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ScienceDirect

Energy Procedia 94 (2016) 290 – 305

Energy Procedia

13th Deep Sea Offshore Wind R&D Conference, EERA DeepWind'2016, 20-22 January 2016, Trondheim, Norway

Parametric Wave Excitation Model for Floating Wind Turbines

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Abstract

This paper presents a parametric wave disturbance model for an improved representation of the overall system dynamics of a floating wind turbine (FOWT). Hydrodynamic panel codes calculate the frequency-dependent first-order wave excitation force coefficient on rigid floating bodies. This transfer function from wave height to the forces and moments on the body is approximated in this work by a linear time-invariant model. With a causal problem definition the fit to an impulse response shows a good agreement in frequency and time domain for spar-type and semi-submersible-type platforms of floating wind turbines. The disturbance model was coupled to a linear structural FOWT model and the effect of the wave height on the tower-top displacement was compared to the nonlinear model with good agreement. Applications of this parametric model are the inclusion of disturbance dynamics in model-based controller design as well as feedforward control for fatigue load reduction.

Peer-review under responsibility of SINTEF Energi AS

Keywords: Floating wind turbine, wave excitation model, disturbance model, system identification, LTI model, controller design

1. Introduction

Offshore wind turbines increase significantly in size as the development and experience with large plants builds up. The rotors of these turbines make the offshore wind turbine the largest existing rotor-dynamic system. Simplified models, which are the focus of this paper, can be used for conceptual optimization and controller design. Especially linearized models provide the fundamental understanding of the system dynamics through eigenvalue analyses and transfer functions. This knowledge is essential for system and controller design. In general, floating wind turbines (FOWT) are simulated in time domain, taking the structural flexibilities into account. The coupling of the structural deformation with hydrodynamics and aerodynamics stresses the importance of transients, which increases the complexity of linear rigid-body models commonly used in ocean engineering. Cummins equation is the standard approach for the time-domain representation of the first-order radiation and diffraction of a floating body. The wave excitation part of Cummins equation is the focus of this paper. Yu and Falnes [1], developed a state-space model of

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Peer-review under responsibility of SINTEF Energi AS
doi:10.1016/j.egypro.2016.09.186

the wave excitation force of a vertical cylinder in heave direction, aiming at the control of wave energy converters. They analyzed extensively the non-causality of the wave excitation function, or force-RAO, which is due to the fact that the wave forces might arrive at the hull prior to the corresponding free-surface elevation at the location of the floating body.

The objective of this work is to find a parameterized representation of the wave excitation force coefficient, the transfer function from the wave height to the six forces and moments on the floating foundation of a wind turbine, $\boldsymbol{G}_{frc} = \boldsymbol{G}_{\eta \rightarrow F}$, see Fig. 1. This means that the wave excitation force time series do not have to be calculated prior to a simulation through an inverse Fourier transform, the wave height is a direct input to the model. Also, this disturbance model is advantageous for the design process of the blade-pitch controller and, furthermore, as an integrated real-time model for model-based control approaches. With wave scanning methods a feedforward control for disturbance attenuation is conceivable, where an incident wave elevation measurement is fed into the LTI model in order to optimize the actuator trajectory for future timesteps. This is comparable to Dynamic Positioning (DP) control, which compensates the motion from second-order hydrodynamic forces. Signal filtering, necessary for an implementation of such a system, is not considered in this work. The methodology in this work follows the model proposed by Yu and Falnes [1]: The solution of the wave excitation function in surge-, heave- and pitch-direction is calculated with a hydrodynamic panel code, see Section 2. The frequency-dependent function is then transformed to time-domain and the resulting impulse response is shifted such that the response in negative times is negligible. This causalized response is then the time-domain data for the system identification. A linear time-invariant (LTI) model is subsequently fitted to the given data with a variable number of poles and zeros in Section 3. The performance of the fitted model can be evaluated with the wave force impulse response directly, but also with the time-domain wave force response to a stochastic wave train. The same wave train can then be used to calculate its corresponding complex energy spectrum, which gives, when multiplied with the wave force transfer function, the wave force response to the same excitation as for the identified model. The method has been applied to two generic floating offshore wind turbine platform geometries, both for the NREL 5 MW reference wind turbine, see [2]. The first is the spar-type shape of the OC3-Hywind model, see [3] with a rather simple cylindrical shape, whereas the second model is the OC4-DeepCwind semi-submersible, see [4]. This one consists of three outer columns with heave-plates at their bottom ends, one central column and braced connectors.

The knowledge of the transfer function from wave height to the system outputs such as rotor speed, tower-top displacement or platform displacements is crucial for the design of controllers using loop-shaping methods. Therefore, the LTI wave excitation model is incorporated in a flexible multibody model for floating wind turbines as shown in Fig. 1, where a general FOWT dynamic system is assembled in terms of linear block diagrams with the identified wave disturbance model. Through a linearization of the nonlinear equations of motion a transfer function from the disturbances like wave height or wind speed to the system states can be obtained. This is shown in Section 4 before summarizing and concluding this work.

2. Time-domain simulation of linear hydrodynamics

As transient load situations are often design-driving for floating wind turbines all relevant standards require various time-domain simulations with wind and wave loads. Therefore, state-of-the-art simulation tools for floating wind turbines are based on a frequency-to-time-domain transformation of the hydrodynamic coefficients. Hydrodynamic panel codes solve a potential flow problem with 3D surface meshes as boundary conditions. Usually the decoupled problems of radiation (or maneuvering) and diffraction (or seakeeping) are considered: The radiation problem is solved for still water with the floating body oscillating at various frequencies. Its linear solution is the 6×6 frequency-dependent radiation damping matrix $\boldsymbol{B}(\omega)$ and the 6×6 frequency-dependent added mass matrix $\boldsymbol{A}(\omega)$. The diffraction problem is solved for a fixed floating body with waves of different frequencies (and directions) as boundary condition. The linear solution of the diffraction problem is the frequency-dependent 6×1 wave excitation force coefficient $\boldsymbol{X}(\omega)$. In frequency-domain the equation of motion can be set up assuming a linear superposition of the radiation and diffraction problem as

$$-\omega^2 \left[\boldsymbol{M} + \boldsymbol{A}(\omega)\right] \tilde{\boldsymbol{\xi}} + j\omega \boldsymbol{B}(\omega) \tilde{\boldsymbol{\xi}} + \boldsymbol{C} \tilde{\boldsymbol{\xi}} = \boldsymbol{X}(\omega) \tilde{\eta}(\omega) \tag{1}$$