

Fully nonlinear time-domain simulation of a backward bent duct buoy floating wave energy converter using an acceleration potential method

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ABSTRACT: A floating Oscillating Water Column (OWC) wave energy converter, a Backward Bent Duct Buoy (BBDB), was simulated using a state-of-the-art, two-dimensional, fully-nonlinear Numerical Wave Tank (NWT) technique. The hydrodynamic performance of the floating OWC device was evaluated in the time domain. The acceleration potential method, with a full-updated kernel matrix calculation associated with a mode decomposition scheme, was implemented to obtain accurate estimates of the hydrodynamic force and displacement of a freely floating BBDB. The developed NWT was based on the potential theory and the boundary element method with constant panels on the boundaries. The mixed Eulerian-Lagrangian (MEL) approach was employed to capture the nonlinear free surfaces inside the chamber that interacted with a pneumatic pressure, induced by the time-varying airflow velocity at the air duct. A special viscous damping was applied to the chamber free surface to represent the viscous energy loss due to the BBDB's shape and motions. The viscous damping coefficient was properly selected using a comparison of the experimental data. The calculated surface elevation, inside and outside the chamber, with a tuned viscous damping correlated reasonably well with the experimental data for various incident wave conditions. The conservation of the total wave energy in the computational domain was confirmed over the entire range of wave frequencies.

KEY WORDS: Backward bent duct buoy; Numerical wave tank; Fully nonlinear; Acceleration potential; Viscous energy loss; Pneumatic chamber; Energy conservation; Oscillating water column.

INTRODUCTION

Since the 19th century, ocean wave energy has often been studied as a key renewable energy resource. Over 1000 patented wave energy take-off devices have been proposed as energy converters in the last several decades. Recently, as a specific functional structure system, an array of porous circular cylinders has been studied for use as an efficient wave energy take-off or attenuation system (Park et al., 2010). In general, wave energy take-off techniques are based on nine ideas (McCormick, 2007). One of the most practical and energy efficient concepts is the Oscillating Water Column (OWC), which is based on a pneumatic power take-off inside the chamber achieved by using specially designed air turbines, such as the Wells, Impulse, and Denniss-Auld turbines.

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Since Masuda (1971) first proposed a commercially-available OWC device, several commercial-level fixed-type OWC plants have recently been constructed and operated successfully (Heath et al., 2000). Numerical analyses of fixed OWC systems have been performed by many researchers (Brendmo et al., 1996; Wang et al., 2002; Delaure and Lewis, 2003). However, most of these analyses were founded on linear-based numerical models. Koo and Kim (2010) recently developed a fully nonlinear time-domain model of a land-based OWC system. Their simulation included viscous energy loss from the chamber skirt and pneumatic pressure from oscillatory airflows in the chamber.

For a floating-type OWC system, Masuda et al. (1987) proposed a special type of OWC, a Backward Bent Duct Buoy (BBDB), which is thought to be one of the most energy-efficient OWC devices. The BBDB has the typical characteristics of dynamic behavior due to its unique body shape, such as a reverse time-mean drift force. Therefore, many studies on the hydrodynamic behaviors of BBDBs, including reverse drifting, have been conducted, either numerically or experimentally (McCor-mick and Sheehan, 1992; Hong et al. 2004a; 2004b; Kim et al., 2006; 2007; Nagata et al., 2008; 2009; Imai et al., 2009; Toyota et al., 2008; 2009). Suzuki et al. (2011) performed a numerical investigation to determine the optimal two-dimensional (2D) hull design of the BBDB using the eigen-function expansion method, with the relevant experiment being conducted by Toyota et al. (2010). Using a 2D numerical wave tank (NWT) technique, Koo and Lee (2011) and Koo et al. (2012) calculated the hydrodynamic behavior of a BBDB and chamber free surfaces with different shaped-corners. A proper viscous damping coefficient was applied to their numerical model, which was deducted from the experimental results.

In this study, a state-of-the-art 2D fully-nonlinear NWT technique was fully described for a simulation of a floating OWC wave energy converter, a BBDB. Using the acceleration potential method associated with pneumatic pressured chamber and viscous energy loss, the hydrodynamic performance of the floating BBDB was simulated in the time domain. The developed NWT technique was based on the potential-fluid theory and the boundary element method with constant panels on the boundaries, on which fully nonlinear free-surface and moving body boundary conditions were applied. A mixed Eulerian-Lagrangian (MEL) scheme was used for a time-varying nonlinear free-surface treatment, along with the Runge-Kutta fourth-order time integration scheme, as a time-marching approach. To accurately predict the time derivative of the velocity potential for the freely floating BBDB, the mode decomposition scheme combined with the acceleration potential was implemented to calculate the body force and displacement by simultaneously solving the equations of body motion and the velocity potential.

In order to consider the effect of pneumatic pressure acting on the free-surface inside the chamber, the damped free surface condition was applied to the NWT technique, which was first presented by Evans (1982), Sarmento and Falcao (1985) and Falnes and McIver (1985). A linear relation between the chamber pressure and airflow velocity at the air duct, as observed in various experiments, was used to model the OWC chamber (Gato and Falcao, 1988; Suzuki and Arakawa, 2000). The time-varying pneumatic pressure, due to instantaneous airflow velocity interacting with free-surface fluctuation, was numerically modeled in an OWC system. The energy loss due to viscous flow at the entrance of the BBDB hull, which could be amplified by the body motions, was also modeled by imposing an artificial viscous damping coefficient upon the free surface inside the chamber. In the potential flow calculation, the viscous damping coefficient can be obtained by a comparison of the experimental data in open chamber conditions, which represents no pneumatic chamber pressure. The difference of chamber free surface elevation between the potential-fluid-based numerical results and the experimental data in open chamber conditions can be interpreted as the viscous damping.

MATHEMATICAL FORMULATION

Boundary value problem for a floating BBDB

In order to simulate a freely floating BBDB associated with a pneumatic chamber and viscous damping, the mixed boundary value problem has to be solved using proper boundary conditions. The boundaries on the computational domain are the free surfaces inside and outside of the chamber, the body surface, the incident wave boundary, the rigid sea bottom, and the rigid end-wall. Using the velocity potential (ϕ) and a continuity equation that satisfied the entire fluid domain, the Laplace equation (Eq. (1)) was chosen as a governing equation under the assumption of inviscid, incompressible, and irrotational flows. However, a special damping can be applied on the free surface inside the chamber to represent the viscous energy loss due to body shape and motion. Using the Green function (G), the Laplace equation can be transformed into a boundary integral equation (Eq. (2)) that is solved with the corresponding boundary conditions on the respective boundaries:

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