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Current effects on nonlinear wave slamming by an Oscillating Wave Surge Converter

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ABSTRACT

A time-domain higher-order boundary element method (HOBEM) based on potential theory with fully nonlinear boundary is developed to simulate an Oscillating Wave Surge Converter (OWSC) rotating in waves in the presence of uniform currents. A domain decomposition method which neglects impact of jet flow to the main flow field is adopted. Auxiliary function is used to calculate the pressure distribution on body surface. The rotating coordinate system with origin fixed at the rotating center is established to avoid the water particle moving into or away from the body during the simulation. An iteration method is employed to assess the values of coupling wave characteristics affected by currents. Good agreement is found between present model and published fist-order boundary element method (FOBEM) model for the interaction of flap and current-free waves. Numerical simulations are then conducted in the presence of following current, opposing current and zero current, respectively. Several parametric studies, such as angle velocity and angular acceleration of the flap, initial phase, wave height and wave length, are performed to study the characteristics of the slamming problem with taking into account currents effects. The numerical results are presented through free surface profiles and pressure distributions.

1. Introduction

To cope with the increasing costs of environment pollutions and climate changes induced by the extensive use of fossil energy, renewable energy technologies are regarded as playing a more and more important role to reduce these influences. Wave energy is certainly a significant one of the four main sources of marine renewable energy i.e. wave energy, tidal energy, ocean thermal energy and wind energy [1] because of its uninterrupted and continuous supply of energy. A wide range of wave energy converters (WECs) has been developed since 1980, in which OWSC devices has been extensively reported and implemented due to viable wave energy harvesting in near shore coastal zone. Oyster is believed to be one of the most promising forms of the OWSC systems. It is a buoyant flap which is hinged at the seabed and has the top edge piercing through the water surface. The large flap is used to extract wave energy from the horizontal motion of the water particle. As waves propagate over the coastal zone, shoaling effect can enhance the hydrodynamic efficiency of this device, and therefore, Oyster is typically installed in the area of water depths of 10–20 m [2]. Yet, Oyster technology has not been fully commercialized because the hydrodynamics of the OWSC devices remains not well-understood. For example, wave slamming occurs usually when the flap hits water surface with high speed, especially, in rough sea states. This leads to a short duration but high magnitude pressure on the body surface. Although extensive researches have been made to investigate the hydrodynamic behavior of Oyster devices theoretically at the early stage, such as Folley et al. [3], Folley and Whittaker [4], Renzi and Dias [5,6] and Gomes et al. [7], majority of OWSC theories are based on linear wave theory and neglect the wave nonlinearity and wave slamming.

Wave slamming on an OWSC was firstly investigated by Henry et al. [8], conducting physical experiments and numerical simulations. They found that the slamming on an OWSC is more complex than a wave hitting a wall due to the strong coupling between the incident wave and the flap motion. Subsequently, Henry et al. [9] further compared the slamming results of two-dimensional (2D) and three-dimensional (3D) experiments, and obtained almost identical characteristics of wave slamming and pressure distribution. Therefore, a two dimensional wedge was commonly used in slamming analysis. On this basis, Wei et al. [10] employed the FLUENT software to simulate the physics of the slamming process. The conclusions indicated that the strongest impact pressure was located at the middle of the flap below mean water level. Afterward, Ferrer et al. [11] demonstrated numerically that when the flap hits the water free surface with high speed, a trapped air pocket will be developed on the seaward side of the flap. While the above works are based on various

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Computational Fluid Dynamics (CFD) models with Navier–Stokes equations solver. Another interesting solution is potential-flow models. Sun et al. [2] applied first-order boundary element method (FOBEM) with the domain decomposition method to simulate the falling jet into the main fluid domain. They attributed the decreased pressure at the jet root with the deadrise angle of the flap to the gravity effect. However, the slamming pressure is more directly related to the wave parameters, i.e. wave length and wave amplitude. Therefore, it is worth to conduct a more systemic and comprehensive study of the effects of wave nonlinearity on the slamming on OWSCs, especially when waves and currents are both present.

The slamming on an OWSC is also similar to the water entry problem of a wedge. Based on the incompressible velocity potential theory, Howison et al. [12], Faltinsen [13] and Korobkin and Scolan [14] used the Wagner theory to concentrates on the water entry of a wedge into calm water. The Wagner theory is mainly applicable to the body with blunt bottom or the wedge with small deadrise angle. Relative to Wagner theory, the fully nonlinear boundary method has many attractive merits, i.e. the rigorous definition of the instantaneous positions of the body surface and the free surface, and the development of a thin and long jet. The proponents of this approach are Zhao and Faltinsen [15], Semenov and Iafarati [16], Xu et al. [17] and Bao et al. [18]. In their works, simulations were made by cutting the tip of the jet as soon as it near the main flow and therefore calculations were completed in single domain. However, sharp and nonphysical spike was usually observed in the time derivative of the pressure as time continues. In this paper, the domain decomposition method [19, 20] is adopted to divide the overlapping domain induced by a jet falling into the main fluid domain into sub-domains. This allows the main flow and the jet to meet the same location in the complex plane but they do not affect each other directly. By applying the match condition (continuity of the pressure and normal velocity) between the outer and the inner sub-domains, the unknown potential in the boundary condition equations can be solved.

All mentioned studies for the slamming effect of the body, however, are based on the wave or clam water tests without taking into account the current effects. Waves and currents generally coexist in real sea condition and their interactions play an important role in the most ocean dynamic processes. The incident wave steepness is reduced by the following current and vice versa for the opposing current [21]. Thus, the presence of the current can lead to wave deformation and the wave energy exchange between the fundamental waves and higher-order waves. For example, the ratio of the higher-order wave energy to the fundamental wave energy is enhance by the following current but weakened by the opposing current [22–25]. Moreover, the form of the jet for wave slamming problem is also altered by currents, which leads to the fact that the peak pressure moves rapidly along the body surface [26]. However, to the authors' knowledge, there has been far less work on wave slamming on an OWSC in the presence of a uniform current, which could be computationally more accurate and physically realistic.

To this end, this study aims to elucidate the mechanism behind wave–current slamming behavior in the Oyster hydrodynamic performance. For the analysis, to allow the developed splash jet to enter the main flow when the Froude number exceeds certain value. The current effect is incorporated by introducing the current velocity into the fully nonlinear free surface boundary conditions. A time-domain higher-order boundary element method (HOBEM) with the domain decomposition approach is adopted to solve the water boundary integral equations of each sub-domain. HOBEM has been widely applied in many nonlinear water wave problems except for wave–current slamming on an Oyster, e.g. submerged breakwater device [23], floating breakwater device [27] and floating platform [28]. The auxiliary function method is introduced to calculate the fluid pressure on the body surface instead of directly assessing the time derivative of the velocity potential. A rotation coordinate scheme is employed on the intersection point of the body and free surfaces to avoid the water particle move away from or into the flap surface. The paper is organized as follow: a description of the fully nonlinear model is introduced in Section 2. In Section 3, the numerical results are compared with the published numerical results. In Section 4, the influences of uniform collinear currents on the slamming problem induced by the Oyster plunging into waves are examined. The effects of some design parameters, such as current direction, angle of deflection, angle velocity, starting position, incident wave height and wave length, are stated. Finally, the conclusions are given in Section 5.

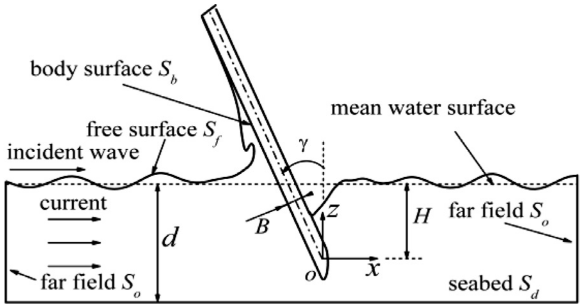

Fig. 1. Schematic diagram of interaction of flap and wave–current.

2. Numerical model

2.1. Boundary conditions

The interaction of wave–current with a forced rotating flap in two-dimensional fluid domain is shown in Fig. 1. The slamming problem is simulated in the paper by rotating the flap into water through a prescribed motion. The end of flap is a semicircle and diameter equal to the width of the flap. To deal with such a problem, a Cartesian coordinate system *O-xz* is defined with the origin at the rotating center, *x*-axis along the direction of propagation of the incident waves, and *z*-axis positive upwards. γ in the figure is the rotating angle from *z*-axis to the centerline of the flap and the angular velocity Ω is the time derivative of γ with respect to time *t*. As shown in Fig. 1, *h* denotes the static water depth and *b* the half thickness of the flap. The vertical distance *d* from the origin to the mean water surface, the acceleration due to gravity *g* and the water density ρ are used for non-dimensionalization in this paper, and all the values are non-dimensionalization in following sections unless it is specified.

The fluid is assumed to be incompressible, inviscid with irrotational flow and so that a velocity potential can be used to describe the fluid motion. On the other hand, considering the effects of current, the total velocity potential $\Phi(x,z,t)$ can be expressed as:

$$\Phi(x,z,t) = \varphi(x,z,t) + Ux, \tag{1}$$

where $\varphi(x,z,t)$ is the perturbation potential caused by waves and U is the velocity of steady-uniform current. Both $\Phi(x,z,t)$ and $\varphi(x,z,t)$ satisfy the Laplace equation:

$$\nabla^2\Phi = \nabla^2\varphi = 0. \tag{2}$$

Due to the existence of currents, the dynamic condition and the kinematic boundary condition on the free surface S_f in Eulerian form should be written as:

$$\frac{\partial\varphi}{\partial t} = -\eta - \frac{1}{2}|\nabla\varphi|^2 - U\frac{\partial\varphi}{\partial x} - \frac{1}{2}U^2, \tag{3}$$

$$\frac{\partial\eta}{\partial t} = \frac{\partial\varphi}{\partial z} - \frac{\partial\varphi}{\partial x}\frac{\partial\eta}{\partial x} - U\frac{\partial\eta}{\partial x}, \tag{4}$$

where $\eta = z\text{-}d$ is the free surface elevation above the mean water line. In this paper, a mixed Eulerian–Lagrangian method (MEL) is adopted to track the time-dependent free surface node. The dynamic condition and the kinematic boundary condition on the free surface S_f can be written as:

$$\frac{d\varphi}{dt} = -\eta + \frac{1}{2}|\nabla\varphi|^2 - \upsilon(x)(\varphi - \varphi_I), \tag{5}$$