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Numerical Simulation of a Floating Offshore Wind Turbine in Waves Using qaleFOAM

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This paper presents a numerical investigation of a floating offshore wind turbine (FOWT) in a complex marine environment consisting of winds and waves. The investigation takes account of the aerodynamics and hydrodynamics of the FOWT system and their interactions simultaneously by using the hybrid model qaleFOAM, which combines a fully nonlinear potential solver with a two-phase Navier–Stokes solver using a domain decomposition approach. The qaleFOAM model is validated by comparing its predictions with experimental and numerical results available in the public domain and then is applied to model the FOWT in a unidirectional focused wave with a peak period of 42.31 s accompanied by a uniform wind of 11.4 m/s. The result reveals a significant interaction between the aerodynamic and hydrodynamic responses of the FOWT in such conditions. Moreover, it demonstrates that the most extreme response of the FOWT may not occur at the highest wave.

INTRODUCTION

In recent years, the focuses of the research and deployment of the wind turbine have shifted from onshore to offshore sites, from fixed to floating foundations. For the reliability and survivability of a floating offshore wind turbine (FOWT) in complex environmental conditions (winds, waves, and currents), it is critical to accurately predict the response and the performance of the FOWT, which consists of multiple physical processes (e.g., the aerodynamics of the turbine blades, the hydrodynamics associated with the floating foundation, the mooring dynamics, and the control system) and their interactions. Generally speaking, FOWTs are designed to be deployed at offshore sites with high wind resources, which are often accompanied by occurrence of extreme waves. Therefore, considerable nonlinearities and significant interactions are expected in these processes.

Two numerical approaches have been widely applied by the industry and by researchers. The first one is a simplified approach in which the linear potential flow theory is used to model the wave/current kinematics, Morison's equation is applied to model the fluid load on the FOWT, and the blade element momentum (BEM) method is used to model the blade dynamics. This approach has a small computational demand and is commonly used in the design of FOWT systems (Jonkman et al., 2009; Robertson et al., 2014). Nevertheless, the nonlinearity associated with the FOWT system and the coupled effect between the turbine blade and its wake are not considered. As indicated above, the nonlinearity and the interactions may be significant, especially when FOWTs are subjected to a high sea state and/or survival conditions. The theoretical limitation of this approach would introduce uncertainty in the numerical processing and challenge the reliability of the predictions, which would not satisfy the research target (Nematbakhsh et al., 2013; Sebastian and Lackner, 2012) and design requirements. The second approach is the high-fidelity computational fluid dynamics (CFD) method, which solves the Navier–Stokes equation and the continuity equation (referred to as "N-S models" in this paper). A number of CFD studies have been carried out for FOWT systems: For example, Tran and Kim (2016) used the STAR-CCM+ to model the FOWT under regular waves and compared their results with FAST software from NREL. Liu et al. (2017) developed a fully coupled tool based on OpenFOAM and analyzed the coupled effect of the aerodynamics and hydrodynamics of FOWTs. Cheng et al. (2019) introduced the unsteady actuator line method into the naoe-FOAM-SJTU solver to simulate similar cases to that applied by Tran and Kim (2016). Such CFD applications have demonstrated the promising accuracy and capacity of the N-S models, especially for dealing with highly nonlinear waves, breaking wave impacts, turbine wakes, and vortex streets (Miao et al., 2017; Fleming et al., 2014), as well as the full integration of aerodynamics, hydrodynamics, and mooring dynamics. However, the N-S models are found to demand high computational resources (CPU time, memory, etc.), in part because the numerical processing of FOWTs requires a large computational domain to accommodate the propagation/evolution of nonlinear waves and the formation of the vortical street in the wake area.

The recent development of the hybrid models can partially address the issue of the low computational efficiency of the conventional CFD approach, based on the hypothesis that a simplified, fast, and lower-fidelity method is applied in the majority of the computational domain (spatial and/or temporal) to replace the time-consuming N-S models. Among those lower-fidelity models, the fully nonlinear potential theory (FNPT) has been considered as a good alternative to the N-S models for simulating the large-scale propagation and evolution of the nonlinear water waves (Hu et al., 2020). For example, in a recent international blind test on focused

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KEY WORDS: FOWT, focused wave, coupled effect, hybrid model, qaleFOAM.