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Spectral Element FNPF Simulation of Focused Wave Groups Impacting a Fixed FPSO-type Body

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A 3D fully nonlinear potential flow (FNPF) model based on an Eulerian formulation is presented. The model is discretized using high-order prismatic – possibly curvilinear – elements using a spectral element method (SEM) that has support for adaptive unstructured meshes. The paper presents details of the FNPF-SEM development, and a model is illustrated to exhibit exponential convergence for steep stream function waves to serve as validation. The model is then applied to the case of focused waves impacting on a surface-piercing, fixed FPSO-like structure. Good agreement is found between numerical and experimental wave elevations and pressures.

INTRODUCTION

Significant efforts have been made for several decades to develop reliable tools for wave–body interaction based on fully nonlinear potential flow (FNPF) theory: models that can handle real-life geometries of offshore structures and floating bodies. Ma and Yan (2009) discuss the pros and cons of boundary element methods (BEM) and finite element methods (FEM). The review paper of Wang and Wu (2011) provides an overview of the efforts made in FEM-based FNPF solvers. BEM, FEM, and pseudo-spectral-based FNPF solvers have successfully been applied to focused wave groups and extreme waves; see, e.g., Grilli et al. (2010), Ma (2007), and Ducrozet et al. (2007). Handling both the wave propagation problem and the wave–body interaction problem within one model remains a challenging task. Today's state-of-the-art tools are often based on a hybrid modelling approach where two different simulation tools are combined through weak coupling. Typically, an FNPF-based wave propagation model is coupled to a two-phase Reynolds-averaged Navier Stokes model using the volume of fluid approximation (VOF-RANS); e.g., see the work of Duz et al. (2016), or for a smoothed particle hydrodynamics (SPH) model, see, e.g., Verbrugghe et al. (2018).

In this work, however, the classical single numerical model approach using the FNPF equations will be pursued. In contrast to most existing FNPF models, the present model is based on the spectral element method (SEM), as first introduced by Patera (1984). SEM combines the high accuracy of the spectral methods with the geometrical flexibility of FEM. High-order accuracy is a key to computational efficiency for large-scale, long-time integration of wave propagation problems (Kreiss and Oliger, 1972). A recent description of the state-of-the-art for spectral element methods, including water wave propagation, is found in Xu et al. (2018).

This paper presents the first FNPF-SEM model supporting truncated surface-piercing bodies in three dimensions. The arbitrary order FNPF-SEM model, which can efficiently handle both the wave propagation problem and the wave–body interaction problem, has support for adaptive unstructured meshes with curvilinear elements to represent arbitrarily shaped bodies. The model relies on recent progress made for FNPF-SEM solvers in two spatial dimensions. Engsig-Karup et al. (2016a) used a σ-transformation for the wave propagation problem and showed how to properly stabilize the model using exact integration of the free surface equations and a mild modal filter. Monteserin et al. (2018) extended this to a mixed Eulerian-Lagrangian (MEL) formulation. The new 3D spectral element method is based on an Eulerian formulation, and the σ-transformation used in Engsig-Karup et al. (2016a, 2016b) is discarded to handle surface-piercing bodies. Truncated surface-piercing fixed bodies are cared for by solving the Laplace problem directly, using curvilinear high-order elements based on transfinite interpolation.

The FNPF-SEM model is applied to the blind test experiment Part I of the Collaborative Computational Project in Wave Structure Interaction (CCP-WSI) initiative. The experimental test case consists of focused waves impacting a fixed body with a geometry resembling a floating production, storage, and offloading vessel (FPSO). The experiments are described in Mai et al. (2016), and several numerical results were reported and initially compared at the 28th International Society of Ocean and Polar Engineering (ISOPE) conference held in Sapporo, Japan in June 2018. The findings of the comparative study are reported in Ransley et al. (2019).

GOVERNING EQUATIONS

The governing equations for the FNPF problem are expressed here in the Eulerian form. Let the fluid domain $\Omega \in \mathbb{R}^d$ be a bounded, connected domain with a piece-wise smooth boundary $\Gamma \in \mathbb{R}^{d-1}$. Let further the time domain be denoted by $T : t \geq 0$.

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KEY WORDS: Spectral element method, high-order numerical methods, unstructured meshes, fully nonlinear potential flow, focused wave, wave–body interaction, FPSO.