Ocean Engineering 78 (2014) 73–88

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Numerical study on the water impact of 3D bodies by an explicit finite element method

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ARTICLE INFO

Article history:
Received 26 April 2013
Accepted 14 December 2013
Available online 31 January 2014

Keywords:
Numerical modeling
Water impact
Explicit finite element method
Impact coefficient
Slamming
Wave converter

ABSTRACT

The hydrodynamic problem of the water impact of three-dimensional buoys is investigated by the explicit finite element method with an Arbitrary-Lagrangian Eulerian (ALE) solver. The fluid is solved by using an Eulerian formulation, while the structure is discretized by a Lagrangian approach, and a penalty coupling algorithm enables the interaction between the body and the fluids. The remap step in the ALE algorithm applies a donor cell + HIS (Half-Index-Shift) advection algorithm to update fluid velocity and history variables. The interface between the solid structure and the fluids is captured by Volume of Fluid method. Convergence studies are carried out for three dimensional hemisphere and cones with different deadrise angles. It is found that the mesh density of the impact domain is very important to the quality of the simulation results. The contact stiffness between the coupling nodes affects the local peak pressure values. The numerical calculations are validated by comparing with other available results, for both the drop cases and the ones with constant impact velocity.

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1. Introduction

Ocean waves are a significant resource of inexhaustible, non-polluting energy. Waves are caused by the wind blowing over the surface of the ocean. In many areas of the world, the wind blows with enough consistency and force to provide continuous waves. A variety of technologies have been proposed to capture the energy from waves, and they differ in their orientation to the waves with which they are interacting and in the manner in which they convert the energy of the waves into other energy forms. Wave energy converters provide a means of transforming wave energy into usable electrical energy.

Point absorbers are one type of wave energy converters that have small dimensions relative to the incident wave length. They can capture wave energy from a wave front that is larger than the dimensions of the absorber. Several types of wave absorbers have been proposed based on different mechanisms of obtaining relative motions between two bodies. Due to their relatively small size, the amount of energy that they can capture is relatively small as compared with devices based on other principles in Guedes Soares et al. (2012) and Silva et al. (2013). To overcome this limitation a possibility is having a large platform fixed or floating around which several small floaters have heaving type of motions, which can then be converted in power by the power take off mechanism in Vantorre et al. (2004), Lendenmann et al. (2007), Estefen et al. (2008) and Marquis et al. (2010). However, in this process it may happen that the floaters when at resonance have too high vertical displacements and will move out of the water, impacting it at the entrance. This problem has been detected by De Backer et al. (2008), who gives a brief introduction on how the power absorption is calculated, how the slamming restriction is formulated and fulfilled, and they found that there is a significant reduction in power absorption due to the slamming restriction. Since, in any case, the penalty to overcome slamming of the point absorbers completely will be too high and a certain level of slamming will usually be allowed, it is important to know the magnitude of the slamming load on the floating objects with different shapes.

De Backer et al. (2009), conducted an experimental study of the impact of 3D bodies during water entry, in order to assess the slamming loads in these buoys appropriate to the wave energy devices under consideration. This paper uses these experimental results as references to validate 3D numerical studies, which follow earlier work in 2D.

Early studies on the local slamming problem focused on the analysis of two-dimensional structures, since slamming on ships has been a major concern and the 2D strip theory has been widely used in ship motions research. The important pioneering study on this subject can be attributed to von Kármàn (1929) who proposed the first theoretical method on the analysis of seaplane landing. Then, Wagner (1932) developed an asymptotic solution for water entry of two-dimensional bodies with small local deadrise angles

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0029-8018/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.oceaneng.2013.12.008

by approximating them with a flat plate, which considered the local water surface elevation. For the idealized case of a wedge entering the calm water, Dobrovol′skaya, 1969 derived an analytical solution by transferring the potential flow problem for the constant water entry into a self similar flow problem in complex plane, which took advantage of the simplicity of the body geometry and is valid for any deadrise angle.

Zhao and Faltinsen (1993, 1996) proposed a nonlinear boundary element method to study the water entry of a two-dimensional body of arbitrary cross-section and generalized the Wagner (1932)′s theory to presented a simple asymptotic solution for small deadrise angles. As a further development work, a fully nonlinear numerical simulation method which includes flow separation from knuckles of a body was presented by Zhao et al., 1996. Sun and Faltinsen (2006) developed a two-dimensional boundary element method to simulate the water flow during the water impact of a rigid horizontal circular and an elastic cylindrical shell. Exact free surface conditions were satisfactory.

Ramos et al. (2000) conducted an experimental program assessing the slam induced loads on a segmented ship model that with several interconnected long wedges while the previous studies dealt with individual 2D wedges, which was analyzed with the method used by Ramos and Guedes Soares (1998).

Most investigations of water entry problems, including the researches mentioned above have been focused on the two-dimensional impact, while fewer study have been conducted on the three dimensional cases which is more consistent with the real impact in engineering. In this field, early studies have been published by some researchers. Shiffman and Spencer (1951) investigated the vertical slamming on spheres and cones based on the analytical solution. They are among the first to notice that the liquid may separate from the sphere, leading to cavity formation, however, the stage of the impact under consideration in this study is before separation which means the penetration depth is less than half of radius. Shiffman and Spencer (1951) also give an explicit relationship of impact coefficient with $f(\beta)=1.6$ for a cone with deadrise angle 30°. E1 Malki Alaoui et al. (2012) recently found the experimentally determined equivalent as $f(\beta)=1.58$ and the non-dimensional slamming coefficient $f(\beta)$ depends only on the deadrise angle β. By means of high-speed shock machine, they studied the slamming coefficient on axisymmetric bodies, and found that *Cs* for hemisphere, unlike the cones, depends on the depth of immersions.

Based on the Wagner′s theory, Chuang (1967) developed an analytical formulation for the pressure distribution on a cone with small deadrise angle, and Faltinsen and Zhao (1997) proposed a theoretical method for water entry of hemispheres and cones with small deadrise angles. Battistin and Iafrati (2003) studied the impact loads and pressure distribution on axisymmetric bodies by numerical solution. In the field of experimental investigation, Chuang and Milne (1971) performed drop tests on the conical bodies, and recently Peseux et al. (2005) carried out the drop tests for cones with small deadrise angles which include 6°, 10° and 14°.

Motivated by the work of Stenius et al. (2006), who conducted the modeling of hydro elasticity in water impacts of ship bottom-panels by using LS-DYNA, Luo et al. (2011) and Wang et al. (2012) investigated the symmetric water impact of two-dimensional rigid wedge sections and ship sections, the predictions from which had very good agreement with comparable measured values and other numerical results by applying the explicit finite element method, and then the effects of the deadrise angle on the slamming load were presented in Wang and Guedes Soares (2012) and Wang et al. (Submitted for publication). They extended the research to the asymmetric water impact of a bow-flared section with various roll angles in Wang and Guedes Soares (2013). In the present work, the explicit finite element method is extended to study the hydrodynamic problem of three-dimensional bodies, including hemisphere and cones with different deadrise angles. The predictions are compared with the experimental results from the drop tests of De Backer et al. (2009) and theoretical calculations based on Wagner (1932)′s method, in terms of impact velocity, acceleration, penetration depth in the water and the pressure histories on the pressure sensors. The comparisons between them are satisfactory in the initial stage of the water entry. Then, the verified method is applied to estimate the impact coefficients on a falling hemisphere and a cone with a deadrise angle 30°, which show good consistency with some analytical and theoretical predictions.

2. Mathematical formulations

In this section, the equations that govern the fluid motion and the interaction between the fluid and structures in this explicit finite element method are recalled.

2.1. ALE description of Navier–Stokes equations

The governing equation for incompressible and unsteady Navier–Stokes fluid is described as:

$$\frac{\partial u}{\partial t}+u\nabla u-2u^F\nabla\varepsilon(u)+\nabla p=b \tag{2.1}$$

$$\nabla u=0 \tag{2.2}$$

where u is the flow velocity, p is the pressure of fluid, b means body force acting on the fluid and $\varepsilon(u)$ represents the deviatoric stress tensor.

The boundary condition and initial condition are

$$\sigma=-pl+2v^F\varepsilon(u) \tag{2.3}$$

$$\varepsilon(u)=\frac{1}{2}(\nabla u+(\nabla u)^T) \tag{2.4}$$

In ALE formulation, a reference coordinate which is not the Lagrangian coordinate and Eulerian coordinate is induced. The differential quotient for material with respect to the reference coordinate is described as following equation.

$$\frac{\partial f(X_i,t)}{\partial t}=\frac{\partial f(x_i,t)}{\partial t}+w_i\frac{\partial f(x_i,t)}{\partial x_i} \tag{2.5}$$

where, X_i is the Lagrangian coordinate, x_i is the Eulerian coordinate, and w_i is the relative velocity.

Therefore, the ALE formulation can be derived from the relation between the time derivative of material and that of reference geometry configuration.

Assume that v represents the velocity of the material, and u means the velocity of the mesh. In order to simplify the above equation, relative velocity w is induced, which is given by $w=v-u$. Therefore, ALE formulation can be obtained from following conservation equations:

(1) The mass conservation equation:

$$\frac{\partial\rho}{\partial t}=-\rho\frac{\partial v_i}{\partial x_i}-w_i\frac{\partial\rho}{\partial x_i} \tag{2.6}$$

(2) The momentum conservation equation

The governing equation of fluid is Navier-Stokes equation which is described by the ALE method:

$$\rho\frac{\partial v_i}{\partial t}=\sigma_{ij,j}+\rho b_i-\rho w_i\frac{\partial v_i}{\partial x_j} \tag{2.7}$$

The stress tensor is expressed by:

$$\sigma_{ij}=-p\delta_{ij}+\mu(v_{i,j}+v_{j,i}) \tag{2.8}$$

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