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Predicting the performance of a floating wind energy converter in a realistic sea

Yingguang Wang [a, b, c, *], Lifu Wang [d]

[a] State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University, Shanghai, 200240, PR China
[b] Collaborative Innovation Center for Advanced Ship and Deep-Sea Exploration (CISSE), Shanghai, 200240, PR China
[c] School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, Shanghai, 200240, PR China
[d] Department of Electrical Automation, Shanghai Maritime University, Shanghai, 201306, PR China

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ABSTRACT

In this paper, the performances of a floating wind energy converter (the National Renewable Energy Laboratory 5 MW wind turbine installed on the ITI energy barge) in a realistic, multi-directional random sea are rigorously investigated. The wind loads acting on the floating wind energy converter are also fully considered in the numerical simulation process. Meanwhile, in order to improve the simulation efficiency, a new state space model (the FDI-SS model) is utilized to approximate the convolution integral term when solving the motion equation of the floating wind energy converter. For comparison purpose, the simulation results when the convolution integral term in the motion equation is approximated by a commonly used state space model based on the time domain (TD) realization theory are also included. The simulation results in this paper are systematically analyzed and compared, and the accuracy and efficiency of the new FDI-SS model are verified. Moreover, the simulation results in this article demonstrate the great necessity of using a realistic, multi-directional random sea state when calculating the generated electrical power and the dynamic responses of a floating wind energy converter.

1. Introduction

This paper investigates the methods for predicting the performances of a floating wind energy converter, i. e., a wind turbine installed on a floating platform moored to a sea bed. In the worldwide offshore wind energy industry, the performance analysis of a floating wind energy converter is typically carried out by solving the converter motion equation with a complicated convolution integral term representing the hydrodynamic memory effects (see e. g., the publications: Jonkman [1-3], Jonkman and Buhl [4], Jonkman and Matha [5], Robertson and Jonkman [6], Wang et al. [7], Xia [8], Xia and Wang [9], etc.). Calculating the convolution integral term is difficult, time consuming and requiring a large amount of memory on a computing machine. Moreover, all the aforementioned research publications have only investigated the performances of floating wind energy converters in an ideal, uni-directional random sea. The wave spectra applied in these research publications are all uni-directional spectra, i.e., assuming that wave energy is traveling in ***one*** direction. In reality, however, wind-generated wave energy does not necessarily propagate in the same direction as the wind; instead, the energy usually spreads over various directions. Therefore, although the analyses in the above-mentioned publications are likely performed correctly and are useful for many applications (for example, when comparing to tank test data for the purposes of model validation), the calculation results in these publications can hardly be used for predicting the floating wind energy converter real world performances, let alone the simulation methods in these publications are also not time-efficient.

To the best of our knowledge, in the existing literature, there is only one paper (Duarte et al. [10]) that has investigated the motion responses of a floating wind energy converter in a realistic, multi-directional random sea. However, in the study of Duarte et al. [10] the wind loads acting on the floating wind energy converter have not been included in the simulation process. Therefore, the predicting results in Duarte et al. [10] cannot be deemed reliable. As pointed out by Duarte et al. in the conclusion of their paper: "…… a preliminary study was performed on the OC4 semisubmersible platform. The comparison between the unidirectional and

* Corresponding author. State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University, Shanghai, 200240, PR China.
E-mail address: wyg110@sjtu.edu.cn (Y. Wang).

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multidirectional sea state without wind loads showed a significant increase in the platform sway and roll motion. These findings should motivate further studies to carefully assess the impact of the multidirectional loads on the platform's ultimate loads and fatigue life."

Motivated by the aforementioned facts, in this article, the performances of a floating wind energy converter (the National Renewable Energy Laboratory 5 MW wind turbine installed on the ITI energy barge) in a realistic, multi-directional random sea will be rigorously investigated. The wind loads acting on the floating wind energy converter will be fully considered in the numerical simulation process. Meanwhile, in order to improve the simulation efficiency, a new state space model (the FDI-SS model) will be utilized to approximate the convolution term when solving the motion equation of the floating wind energy converter. The simulation results will be systematically analyzed and compared, and some valuable conclusions will finally be pointed out.

2. The motion equations of the floating wind energy converter

The vector-form time domain motion equations of a floating wind energy converter subjected to wind, wave and other loads can be expressed as:

$$[\mathbf{M}_{RB} + \mathbf{A}(\infty)]\ddot{\mathbf{x}}(t) + \int_0^t \overline{\mathbf{K}}(t-\tau)\dot{\mathbf{x}}(\tau)\mathrm{d}\tau + \overline{\mathbf{C}}\mathbf{x}(t) = \mathbf{P}_{wave}(t) + \mathbf{P}_{wind}(t) + \mathbf{P}_{others}(t) \tag{1}$$

where $\mathbf{M}_{RB}$ is the rigid body inertia matrix, $\mathbf{A}(\infty)$ is the constant infinite-frequency added mass matrix, $\mathbf{x}(t)$ is a vector of linear or angular displacements and $\overline{\mathbf{C}}$ is a matrix containing the hydrostatic restoring forces or moments coefficients. Meanwhile, in Eq. (1) $\overline{\mathbf{K}}(t)$ is a matrix of retardation functions. Due to the motion of the floating wind energy converter, waves will be generated in the free surface. These waves will persist at all subsequent times and affect the motion of the floating wind energy converter. This is known as the hydrodynamic memory effects, and they are captured in Eq. (1) by the convolution integral term which is a function of $\dot{\mathbf{x}}(\tau)$ and the retardation functions $\overline{\mathbf{K}}(t)$. Calculating the convolution integral term in Eq. (1) is difficult, time consuming and requiring a large amount of memory on a computing machine. In this paper, in order to improve the computational efficiency, a new state space model (the FDI-SS model) will be utilized to fit a parametric model to this convolution integral term. This will be further explained in the next section.

On the right hand side of Eq. (1) $\mathbf{P}_{wave}(t)$ denote wave loads (forces or moments), $\mathbf{P}_{wind}(t)$ denote wind loads, and $\mathbf{P}_{others}(t)$ denote other loads due to hydrodynamic viscous effects and mooring lines forces.

The frequency domain counterpart of Eq. (1) is written

$$\left(-\omega^2[\mathbf{M}_{RB} + \mathbf{A}(\omega)] + j\omega\mathbf{B}(\omega) + \overline{\mathbf{C}}\right)\mathbf{X}(j\omega) = \mathbf{P}_{wave}(j\omega) + \mathbf{P}_{wind}(j\omega) + \mathbf{P}_{others}(j\omega) \tag{2}$$

where $\mathbf{A}(\omega)$ denotes the added mass matrix, $\mathbf{B}(\omega)$ denotes the damping matrix and j denotes the imaginary unit. In the practice of ocean engineering, it is routine work to compute the matrices $\mathbf{A}(\omega)$ and $\mathbf{B}(\omega)$ by a 3D hydrodynamic boundary element method computer code.

We will rely on a result from Ogilvie [11] to obtain the relationship between the parameters of the time domain equation (1) and those of the frequency domain equation (2):

$$\mathbf{A}(\omega) = \mathbf{A}(\infty) - \frac{1}{\omega}\int_0^\infty \overline{\mathbf{K}}(t)\sin(\omega t)\mathrm{d}t \tag{3}$$

$$\mathbf{B}(\omega) = \int_0^\infty \overline{\mathbf{K}}(t)\cos(\omega t)\mathrm{d}t \tag{4}$$

Eq. (4) is rewritten using the inverse Fourier transform

$$\overline{\mathbf{K}}(t) = \frac{2}{\pi}\int_0^\infty \mathbf{B}(\omega)\cos(\omega t)\mathrm{d}\omega \tag{5}$$

Fourier Transforming $\overline{\mathbf{K}}(t)$ leads to

$$\overline{\mathbf{K}}(j\omega) = \int_0^\infty \overline{\mathbf{K}}(t)e^{-j\omega t}\mathrm{d}t = \mathbf{B}(\omega) + j\omega[\mathbf{A}(\omega) - \mathbf{A}(\infty)] \tag{6}$$

3. Identification of the hydrodynamic memory effects

As explained in Section 2, calculating the convolution integral term in Eq. (1) is difficult, time consuming and requiring a large amount of memory on a computing machine. In this paper, in order to improve the computational efficiency, a state space model will be developed to fit a parametric model to this convolution integral term as follows:

$$\mu = \int_0^t \overline{\mathbf{K}}(t-\tau)\dot{\mathbf{x}}(\tau)\mathrm{d}\tau \approx \left| \begin{array}{l} \dot{\mathbf{z}} = \mathbf{A}'\mathbf{z} + \mathbf{B}'\dot{\mathbf{x}} \\ \mu = \mathbf{C}'\mathbf{z} \end{array} \right. \tag{7}$$

We can notice that in order to derive the state-space system, the matrices $\mathbf{A}'$, $\mathbf{B}'$ and $\mathbf{C}'$ must be first calculated. An approach based on the time domain (TD) realization theory can be used to perform the identification of the state-space system. In the following the theoretical background of this approach will be elucidated. We recall that the matrices $\mathbf{A}(\omega)$ and $\mathbf{B}(\omega)$ of a floating wind energy converter can be calculated using a hydrodynamic boundary element method computer code. After $\mathbf{B}(\omega)$ is calculated, the inverse Fourier transform in Eq. (5) can then be used to obtain the retardation functions $\overline{\mathbf{K}}(t)$. However, the inverse Fourier transform process in Eq. (5) will inevitably lead to additional errors.

For numerical implementation, the cosine transformation described in Eq. (5) can be carried out by using a trapezoidal integration rule as follows:

$$\overline{K}_{ij}(t) = \frac{\Delta\omega}{\pi}\sum_{k=1}^{k_{\max}-1} 2B_{ij}(k\Delta\omega)\cos(k\Delta\omega t) + \frac{\Delta\omega}{\pi}\left[B_{ij}(0) + B_{ij}(k_{\max})\cos(k_{\max}\Delta\omega t)\right] \tag{8}$$

where k_{max} is the number of the frequency vector entries calculated using a boundary element method computer code. $\Delta\omega$ is a step size of the angular frequency. Once the retardation functions (impulse-response functions) are obtained by Eq. (8), an identification scheme based on the Hankel Singular Value Decomposition (SVD) can subsequently be applied. This method was proposed by Ref. [12] and is available in the MATLAB function *imp2ss*. However, because errors have been introduced in the process of calculating $\overline{\mathbf{K}}(t)$ as explained previously, the identified state-space system