Applied Ocean Research 76 (2018) 110–124

Contents lists available at ScienceDirect

Applied Ocean Research

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

Experimental and numerical study of free water exit and re-entry of a fully submerged buoyant spheroid

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ARTICLE INFO

Keywords:
Free water exit and re-entry
Experiment
Boundary element method
Auxiliary function method
Jet

ABSTRACT

The entire process of free water exit and re-entry of a fully-submerged spheroid with a density slightly less than that of water is investigated by using model experiments and numerical simulations. In the experiments, an initially static body with a density slightly less than that of water was released underwater and high-speed photography was used to monitor the motion of the body and the deformation of the free surface. In addition, a numerical method is developed based on the boundary-element method for the velocity potential with fully nonlinear boundary conditions and is used to numerically analyze the free-surface breakup and reformation. Numerical results are quantitatively consistent with experimental data. The results demonstrated that an upward-oriented liquid jet, or "splash," forms after the body fully re-enters water. It is found that this jet originates from a local high-pressure region just below the free surface that results from the impact of water quickly converging to the vacancy above the body. The local high-pressure region is transient, so the acceleration, pressure, and fluid force exerted on the body are disturbed abruptly. According to the results, initial submergence depth and density of the body are two dominant parameters. Enhancing initial submergence parameter λ or decreasing the body density ρ_1 (still larger than a critical density $\rho_{1,c}$ to avoid the body exiting water totally) will induce a more severe impact of converging water after the free surface reforms, and consequently cause larger variations in the amplitude of the fluid force and of the acceleration and in the pressure on the body.

1. Introduction

Water entry and exit of bodies has been the subject of a wide range of investigations in many fields such as naval architecture, ocean engineering, coastal engineering, and hydroballistics. Such applications usually involve different stages of the relative motion between the body and the free surface. For example, the bow or the propeller of a ship emerges from the water and then re-enters the water in rough seas, or the buoy of a wave-energy collector emerges from and then re-enters the water as waves pass by. Another interesting and popular example is stone skipping, where the stone hits the free surface at an angle (water entry) and then skips and departs (water exit) from the water [1]. In many cases, the deformation of the water surface can be very large and complicated during water exit and re-entry, including the spike and breakup of the free surface, the attachment and detachment of the thin liquid film, and the generation and splashing of the liquid jet. All of these factors present a major challenge for both experiment and simulation. From the physics aspect in particular, the principles of free-surface evolution during water exit and re-entry are significant and need to be further studied.

Since the pioneering work by Von Karman and Wagner [2,3], a large body of work on water entry has been developed. Typically, such investigations are based on analytical or semi-analytical solutions, such as those by Armand and Cointe [4], Howison et al. [5], Scolan and Korobkin [6], Korobkin and Scolan [7], and Moore et al. [8] In addition to analytical or semi-analytical solutions, extensive work has been done by using numerical methods. One of the most common numerical methods used is the boundary-element method (BEM), which is well suited for this type of impact problem because of the short time and confined area involved. By using the BEM with fully nonlinear boundary conditions, Zhao and Faltinsen [9], Lu et al. [10], Battistin and Iafrati [11], Wu et al. [12], Wu [13], Xu et al. [14,15], Sun and Wu [16], and Wu and Sun [17], studied different types of water entry including two-dimensional (2D) wedge, cylinder, and axisymmetric bodies and three-dimensional (3D) bodies. Another way to study water entry is by using test models, which are usually used to verify analytical solutions and numerical results. Experimentally, water-entry test models can be divided into three broad categories: The first is water entry without air-cushion and cavitation effects [12,18–22], which usually corresponds to a low-speed body vertically entering the water at

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https://doi.org/10.1016/j.apor.2018.04.013
Received 6 January 2018; Received in revised form 2 April 2018; Accepted 25 April 2018

a large deadrise angle. The second is water entry with air-cushion effects [23–27], which usually corresponds to a body entering the water with a very small deadrise angle. Finally, the third category is water entry with cavitation effects [28,29], which usually corresponds to high-speed, oblique water entry. For more information, the reader is referred to Faltinsen et al. and Sun and Wu, who have both published reviews on water entry [30,31].

Water exit is less studied than water entry, perhaps because fluid loading often is less excessive than for water entry. In numerical simulations, two major difficulties arise in the water-exit problem; these are related to free-surface breakup and water detachment from the body [32]. Early work on water exit was usually based on the assumption of a flat free surface [33–35]. Korobkin proposes a linearized water-exit model based on the linearization of the boundary conditions on an initially flat free surface [36]. By using this model, Korobkin and Korobkin et al. studied the water exit of 2D and axisymmetric bodies with constant and varying acceleration, respectively [36,37]. Another approach has been to adopt the BEM with fully nonlinear boundary conditions. Greenhow and Moyo, Liju et al., and Rajavaheinthan and Greenhow studied the water exit of 2D and axisymmetric bodies at a constant velocity or acceleration [38–40]. However, their simulations all terminate before the breakup of the free surface or before the body pierces the surface. Ni et al. considered the entire process of the forced water exit of an axisymmetric body [32] in which the body is initially fully submerged and is given a constant vertical velocity. They studied the deformation of the free surface, including breakup and detachment of the body, based on a fully nonlinear theory. This work was extended by the study of Ni and Wu of the free water exit of a buoyant, small-density body, in which a critical body density separating full and partial water exit was derived by using slender-body theory [41]. Greenhow and Lin studied experimentally the forced water exit of an initially fully submerged neutral-buoyancy cylinder with a density equal to that of water [42]. A constant force equal to the cylinder weight was exerted by a string on the cylinder. The result was a large deformation of the free surface, based on which they discussed the “waterfall breaking” phenomenon [43]. They also conjectured that a low-pressure region would appear as the free surface detached from the body. Colicchio et al. designed a water-exit apparatus to study the water exit of a 2D circular cylinder [44]. The density of the cylinder was 0.62 times that of water and the entire free-water-exit process was recorded by high-speed photography and analyzed by using particle image velocimetry. They found that, before the cylinder detached from the water at a high speed, bubbles became entrapped inside the water column at the lower side of the cylinder surface, and the bubble region had negative pressure. In recent work, Wu et al. studied the forced and free water exit of a 3D sphere [45]. Both the deformation of the free surface and the motion of the sphere were recorded by using a high-speed camera, and they analyzed the velocity and acceleration of a light sphere with a density of 0.1 times that of water during its free water exit.

Compared with single water entry and exit, the process of continuous water entry and exit has been far less studied. Baarholm and Faltinsen considered a 2D problem of wave interaction with a superstructure [46], in which an incoming wave hits a platform and the wetted surface increases (water entry). After the wetted surface area reaches a maximum, it decreases (water exit). They made extensive simulations and detailed comparisons with experiments. Piro and Maki studied 2D water entry and exit of flexible bodies by using a coupled fluid-structure interaction solver [47,48]. The fluid domain was modelled by using the finite-volume method and the free surface was captured by using the volume-of-fluid method. The wedge entered the water at a given velocity and constant deceleration. When the velocity reached zero, the wedge started moving upwards with constant acceleration (water exit). Their model was compared with the semi-analytical theory of Korobkin et al [49]. Tassin et al. considered the 2D water entry and exit of a body with time-varying shape by using the modified Logvinovich model during the entry stage and the von Karman model during the exit stage [50]. By comparing the results with those of computational fluid dynamics of Piro and Maki [47], Tassin et al [50]. suggested that the von Karman model underestimates the time interval required for the exit stage. By using the linearized water exit model developed by Korobkin et al. [36], Khabakhpasheva et al. [51,52] considered a problem similar to that considered by Tassin et al. [50] For a flexible wedge, Shams et al. used experimental and semi-analytical methods to study the free-surface elevation and the overall distribution of hydrodynamic slamming from forced water entry to exit [53]. They used the potential flow theory to predict the hydrodynamic forces and the Euler–Bernoulli beam theory to model the structural response. To verify the numerical results, they were compared with those of experiments that used particle image velocimetry. Shams et al. found that the free-surface deformation and pressure field in the water-exit stage differ significantly from that in the water-entry stage.

The derivation of Ni and Wu [41] predicts that an initially fully submerged buoyant body whose density is less than that of water but greater than the critical density partially exits the water before completely re-entering the water. Upon reviewing the previous research, we find few investigations that consider the full free water exit and re-entry process of a buoyant body, be that by experimental or numerical methods. One of the difficulties faced by numerical methods is that the free surface is broken up when the body exits and then reforms when the body re-enters. Nevertheless, some interesting physical phenomena appear, such as an upward liquid jet, or a “splash”, generated at the free surface after body re-entry. Few investigations look into these physical phenomena and the reasons behind them, as well as how these phenomena affect the fluid force exerted on the body and the subsequent body motion. The main reason for the present work is to explore how the free surface behaves and deforms from a point of hydromechanical view. There are two key focuses and purposes of this study. One is the mechanism behind the free-surface deformation, for example, the formation of the splash. The other one is to study the variation law of the hydrodynamics and motion of the body during water exit and re-entry. This would be useful in marine engineering, hydroballistics and even sports. For example, measurement has been made of the pressure/acceleration changes during water exit and re-entry of the head of a breaststroke swimmer [54].

The rest of the paper is organized as follows. The experimental setup is introduced in details in Section 2, including the experimental principle, experimental model, and experimental data processing method, etc. The numerical method, BEM, with fully nonlinear boundary conditions is introduced briefly in Section 3. A case study has been done in Section 4 based on the comparison with experimental data. The effect of the physical parameters is discussed in Section 5, including the initial submergence parameter and the density of the buoyant body. Finally, conclusions and final remarks are summarized in Section 6.

2. Experimental setup

Fig. 1 shows in detail the experimental apparatus for studying water exit. The setup consisted essentially of a water tank, drive system, control system, model, camera system, and lighting system. The principal dimensions of the transparent rectangular water tank were 3600 mm × 80 mm × 1200 mm and the water was 1035 mm deep. The water tank was made of large-sized acrylic glass and a steel framework, which allowed optical accessibility and structural stability, as shown in Fig. 1(a). In the experiment involving forced water exit, the technique to drive the body and simultaneously maintain an undisturbed free surface has always been a challenge. One common method to address this problem is to pull the body out of the water by pulling on a string attached to the top of the body [42,55]. However, the string inevitably perturbs the free surface before the body penetrates it, thereby making it difficult to study its deformation. To resolve this problem, we exerted a force on the body by using an L-type rod with an electromagnet rather than a string, as shown in Fig. 1(c). The L-type rod was made by the