Improved control of floating offshore wind turbine motion by using phase-resolved wave reconstruction and forecast

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ABSTRACT

Floating Offshore Wind Turbines (FOWT) can be actively controlled to minimize their wave induced motions, improving wind energy harvesting efficiency and increasing structural life by reducing fatigue loads. Here, we report on the development and validation of Wave Reconstruction and Prediction (WRP) algorithms that improve the active control of floating structure motions, achieved, e.g., by moving mass or ballast. Specifically, given a sensing method, here assumed to be LiDAR-like, that acquires dense spatiotemporal surface elevation data at some distance from the FOWT in the incident wave direction, we present and validate deterministic WRP algorithms, based on fast nonlinear and dispersive Lagrangian wave models, and integrate their predictions with in-the-loop hardware and a real time control system that is informed by computations with a digital twin (DT) model of the floating structure. We implement multiple WRP wave models including a model based on linear wave theory (LWT) with a correct dispersion accounting for nonlinearity (LWT-CDR) and a 2nd-order “Choppy” wave model with improved nonlinear dispersive properties (ICWM), initialized with a linear prediction. Although we run laboratory experiments of the complete system, which are reported elsewhere, here the WRP implementation is validated against fully nonlinear wave flow simulations in a Numerical Wave Tank (NWT), which shows both LWT-CDR and ICWM models appear to provide reasonable short-term predictions at the float. Implications for the real time control system are discussed; in a companion paper, the use of short-term wave predictions with the WRP is shown to improve the real time control of float motions in waves.

KEYWORDS: Phase-resolved wave prediction, motion control systems, floating offshore wind turbines

INTRODUCTION

Many offshore wind farms are in development along the US East Coast, with about 3GW of total installed power, that will be equipped with turbines installed on static foundation support structures. The current goal of the US administration, however, is to install ten times as much offshore wind power in US waters by 2030, and to meet this goal, it will be necessary to develop farms also in deeper waters, beyond the continental shelf, made of floating offshore wind turbines (FOWT). In some areas of the US, such as the Gulf of Maine or the West Coast, which feature a narrow shelf, floating offshore wind turbines (FOWTs) are the only viable option.

FOWTs are composed of a float, usually a single spar or multiple connected cylinders, anchored using a slack mooring system, and a support structure attached to the float (e.g., a cylindrical tower with varying inertia), with on top a nacelle that includes an electric motor and a transmission system, on which the turbine blades are attached. Such a floating and top heavy system may significantly oscillate under the action of wind, but mostly ocean waves, particularly in heavy sea states, with the roll/pitch motions causing an eccentricity of the heavy nacelle that significantly increases structural stresses, e.g., at the tower bottom, hence reducing the FOWT fatigue life, and significant motions of the turbine blades that will affect their aerodynamic efficiency and, hence, their energy harvesting ability.

To improve the energy capture and increase the fatigue life of such systems (which both affect the levelized cost of electricity; LCOE), it is thus important to minimize the FOWT wave-induced motions, which can be achieved through using active control methods, e.g., through moving mass or water ballast within the FOWT float. Such methods are actuated by Model Predictive Control (MPC) algorithms that can anticipate the float motions, usually based on a model or “digital twin” (DT) of the system that assimilates the past motion history (e.g., Casanovas, 2014; Ma et al., 2018). Such algorithms are reviewed in our companion paper (Steele et al., 2023). Earlier studies, however, have shown that the optimal control of a FOWT (or any float) motions requires predicting the wave excitation force a short time in the future (e.g., 5-10 s; Ma et al., 2018), as a result of the causality principle in irregular waves (e.g., Babarit and Clément, 2006; Fusco and Ringwood, 2010). It should be stressed that, similar to the optimal control of wave energy converters (WECs; e.g., Wu et al., 2009; Grilli et al., 2011b; Faedo et al., 2017; Hals et al., 2011; Zou et al., 2017), it is key in this problem to accurately predict the phase of waves impacting the FOWT float, since any significant phase mismatch will impede the control and, in the worst-case scenario, make matters worse. Indeed, while in WECs, the control aims at maximizing the wave-induced motions of some mechanical system, for FOWTs, control aims at minimizing float motions; hence, a faulty