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Simulation and analysis of wave-structure interactions for a semi-immersed horizontal cylinder

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ABSTRACT

The paper is concerned with the use of the open source computational fluid dynamics software package, OpenFOAM® for predicting and analysing the behaviour of a semi-immersed horizontal cylinder subject to different types of wave conditions. This study involves two separate cases of wave-structure interaction involving a semi-immersed horizontal cylinder, which may represent the simplified form of a cylindrical component of a wave energy converter. First, the flow around a fixed semi-immersed horizontal cylinder subject to regular waves is studied, in which the horizontal and vertical forces are computed and compared to linear wave theory and available experimental data. Further, a semi-immersed horizontal cylinder with a prescribed oscillatory vertical motion is considered to determine the surface wave elevations generated by the motion of the cylinder. The measured numerical surface elevations are also compared with theoretical predictions and experimental data. Both cases considered in this paper are simulated in a numerical wave tank where wave relaxation zones are utilised to avoid wave reflections. It is concluded that the numerical data produced by OpenFOAM® provide good overall agreement within the limitations of the relevant theory and experimental data.

1. Introduction

The marine renewable energy industry is still at a nascent stage, but is considered a key part of the strategy to hit the targets of renewable energy supply set by the UK government for 2020. Whilst innovative marine renewable energy device technologies have received a great deal of interest in generating clean and sustainable energy, the technicalities of operating them in hostile environments remain complex and challenging. In practice, wave energy converters (WEC) are required to operate efficiently under many different types of wave conditions and designed to optimally extract energy from ocean waves. To achieve this goal, complex wave-structure interactions involved in WEC operation need to be modelled accurately under a wide range of conditions. Existing theoretical solutions are based on approximations which are often too restrictive to simulate the WEC performance accurately. Linear potential theory is widely used and is valid if the wave amplitude and body motions are not too large compared to the body dimensions, and if the wave steepness is not too great. These methods accurately take into account wave diffraction and radiation effects, but neglect viscous effects and non-linear effects. For smaller bodies in larger and steeper waves, empirical methods (e.g. the MOJS equation by Morison, O'Brien, Johnson and Schaaf, 1950) are more appropriate as they can incorporate non-linear and viscous effects, but they may not accurately model wave diffraction and radiation effects. Computational fluid dynamics (CFD) methods are capable of incorporating all non-linear wave diffraction, radiation and viscous effects and can therefore provide a solution which is valid over a wide range of wave and body motion regimes.

The main aim of this study is to gain a better understanding of the hydrodynamic analysis of wave-structure interactions for a semi-immersed horizontal cylinder when operating under different types of wave conditions. This study also serves as a foundation to provide the fundamental knowledge of the interactions of a cylindrical attenuator type WEC with ocean waves. The simulations in this study are carried out using OpenFOAM®, an open source CFD software package, which uses the finite volume method for solving the discretized Navier-Stokes equations. Two separate cases of a semi-immersed horizontal cylinder are considered, which may represent the simplified form of a cylindrical component of a WEC. The first case is carried out to model the structure as a fixed obstacle, in the form of a semi-immersed horizontal cylinder, which is placed in the numerical wave tank (NWT) and subject to an

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incident wave at one end of the tank. The wave induced vertical and horizontal forces (lift and drag) acting on the cylinder are then computed from the pressure and the shear stress data. In the second case, the structure is floating and consideration is given to a semi-immersed horizontal cylinder subject to a forced sinusoidal vertical displacement. The resulting surface wave elevations generated by the structure are then computed for various structure oscillation amplitudes and frequencies. Results for both cases are compared with existing theories which are valid under certain simplified assumptions. Available experimental data in the literature are also compared with the numerical results. Both cases are simulated in a two-dimensional (2D) NWT using waves2Foam, a third party toolbox developed by Jacobson et al. (2012) within OpenFOAM® for wave generations and wave absorptions.

Various authors have considered wave interaction with a fixed semi-immersed horizontal cylinder, such as Dean and Ursell (1959), Dixon et al. (1979), Dixon (1980), Martin and Dixon (1983), Andersson (2011), Westphalen et al. (2012), Bihs and Ong (2013), Chen et al. (2015) and Ong et al. (2017). Martin and Dixon (1983) carried out a linear wave theory prediction for the forces acting on a fixed cylinder. They also generated experimental data for various wave frequencies and medium wave amplitudes for comparison with linear wave theory. Martin and Dixon (1983) used classical potential theory, in which the two dimensional diffraction boundary-value problems are solved linearly using Ursell's multipole method. Dean and Ursell (1959) also carried out experiments for measuring the forces acting on a fixed horizontal cylinder for various wave frequencies but under low wave amplitude conditions. Dixon et al. (1979) and Dixon (1980) used an equation based on Morison et al. (1950) to predict the vertical and horizontal wave forces acting on a fixed horizontal cylinder and compared them with the experimental data conducted as part of the Edinburgh Wave Power Project. Westphalen et al. (2012) reproduced some of the experimental data by Dixon et al. (1979) on a fixed horizontal cylinder using STAR-CCM+® and ANSYS CFX®. Andersson (2011) carried out similar numerical investigation using OpenFOAM® and compared his numerical results with Westphalen et al. (2012). Both Westphalen et al. (2012) and Andersson (2011) simulated a single wave frequency and wave height for each of the three different cylinder submergence depths. They mainly concentrated on the large amplitude waves in order to establish the non-linear behaviour of the vertical forces acting on the cylinder. This paper, however, examines the gradual transition of the linear to non-linear behaviour of the horizontal and the vertical forces on the cylinder when subject to a series of wave cases with different wave heights and wave frequencies. Bihs and Ong (2013) carried out 2D numerical simulations using a CFD model to investigate free surface waves past a single semi-submerged cylinder, whilst Ong et al. (2017) carried out similar study on both single and two semi-submerged horizontal cylinders under turbulent flow. Both studies focused on the vertical forces induced on the cylinder(s), in which the results are compared with experimental data by Dixon et al. (1979). Chen et al. (2015) also investigated wave forces on partially submerged fixed circular and square cross section cylinders in a wave tank numerically based on the Navier-Stokes equations. Chen et al. (2015) compared their numerical results with a modified Morison equation (Dixon, 1980) and suggested that the equation tends to underestimate the wave forces. The wave properties and water depth chosen by Chen et al. (2015) are all outside of the range selected in this paper.

Various studies were carried out on an oscillating cylinder in free surface flow by Tasai (1960, 1961), Frank (1967), Vugts (1968), Ramos and Guedes Soares (1997) and Gadelho et al. (2014), they concentrate on determining the hydrodynamic coefficients and the forces on the oscillating cylinder. Recently, Gadelho et al. (2014) presented a study to determine the hydrodynamic coefficients of an oscillating 2D cylinder using OpenFOAM® and compared the results for heave and sway motions of the cylinder in deep water with the experimental data by Sutulo et al. (2009, 2010). Whilst Chung (2015) investigated the effects of the oscillating cylinder motion on the free surface deformations, the cylinder was fully submerged beneath the free surface. The second case in this paper is based on a study by Yu and Ursell (1961, 1949), where potential flow theory is used to predict surface wave amplitudes that are generated when a semi-immersed horizontal cylinder is subject to a small forced oscillation in the vertical direction. The theory is valid for finite water depths and results were generated for a wide range of wave frequencies. Yu and Ursell (1961) also generated experimental wave amplitude data in a physical tank which were compared with their linear wave theory predictions.

Section 2 of this paper provides a description of the methodology and the theoretical analysis for this study. It describes the governing equations leading to the Navier-Stokes equations solved within OpenFOAM® and the definition of the NWT. The features of the wave generation toolbox, waves2foam are explained to show how waves generated in a physical wave tank can be replicated in a NWT. Section 2 describes the theoretical analysis of the wave induced forces on a semi-immersed horizontal cylinder using a linearised wave theory by Martin and Dixon (1983). Comparisons are also made with a non-linear theory provided by Dixon et al. (1979) and Dixon (1980), which uses an empirical formula based on Morison et al. (1950), to predict the horizontal and the vertical wave forces. Section 2 also shows a brief summary of the theory developed by Yu and Ursell (1961) for predicting surface waves generated by an oscillating cylinder. Section 3 of this paper focuses on the application of the numerical method discussed in Section 2 in order to simulate the fixed cylinder and the oscillating cylinder cases. The numerical results are analysed and compared with both the theoretical predictions and experimental data from the literature. The numerical results presented in Section 3 also show the transition of the wave forces and surface wave amplitude ratios of the cylinder in more detail towards non-linearity and divergence from linear theory, as well as the validity and limitation of the linear theory. Section 4 is devoted to the overall conclusions of the work carried out in this paper.

2. Theoretical analysis

2.1. Governing equations for fluid flow

This study was carried out using OpenFOAM® (Open Field Operation And Manipulation), an open source CFD software package comprised of C++ libraries and codes developed by OpenCFD Ltd at ESI Group. OpenFOAM® consists of a wide range of features and capabilities for solving continuum mechanics such as chemical reactions, turbulence, heat transfer, solid dynamics and electromagnetics (Greenshields, 2015). The solvers used in this study are interFoam and interDyMFoam. Both solvers are designed for multiphase flows which use a VOF (volume of fluid) phase-fraction based interface for solving two incompressible, isothermal immiscible fluids. Whilst interDyMFoam is designed for similar applications as in interFoam, it has the option of mesh motion and mesh topology changes. Both solvers use a finite volume method for discretizing the Navier-Stokes equations, in which the fluid flow domain is discretized by creating a grid mesh over the entire domain of interest. In a Cartesian coordinate system (x,y,z), the governing equation of motion for a time-dependent three-dimensional multiphase (air and water) incompressible laminar fluid is described as

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla\cdot[\rho \mathbf{u}\mathbf{u}^T] = -\nabla p^* + \nabla\cdot[\mu \nabla \mathbf{u}] + \sigma_T \kappa_\gamma \nabla \gamma \ , \tag{1}$$

where t is the time, ∇ is a vector differential operator, $\mathbf{u}$, $\mathbf{u}^T$ is the velocity vector and velocity vector transpose respectively of a fluid element, p^* is the gauge pressure, μ is the dynamic viscosity of the multiphase fluid, ρ is the density of the multiphase fluid, σ_T is the surface tension coefficient, κ_γ is the surface curvature of the air-water interface, $\gamma (0 \le \gamma \le 1)$ is the water volume fraction in a mesh cell ($\gamma = 0$ for air only and $\gamma = 1$ for water only). Coupled with the equation of motion (1), for incompressible flows, the equation of continuity can be written as