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Simulation of Steep Focused Wave Impact on a Fixed Cylinder Using Fully Nonlinear Potential Flow and Navier–Stokes Solvers

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Cylindrical monopile foundations are commonly applied in coastal and offshore structures at intermediate water depth, where waves may contain highly nonlinear components. The study of the interactions between nonlinear waves and cylindrical foundations is of importance in engineering practice for the evaluation of the stability of these foundations and their survivability in extreme environmental conditions. In this paper, a newly developed finite volume free surface solver based on the fully nonlinear potential flow theory and the existing Navier–Stokes multiphase flow solver in OpenFOAM are adopted for the comparative study of the focused wave impact on a fixed cylinder. Whenever possible, numerical results from the two models are compared to each other and to the available experimental measurements to demonstrate their accuracy, efficiency, and applicability for the particular flow problem.

INTRODUCTION

Concerns about the adverse effects of global warming and the ever increasing demand for energy have led to a remarkable increase of investments and research activities in offshore renewable energy. The survivability of offshore renewable devices and traditional offshore structures remains challenging as a result of increased storminess and rising sea levels, which will expose such devices and structures to even harsher environmental conditions. These conditions, in turn, can lead to unexpected and increased loading on offshore structures, eventually causing damage and even failure. Therefore, investigation of the survivability and stability of offshore structures under extreme environmental conditions is of importance for their safe operation.

Various numerical and experimental approaches have been adopted for the study of wave–structure interaction (WSI) problems. For numerical approaches, numerical wave tank (NWT) models based on Navier–Stokes (NS) equations and volume of fluid (VoF) (Jacobsen et al., 2012; Higuera et al., 2013a, 2013b; Martínez-Ferrer et al., 2018) have become increasingly popular in research communities (Lin et al., 2017, 2020; Chen et al., 2019). Linear and Fully Nonlinear Potential Flow (FNPF) based models, which are capable of solving the WSI problems under nonbreaking wave conditions (Bai and Eatock Taylor, 2007, 2009; Shao and Faltinsen, 2014; Lin et al., 2019; Ma et al., 2001a, 2001b), are still predominantly used by industrialists for the design and evaluation of offshore and marine structures.

For example, Chen et al. (2014) systematically investigated the nonlinear wave interactions with a cylindrical monopile foundation in regular and focused waves using OpenFOAM. Chen et al. (2014) found that, with sufficient mesh cells in a wavelength and through implementing proper wave generation and absorption boundary conditions, the NS-VoF model can provide accurate numerical results with acceptable computational time. By using the numerical wave generation and absorption tools (waves2Foam) in OpenFOAM, Paulsen, Bredmose, Bingham, and Jacobsen (2014) investigated the steep regular wave-induced forcing on a fixed circular cylinder. It was concluded that the wave-induced 'ringing' phenomenon is more significant in deep water than at an intermediate water depth. Moreover, Paulsen, Bredmose, and Bingham (2014) proposed an efficient one-way coupled FNPF-NS-VoF solver to investigate wave loads on a circular cylinder at an intermediate water depth.

Apart from the time-consuming high-fidelity NS-VoF model, FNPF-based models are proven to be an efficient tool for modelling WSI problems under nonbreaking wave conditions. Ma et al. (2001a,b) developed a 3-D finite element method (FEM) FNPF solver to investigate the interactions between regular waves and a vertical fixed cylinder. Bai and Eatock Taylor (2007, 2009) proposed a time-domain FNPF model based on the boundary element method (BEM) to deal with wave interactions with fixed and floating flared structures. Based on a novel spatial discretizations approach, Engsig-Karup et al. (2019) described a mixed Eulerian–Lagrangian spectral element method (SEM) to investigate nonlinear wave interactions with fixed structures, and Bosi et al. (2019) developed a depth-integrated model using the spectral/*hp* element method for nonlinear WSIs. Although the work in Mehmood et al. (2015, 2016) has demonstrated the capability of OpenFOAM in fully solving the Laplace equation of velocity potential, considering both kinematic and dynamic free surface boundary conditions, they only presented preliminary results for the generation and propagation of 2-D waves of small steepness. Recently, the present authors (Lin et al., 2019) have further extended the work and developed an FNPF model based on the 3-D finite volume method (FVM) (Causon et al., 2011) in OpenFOAM to investigate WSI problems using OpenMPI for parallel computing implementation.

To examine the accuracy, applicability, and relative efficiency of the newly developed in-house FNPF solver in OpenFOAM (Lin et al., 2019, 2021) for problems of steep wave interactions with structures, the test cases of the impact of nonlinear focused waves on a fixed cylinder will be simulated by using both the FNPF and the NS-VoF solvers in OpenFOAM. This is achieved

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KEY WORDS: Wave–structure interaction, monopile foundation, extreme wave conditions, focused wave group, fully nonlinear potential flow, Navier–Stokes equations, OpenFOAM.