For mooring systems, a quasi-static approach [35] for taut or slack catenary lines considering stretching was developed. For control strategies [36], a combination of a generator-torque controller and a full-span rotor-collective blade-pitch controller was implemented. The paper detailed outline of the utilized coupled aero-hydro-servo-elastic methods and then conducted a series of verifications by means of experimental results. It benefits our understanding of the coupled dynamical theories on FOWTs and facilitates the development of additional FOWTs numerical codes.

This paper is organized as follows: In Section 2, theories regarding the kinematics and kinetics, aerodynamics, hydrodynamics, mooring system modelling, and control strategies in the code are presented, respectively. In Section 3, a brief description of the model and the experiment is presented. Finally, verifications of the accuracy of the code, by means of a series of code-to-experiment comparisons, are presented in Section 4.

2. Theoretical background

2.1. Kinematics and kinetics

The kinematics and kinetics are vital for a FOWT system, thus the relevant theories are introduced in this subsection as follows: the method for rotational and translational motions of a body is presented first. Then, a description of the topological configuration, coordinate systems, and degrees of freedom is given. Finally, the establishment of the system's dynamical governing equations using Kane's dynamical method is detailed.

According to Euler's theorem on rotations [37], a limited rotation of a body about one point can be decomposed as three limited angles corresponding three different coordinate axes. The Cardan angles method [29] is used to describe these angles because it is simple and suitable in the case of small angular motion of a FOWT. As shown in Fig. 1, we assume that the rotational motion of a body about a point in a Cartesian coordinate system can be decomposed into the following steps (a 1-2-3 Euler rotation sequence): (1) the frame $\boldsymbol{e}^{(0)}$ moves to $\boldsymbol{e}^{(1)}$ by rotating about $\boldsymbol{e}_1^{(0)}$ at the degree of α; (2) the frame $\boldsymbol{e}^{(1)}$ then rotates about $\boldsymbol{e}_2^{(1)}$ at the degree of β to the frame $\boldsymbol{e}^{(2)}$; (3) finally, the frame $\boldsymbol{e}^{(2)}$ moves to its actual position $\boldsymbol{e}^{(3)}$ by rotating about $\boldsymbol{e}_3^{(2)}$ at the degree of γ. In this process, α, β and γ are the so-called "Cardan angles".

Based on the Cardan angles method, the direction cosine matrix between frames can be written as:

$$\boldsymbol{T}^{03} = \begin{bmatrix} cos\beta \cdot cos\gamma & -cos\beta \cdot sin\gamma & sin\beta \\ sin\alpha \cdot sin\beta \cdot cos\gamma + cos\alpha \cdot sin\gamma & -sin\alpha \cdot sin\beta \cdot sin\gamma + cos\alpha \cdot cos\gamma & -sin\alpha \cdot cos\beta \\ -cos\alpha \cdot sin\beta \cdot cos\gamma + sin\alpha \cdot sin\gamma & cos\alpha \cdot sin\beta \cdot sin\gamma + sin\alpha \cdot cos\gamma & cos\alpha \cdot cos\beta \end{bmatrix} \quad (1)$$