Ocean Engineering 130 (2017) 557–566

Contents lists available at ScienceDirect

Ocean Engineering

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

A three-dimensional numerical approach on water entry of a horizontal circular cylinder using the volume of fluid technique

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ARTICLE INFO

Keywords:
Water entry
Volume of fluid (VOF)
Horizontal circular cylinder
Free-surface flows

ABSTRACT

In this paper, complicated hydrodynamics of a horizontal circular cylinder entering water is investigated numerically for low Froude numbers. A numerical approach is used to model the solid-liquid interactions in presence of a free-surface. The governing equations for the 3D incompressible fluid flow are continuity and Navier-Stokes equations along with an equation for the free surface advection. To track the free-surface motion, the fast-fictitious-domain method is integrated into the volume-of-fluid (VOF) technique. The governing equations are solved everywhere in the computational domain including the horizontal cylinder. A rigid body motion is applied to the region occupied by the circular cylinder. The no-slip boundary condition on the solid-liquid interface is exerted implicitly via increasing the viscosity of the region occupied by the solid. To validate the numerical scheme, the results are compared with those of the experiments available in the literature. The effects of cylinder diameter, length, impact velocity, and cylinder-water density ratio on the non-dimensional depth are also investigated.

1. Introduction

Water entry problems have been studied theoretically and experimentally by many researchers and scientists for more than a century due to their extensive applications in numerous industries especially ocean and coastal engineering. Some water entry applications are namely: hydrodynamic loading on ships, ship slamming, launching of torpedoes, see-landing of aerial vehicles, missile projectiles' impact upon entering water, and even steel-making processes. However, cavity formation behind the solid object and capillary effects at the contact line between the surface of the solid and liquid complicates the understanding and analysis of this phenomenon.

Worthington and Cole (1897) presented an initial image of water impact cavity and splash by using single-spark photography. Water entry of vertical spherical objects was studied systematically by Worthington (1908). The solid-liquid interaction knowledge was improved comprehensively by later studies. Watanabe (1934) performed a quantitative experimental work to measure the impact force on an object upon entering water. The effect of various surface conditions of a sphere on the cavity formed during its water entry was investigated by May (1951). He also conducted (May, 1952) many experiments to analyze the effect of various parameters on the cavity which formed behind the solid. The effect of atmospheric pressure, solid velocity, and surface tension on the entry of spheres into water was studied by Gilbarg and Andersok (1948). It was concluded that the closure of splash was mostly dependent on an increase in atmospheric density and solid velocity. They also found that the splash closure was influenced by surface tension only in cases where the solid radius, velocity, and the atmospheric density are small. Several experiments were performed by Abelson (1970) to investigate pressure drop behind a solid object moving inside a liquid. The initial force of the impact on a sphere striking a liquid surface was estimated experimentally by Moghisi and Squire (1981). They also improved the correlation for the drag coefficient of a sphere during its initial entry into a liquid. Greenhow and Lin (1983) presented typical images for the free surface deformation during the water entry of two-dimensional cylinders. They assumed the length of the cylinder to be nearly the same as that of the tank to create a two-dimensional cavity following the cylinder impact. A whole cavity evolution for a horizontal cylinder was not created in their experiments since the depth of water was supposed to be shallow. Hu and Koterayama (1996) experimentally and numerically investigated the hydrodynamic forces acting on a rectangular cylinder and a circular cylinder undergoing slow drift oscillation in regular waves. The viscous flow around a two-dimensional oscillating cylinder was modelled using a finite-difference method. Lee et al. (1997) considered the effect of Bernoulli pressure and surface tension on the splash closure. They found that both inertia and gravity effects are relevant to the deep closure for water entry with low Froude numbers. Thoroddsen et al.

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http://dx.doi.org/10.1016/j.oceaneng.2016.12.018
Received 14 December 2015; Received in revised form 1 October 2016; Accepted 18 December 2016
0029-8018/

(2004) worked on the horizontal jetting ejected from the impact point of a sphere with a high velocity at the initial stage. It was found that this initial axisymmetric jetting spreads radially outwards at a speed of up to 30 times of the sphere velocity. They also concluded that the initial jetting forms within mostly 100 μs from the first contact of the sphere on water. Experimental-theoretical studies for water entry of hydrophobic spheres and vertical cylinders were presented by Aristoff and Bush (2009) and Aristoff et al. (2010). A regime diagram for hydrophobic spheres with the same wetting properties based on non-dimensional parameters affecting the cavity formation behind the sphere were also presented. A theoretical model for predicting key parameters namely the depth and time of pinch-off, depth of sphere at the pinch-off time and volume of cavity behind the sphere were also developed.

A new Lagrange-multiplier based on the fictitious-domain method for the direct numerical simulation of fluid-solid interaction was proposed by Glowinski et al. (1999). They also utilized this multiplier for fluidization, sedimentation, and many other applications (Glowinski et al., 1999, 2001; Glowinski, 2003). The fast computation scheme proposed by Patankar (2001) was used by Patankar and Sharma (2005) to simulate rigid particulate flows. In this method, computation domain included both solid and liquid and the governing equations were solved everywhere. The solid velocity was calculated by integrating in the solid zones since the total linear and angular moment in each individual solid zone was supposed to be conserved. Zhu et al. (2006) numerically analyzed the water entry and exit of a horizontal circular cylinder with both forced and free vertical motions using the Constrained Interpolation Profile (CIP) method. The governing equations were solved numerically on a non-uniform, staggered Cartesian grid. The numerical results of the free-surface deformation, the vertical motion of the cylinder as well as the water entry and exit forces were compared with the experimental results. Hu and Sueyoshi (2010) introduced two numerical approaches namely the CIP-based Cartesian grid method and the MPS method to simulate the strongly nonlinear wave-body interaction problems such as ship motions and green-water impact on deck. The numerical results were validated with experimental data for a dam break problem. An experimental investigation of the trajectories, forces, and cavity formation behind spinning hydrophobic and hydrophilic spheres were presented by Techet and Truscott (2011). Several cases were presented for non-spinning spheres including half hydrophobic and half hydrophilic. They concluded that the spin induced less lateral forces compared to asymmetrical cavity formation. Mirzaii and Passandideh-Fard (2012) developed a 2D numerical algorithm for simulating the interactions between a liquid and a solid object in presence of a free-surface. The fast-fictitious-domain method was integrated into the volume of fluid (VOF) technique to track the free surface motion. The model was also used to simulate the free fall of one and two circular particles inside a liquid. Two-dimensional numerical simulations of the water entry and exit of horizontal circular cylinders at a constant velocity were described by Hafsia et al. (2009). The simulated results were compared with the numerical results of Lin (2007). The free surface deformation around the cylinder in the downward direction was accurately predicted. A proposed experimental setup for characterizing the vertical motion of a horizontal circular cylinder through a free surface was presented by Goharzadeh and Molki (2012). Their experimental results gave insight on hydrodynamic impact phenomena and surface waves. Yang and Qiu (2012a, 2012b) investigated 3D slamming problems for water entry of solid bodies with vertical and oblique velocities using the CIP method. A pressure-based algorithm was introduced for non-advection calculations while the advection terms were modelled by the 3D CIP method. They also calculated hydrodynamic forces on a wedge, a cusped body, and a sphere and compared the numerical results with those of the experiments. Yang and Qiu (2012a, 2012b) calculated slamming forces on 2D and 3D bodies using the CIP method. The advection terms were calculated using a compact upwind scheme while the multiple phases were simulated by a pressure-based algorithm. 2D wedges with deadrise angles varying between 0 and 60° were considered to validate the numerical scheme. Their 2D model was extended to 3D and was applied for simulating a cylinder and a catamaran entering calm water. Lue et al. (2012) studied experimentally and numerically the slamming load and response of complex steel wedge with a deadrise angle of 22°. They measured impact acceleration, slamming pressure, and stress responses and compared the results with those of the simulations. They found that the numerical model well predicted the stress trends and its maximum. Ryzhakov et al. (2013) investigated the behavior of the sea-landing of an unmanned aerial vehicle using the Particle Finite Element Method. They reported the maximum load exerted upon the floats to vary between 4 and 6 kN depending on water accumulation in the vehicle. Three assumptions of water accumulation (front, rear, lateral) were also considered. They found the vehicle to be stable and floatable in all scenarios. Larsen (2013) studied the possibility of water entry problems using the CD-adapco CFD-software STAR-CCM+ with a focus on circular cylinders. Two scenarios were considered, a cylinder with a constant velocity and a free-falling cylinder. He also compared the numerical results of three-dimensional water impact of a cylinder with 8° impact angle with those of experiments and a good agreement was observed. Gu et al. (2014) simulated water entry of solid objects with various shapes and configurations by applying the Navier-Stokes equations on a fixed Cartesian grid. The level set method was used to capture the free surface deformation. Moving objects were modelled using the partial cell method combined with a local relative velocity approach. They modelled vertical and oblique water entry of wedges with different heel angles and compared the results with those of the simulations available in the literature. Wang and Soares (2014) studied the water impact of three-dimensional buoys by an explicit finite element method with an Arbitrary-Lagrangian Eulerian solver. The fluid-solid interface was modelled using the VOF method. The convergence studies were achieved for three dimensional hemisphere and cones with various deadrise angles. The numerical results were found to be highly influenced by the domain mesh size. Abraham et al. (2014) numerically evaluated the forces and motions of a sphere falling on a water surface from an elevation above the free-surface. They concluded that the drag force was highly dependent on the momentum transfer from the sphere to the adjacent liquid. Three-dimensional effects on water entry of the horizontal cylinders were investigated by Wei and Hu (2014). They examined four length to diameter ratios, two cylinder-water density ratios, and two falling heights in their experiments. The effect of diameter on the cylinder depth, however, was not considered. They concluded that the measured jetting speeds for all studied cases were approximately equal at the initial stage since the kinetic energy of the flow was nearly two-dimensional. A numerical study on the dynamic response of a generic rigid water-landing object during water impact was presented by Challa et al. (2014). They validated the numerical results with those of the experiments. They investigated a wide range of conditions considering variations in vertical velocity, entry angle, and object weight. The numerical results showed that the first coupled Fluid-Structure Interaction (FSI) model could capture the water-impact response accurately for all range of drop tests considered. A detailed study on the local pressures acting on the surface of a quasi-rigid cylinder during vertical water entry into a flat water surface was accomplished by Nuffel et al. (2014). Their works encompassed the impact pressure results of a large set of slamming drop experiment with a cylindrical model. They found that for deadrise angles larger than 4.25°, the Wagner theory (Wagner, 1932) was a good approximation for impact pressures acting on a horizontal rigid cylinder during vertical water entry. A series of experimental studies on water entry of circular cylinders with inclined angles was presented by Wei and Hu (2015). They focused on the effect of inclined angles as well as density and length-to-diameter ratios. Both quantitative and qualitative analyses were carried out based on the experimental results. They reported that the cylinder with a lower inclined angle experienced a larger drag