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Numerical simulation of fully nonlinear wave interaction with submerged structures: Fixed or subjected to constrained motion

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ABSTRACT

The interaction between fully nonlinear water waves and fully submerged fixed or moving structures is investigated. A three-dimensional numerical wave tank model, based on potential theory is extended to include a submerged horizontal or vertical cylinder of arbitrary cross section. The vertical cylinder is allowed to have a constrained motion while attached to a rigid cable, which could represent the submerged payload of an offshore crane vessel subjected to wave actions. In this fully nonlinear time-domain approach, the higher-order boundary element method is used to solve the mixed boundary value problem based on an Eulerian description at each time step. The 4th-order Runge–Kutta scheme is adopted to update the free water surface boundary conditions expressed in a Lagrangian formulation. Interaction between waves and a submerged fixed horizontal cylinder is then computed by the model and compared with experimental and other numerical results. After that, a parametric study is performed to obtain numerical results for the vertical cylinder undergoing forced pitch motions. More simulations are carried out to investigate the hydrodynamic features of the submerged vertical cylinder in water waves attached to a cable for constrained motion and moving towards the sea bed at a constant velocity.

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1. Introduction

Offshore installation operations are relevant to all structures situated offshore, as most of them are built onshore, then transported and installed at the operating site. For example, for an oil production platform, the topside part and the foundation part are always constructed separately, and they are only assembled at sea at the final stage. The offshore installation operations are therefore the key factor that must be taken into account in the design of offshore structures. Different types of structures require different methods of installation, and heavy lift is the most common method of installation of offshore structures. In this method, the structure is lifted off the transportation vessel by a crane vessel and lowered into position.

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An offshore lift operation in the ocean wave environment is a very complicated process, where the interaction between response of the crane vessel and motion of the payload is coupled. Even small disturbances in the state of the system can entail the danger of collisions of the payload with the ship or other objects. Evaluating the stability of the crane vessel and the motion of the payload simultaneously is therefore a challenging task. However, we could treat the coupled system as two relatively independent sub-systems: the vessel and the payload. In the present paper, we only focus on the motion of payload which is fully submerged in waves and subject to constrained motions.

The study of submerged bodies in water waves has received considerable attention for many years and several papers have been dedicated to the analytical, numerical and experimental study of the hydrodynamic response of such submerged structures. Among them, the interaction between monochromatic gravity waves and a fixed submerged horizontal circular cylinder, with its axis parallel to the crests of the incident wave, was first studied by Dean (1948), using a linearized potential theory and the conformal mapping technique. In that study Dean showed that, to the first order there is no reflection of incident waves by the circular cylinder, and that transmitted waves only undergo a phase shift when passing the obstacle. Ursell (1950) subsequently obtained the complete linear solution and reproduced Dean's conclusions. Ogilvie (1963) and Mehlum (1980) confirmed and extended the work by Dean (1948) on the diffraction problem. The work of Ursell (1950) and Ogilvie (1963) also investigated the wave radiation problem for a circular cylinder in forced oscillations and showed that it is possible to absorb all the power in a sinusoidal wave, by forcing a cylinder to move in a circular path.

The first experimental study related to this phenomenon was undertaken by Chaplin (1984) in order to calculate the nonlinear forces and the nonlinear features of the reflected and transmitted waves originating from a fixed submerged horizontal cylinder. His study revealed the nonlinear components of these forces with frequencies up to 3 times the fundamental wave frequency. Since then, analysis of the hydrodynamic performance of submerged bodies has become increasingly important with the growing interest in offshore activities, especially in the ocean wave energy context which involves exploiting the wave induced motion of oscillating submerged bodies. This has led to a number of numerical studies. Vada (1987), for example, used an integral equation method based on Green's theorem to solve the second-order wave diffraction problem for a submerged cylinder of arbitrary shape. His results were in good agreement with those of Ogilvie (1963) and Chaplin (1984). Wu (1993) formulated a mathematical model to calculate the forces exerted on a submerged cylinder undergoing large-amplitude motions. He satisfied the no-flow boundary condition on the submerged body on its instantaneous position, while the free surface condition was linearized. The solution for the potential was expressed in terms of a multipole expansion. In particular, Wu (1993) obtained results for a circular cylinder undergoing prescribed motions in a wave field.

Chaplin (2001) and Schønberg and Chaplin (2003) performed more detailed experimental and numerical studies of the nonlinear wave interactions with a submerged horizontal cylinder. Following that, Koo et al. (2004) developed a two-dimensional fully nonlinear numerical wave flume based on the potential theory, MEL time marching scheme, using a boundary element method. This model was applied to determine wave characteristics and wave loads on submerged single and dual cylinders.

Among more recent studies, Conde et al. (2009) performed another experimental study in conjunction with numerical analysis to study the fully nonlinear behaviour of a two-dimensional horizontal cylinder in waves. Guerber et al. (2010) extended a two-dimensional fully nonlinear potential wave model to include a submerged horizontal cylinder of arbitrary cross-section. Chen (2012) developed a new vortex based panel method for the numerical simulation of a 2-D potential flow around a hydrofoil submerged under a free surface with energy dissipation. An and Faltinsen (2013) studied the forced harmonic heave motions of horizontally submerged and perforated rectangular plates both experimentally and numerically at deep and shallow submergence. Some recent studies have also been undertaken to apply viscous models to fixed submerged bodies of various shapes. Bai et al. (2010), for example, studied two-dimensional submerged dikes interacting with viscous free surface waves using the Cartesian cut cell approach; Lam et al. (2012) modelled the laminar and turbulent flows around wavy rectangular cylinders; and Sarkar and Ratha (2014) carried out an experimental investigation on the flow field around submerged structures on horizontal plane beds.

From the above discussion, we can notice that most of the previous numerical investigations using potential flow models mainly focused on the study of submerged horizontal circular cylinders or plates in water waves, due to the ease of implementation. The dynamic response of a fully submerged payload subject to constrained motions under the action of waves, however, is not well understood. The main difficulty associated with this process lies in the large motion that the payload might experience in waves when the payload supported by a cable is lowered down at a constant speed. In such a situation, the conventional frequency-domain analysis may not be applicable. At the same time, even in the time-domain approach, a volume-discretized method, such as the Finite Element Method (FEM), might encounter some unsolvable difficulties in the mesh generation for the highly-deformed computational domain. The authors are not aware of any published results for a fully nonlinear three-dimensional study of a submerged crane vessel payload undergoing constrained motions in waves.

The present study aims at obtaining a good insight into this problem by using numerical simulation. The approach presented here uses a 3D fully nonlinear potential flow model based on the Boundary Element Method (BEM), which is an extension of the programme developed by Bai and Eatock Taylor (2006, 2007, 2009) for simulating the wave radiation, wave generation, propagation and interaction with structures. The original code has been modified to make it capable of considering fully submerged bodies either fixed or subjected to forced and/or constrained motions under wave actions. The overall approach is as follows. First the mathematical formulation is presented in Section 2, followed by its numerical

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