Ocean Engineering 140 (2017) 369–376

Contents lists available at ScienceDirect

Ocean Engineering

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

Experimental study on large deformation of free surface during water exit of a sphere

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ARTICLE INFO

Keywords:
Water exit
Experiments
Free surface
Large deformation

ABSTRACT

During water exit of a solid body, the free surface is disturbed and deformed. To study the free-surface deformation and its dynamic change such as breakup, a set of water-exit equipment was designed and a series of experiment on water exit of a sphere were conducted. High-speed photographic technologies were adopted to capture the whole process of water exit and the large deformation of the free surface. Work was divided into forced water exit and free water exit. In the forced water exit, either a fully-submerged or a partially-submerged sphere was pushed out of water at a constant speed. The influence of the velocity or Froude number was investigated. In the free water exit, an initially static sphere with an equivalent density smaller than water was released underwater by using an electromagnet. Water exit at different initial submergence depth was conducted. Velocity and acceleration of the light sphere are analysed.

1. Introduction

Water entry and exit has been a topic of wide range of applications in naval architecture, ocean engineering and costal engineering, etc. For example, for a ship in rough seas, its bow will repeatedly emerge from water and then hit water surface, which forms a continuous water exit/entry process (Chen et al., 2014). Relative to water entry, there has been far less work on water exit. Part of the reason is that water exit can be taken as a kind of 'loads-off' process from the view of the body, compared to the 'loads-on' one during water entry. However, from the view of free surface, water exit can also be very violent, especially for the high-speed water exit of a blunt body. The water-exit process of a blunt body may involve in complex physical phenomena such as large deformation and breakup of the free surface, sliding and detachment of the thin liquid layer and mixture of liquid and gas. The flow field is unsteady and highly nonlinear as a result. On the other hand, the hydrodynamic feature in the water exit phase is also important in a hydroelastic problem where the water entry and exit provides excitations to an elastic system. The force during water exit phase affects the force impulse and then the elastic response of the corresponding elastic system, for example in a whipping problem. Sun and Helmers (2015) has shown the importance of accurate evaluation of the force during water exit phase in a simpler elastic system. The complexity of the water exit makes the theoretical analysis and numerical simulation challenging usually (Greenhow and Moyo, 1997; Baarholm and Faltinsen, 2004; Korobkin, 2013; Rajavaheinthan and Greenhow, 2015; Ni and Wu, 2017). Relatively model test is a direct method to capture these complex physical phenomena.

Greenhow and Lin (1983) studied the forced water exit of a neutrally buoyant cylinder, whose weight equals the buoyancy when it is fully submerged. A string was attached on the top of the cylinder and a constant force equal to the cylinder weight was exerted on the cylinder through the string to force it exit water from its fully submerged position. The free surface elevations and breaking was observed and discussed. Greenhow (1988) studied the forced water exit of a cylinder by model tests and by two-dimensional (2D) boundary element method (BEM) based on Cauchy's theorem. Cases with different Froude number were considered. The work of Greenhow and Lin (1983) and Greenhow (1988) provided much insight into the physics related to water exit of a 2D body. Miao (1989) studied hydrodynamic forces of 2D circular cylinders during forced water exit with constant speed. The camera was used to capture the process of the cylinder penetrating the free surface and the pressure sensors were adopted to measure the change of the hydrodynamic pressure on the surface of the cylinder. Liju et al. (2001) used an engine to drive a thin bar moving upwards and downwards. Axisymmetric small bodies in different sizes and shapes were installed at the upper end of the thin bar. Under the upward thrust of the thin bar, the small body would emerge from water at various velocities or Froude numbers. They also changed the fluid medium with various viscosity or Reynolds number and surface tension or Weber number. On the other hand, they adopted axisymmetric BEM to simulate the water exit process of the body. The

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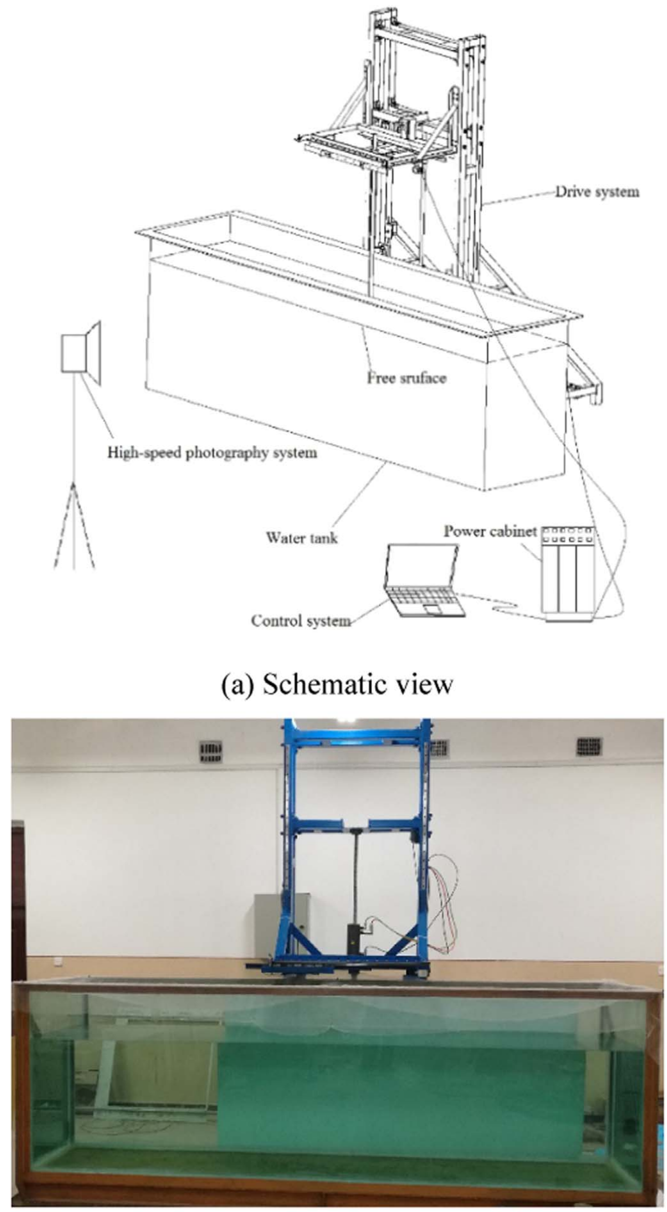
http://dx.doi.org/10.1016/j.oceaneng.2017.06.009
Received 24 October 2016; Received in revised form 12 May 2017; Accepted 4 June 2017
Available online 09 June 2017
0029-8018/

experimental and numerical study of Liju et al. (2001) provided insight of free-surface deformation during water exit of an axisymmetric body. However the scale of their body was very small and just in centimeter and the speed of the body was quite small correspondingly. Besides, their attention was on the deformation of the free surface before the body penetrating through free surface, which they called 'surge effect', but neither the breakup of free surface nor the detachment of water layer. Further numerical simulation of water exit based on BEM, please refer to the work of Ni et al. (2015) for forced water exit and Ni and Wu (2017) for free water exit.

Zhang et al. (2002) used weights and fixed pulley to pull the body out of water by virtue of gravity of the weights. The exit speed of the body could be changed by the mass of the weight. Particle Image Velocity (PIV) technology was adopted to observe the motion of the fluid around the body during water exit. Liu et al. (2003) and Chu et al. (2010) studied water exit of a body in a de-pressurized water tank. Cavitation formed at the surface of the body could be observed in the experiments at high speeds. Different numerical simulation based on the Marker and Cell (MAC) method or Volume of Fluid (VOF) method which is used in FLUENT software was adopted to compare with experimental data. Kleefsman and Veldman (2004) applied an improved VOF method to simulate problems with large free-surface displacement, including water exit of a circular cylinder. Their numerical simulations on 2D water exit were compared with photographs of Greenhow and Lin (1983) and good agreement was achieved. Zhu et al. (2005) applied a CFD method to simulate the water entry and exit of a circular cylinder. The break-up of the water surface where a mixture of air and water was attached to the body bottom was well simulated. Tveitnes et al. (2008) developed a test rig to drive a wedge section enter or exit water vertically at near constant velocity. They found that the hydrodynamic force resisted upward movement of the wedge during its water exit and played a role as drag. The drag coefficients were estimated for wedges with different deadrise angles at different water-exit stages based on experimental data. Colicchio et al. (2009) designed a set of experimental device to simulate water entry and exit of a 2D cylinder. The density of the cylinder was smaller than water and the free water exit was recorded by high-speed photography. It was found bubbles would be trapped at the lower surface of the cylinder after it emerged from water at a high speed. Numerical simulation based on Level Set method showed the region filled by the bubbles had negative pressure. Shi et al. (2012) used high-speed camera to shoot the water exit of a very small slender body of revolution at high speed. The trajectory of the body and the evolution of the cavity attached on the body surface were recorded. Their attention was on the critical speed of the body when the partial cavity transformed into super cavity. Sun et al. (2014) designed a set of water-exit experimental device, which transformed the gravitational potential energy of a pendulum into the kinematic energy of a slender body. Water exit of this slender body as well as the evolution of partial cavity on the body was recorded by camera. Moshari et al. (2014) used VOF scheme for solving two phase flow during the water exit of a circular cylinder. Vertical and oblique water exit and re-entry of a 2D cylinder and vertical water exit of a 3D cylinder were all simulated and it denoted 3D simulation had a better agreement with experimental data.

In previous experimental study on water exit, it seems that there has been little work which focuses on the deformation of the free surface during the whole process of water exit of a blunt body of revolution, such as a sphere. Especially experimental data are scarce on how the water free surface is broken up by the body and how the liquid detaches from the body. On the other hand, as pointed by Ni et al. (2015), the deformation of free surface is very important either to the physical laws or to the hydrodynamics and motion of the body. This forms the prime motivation of the current work and gives its distinctive focus. We design a set of multifunctional experimental device for water exit and conduct a series of experiments by using spheres with different density. Both forced water exit and free water exit have been conducted, respectively. The focus of this paper is on the large deformation of free surface including breakup and detachment under different parameters such as Froude number by using experiments.



(a) Schematic view

(b) Real objects

Fig. 1. Equipment of the experiment.

2. Test equipment and experimental procedure

Fig. 1 provides the sketch map and photo of the self-designed experimental device for water exit. As it can be seen in Fig. 1(a), the experimental set-up is mainly composed of water tank, drive system, control system, power cabinet and high-speed photography system. Water tank is made of double-layer transparent acrylic material, whose frame structure is fastened by angle steel, as shown in Fig. 1(b). The principal dimension of water tank is: length 3600 mm, width 800 mm and depth 1200 mm. The water depth in our tests is 1035 mm. Drive system is installed on one side of water tank. The multi-functional drive system is composed of three parts: the support frame, the vertical movement platform and the horizontal movement platform, the latter two of which can move at constant or variable speed. By means of