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Numerical Investigation of Steep Focused Wave Interaction with a Vertical Cylinder Using a Cartesian Cut-cell Method

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A three-dimensional numerical study has been undertaken to investigate the interactions of a steep focused wave and a vertical circular cylinder. The large-eddy simulation approach has been adopted in this study, where the model is based on the filtered Navier–Stokes equations, with the dynamic Smagorinsky subgrid model being used for the unresolved scales of turbulence. The governing equations have been discretised using the finite volume method, with the air–water interface being captured using a volume-of-fluid method and the Cartesian cut-cell method being implemented to deal with the cylinder and moving wavemaker in the Cartesian grid. Numerical results are presented and compared with the available experimental measurements in terms of the wave elevations and pressure on the cylinder. Detailed free surface profiles during wave impact are shown and discussed.

INTRODUCTION

Extreme waves have become more common in the coastal and offshore region as a result of climate change. The wave–structure interaction is a key aspect in the safe and cost-effective design of coastal and offshore structures and marine renewable devices. Monopile structures are among the most common types of installations for coastal and offshore applications. To assess the reliability and survivability of these structures in presence of extreme loads, such as those applied by focusing waves (Yan et al., 2015), the development of tools is required.

The Morison equation and potential flow theory (Ma et al., 2015) have been widely used in the literature to roughly predict the hydrodynamic loads on structures. However, it is challenging to study the wave impact on coastal and offshore structures by using these two approaches during wave breaking, especially with splash-up and air entrainment.

With developments of computational fluid dynamics (CFD) and increases in computer power, recent models for studying the wave-structure interaction solve the Navier–Stokes equations coupled with a free surface calculation (Lin, 2008). Several methods have been developed by solving the Navier–Stokes model on a fixed grid by using the volume-of-fluid (VOF) method (Lin and Liu, 1998; Xie, 2012), the level-set method (Christou et al., 2020), the particle-in-cell method (Chen et al., 2018), the height function method (Ai et al., 2019), and the two-fluid coupled with cut-cell method (Qian et al., 2006). A numerical model has also been developed with an adaptive unstructured mesh method to reduce the computational effort without sacrificing accuracy (Xie et al., 2017). Many researchers have employed the open-source code OpenFOAM to study focusing waves based on the Reynolds-averaged Navier–Stokes equations (Chen et al., 2014; Hu et al., 2016; Martínez Ferrer et al., 2016; Ransley et al., 2019). Alternatively, there are also some meshless methods, such as the smoothed particle hydrodynamics (SPH) method (Lind et al., 2012), the moving particle semi-implicit (MPS) method (Khayyer et al., 2019), and the meshless local Petrov-Galerkin (MLPG_R) method (Ma, 2005). The large-eddy simulation approach has also been used for wave-structure interaction problems (Yang and Stern, 2009; Mo et al., 2012; Xie et al., 2020).

Recently, to improve the efficiency of the numerical model, some hybrid models (Yan et al., 2020) have been developed to couple the potential flow model (Yan and Ma, 2007) and the Navier–Stokes model, where the Navier–Stokes model is adopted near the structure and the potential flow model is employed in the far field. The hybrid models are shown to be more efficient than using the full Navier–Stokes model alone, to achieve sufficient accuracy. A hybrid model for coupling incompressible and compressible Navier–Stokes solvers has also been developed in the framework of OpenFOAM (Martínez Ferrer et al., 2016).

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KEY WORDS: Focusing waves, wave-structure interaction, volume-of-fluid method, moving body, 3D Navier–Stokes equation, Cartesian cut-cell method.