Numerical and Experimental Study on Water Exit and Re-entry of a Fully-submerged Buoyant Body

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HIGHLIGHTS

- The whole process of a light body exiting from and then re-entering water has been simulated.
- A numerical procedure is proposed for rejoining free surface after body re-entering water.

1. INTRODUCTION

Water entry and exit have been topics of wide range of applications in naval architecture, ocean engineering and costal engineering, etc. They usually correspond to different stages of the relative motion between the body and free surface during one incident. For example, the bow or a propeller of a ship emerges from and then re-entering water in rough seas and a buoy emerges from and then re-entering water when waves pass by.

For continuous water exit and entry, Baarholm & Faltinsen (2004) considered a 2D problem of wave interaction with a superstructure. Incoming wave will hit the platform and the wetted surface will increase (water entry). When it reaches a maximum, the wetted surface will then decrease (water exit). Extensive simulations were conducted and detailed comparison with the experiment was made. Prio & Maki (2011, 2013) studied 2D water entry and exit of flexible bodies using a coupled fluid-structure interaction solver. The fluid domain was modelled using FVM and the free surface was captured with a Volume of Fluid (VOF) method. The wedge entered the water with a given speed and constant deceleration. When the speed becomes zero, it started moving upwards with constant acceleration (water exit). Their model was compared with the semi-analytical theory of Korobkin et al. (2006). Tassin et al. (2012) 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. Through comparison with the CFD results by Prio & Maki (2011), it is suggested that the von Karman model underestimated the time of exit stage.

Based on the derivation of Ni & Wu (2016), it can be predicted an initial fully-submerged light body, whose density is smaller than water but larger than a critical density, will oscillate at the free surface under buoyancy and gravity after release. Parts of body surface will emerge and immerse water continuously. It seems that there has been little work on this phenomenon within the framework of BEM with the fully-nonlinear boundary conditions. One of the difficulties is that the free surface will be broken up by body exiting and then re-joined after body re-entry. This paper shall consider this continuous water exit and re-entry of a light body and also do the experiments to validate the numerical model and results.

2. MATHEMATICAL MODEL

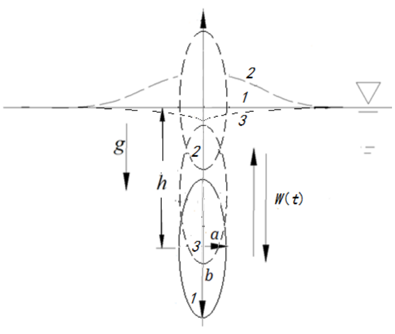

Fig. 1 Sketch of the problem

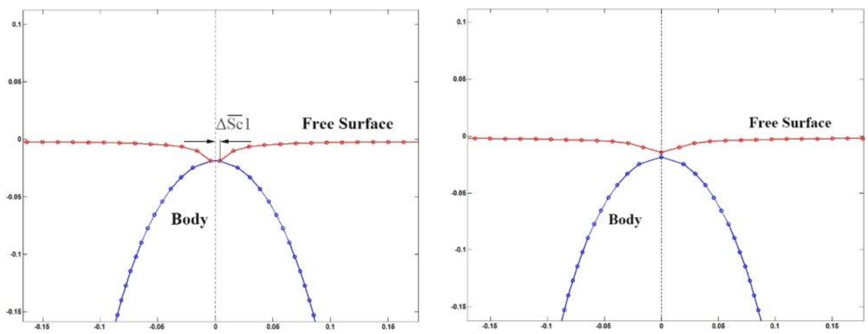

Fig. 2 Sketch of numerical procedure for rejoining of free surface

Fig.1 gives a sketch of the problem, which shows an initially fully-submerged spheroid exiting water partially under net buoyancy and then falling back, corresponding to 1-2-3. The body with density ρ_B has two semi-axes, b and a, where $0 < a \le b$ and its centre is h below undisturbed free surface initially. When the body motion is along the z axis, the flow is then axisymmetric. The fluid is assumed inviscid and incompressible, and the flow is irrotational. Thus, a velocity potential Φ can be introduced, which satisfies Laplace's equation

$$\nabla^2\Phi = 0, \tag{1}$$

in the fluid domain. The impermeable boundary condition on the wetted part of the rigid body surface s_b is

$$\frac{\partial\Phi}{\partial n} = W(t)\cdot n_z, \tag{2}$$

where $W(t)$ is the vertical velocity of the body, which is a function of time and needs to be found at each time step and n_z is the z component of normal vector $\boldsymbol{n} = (n_r, n_z)$ of the body surface pointing out of the fluid domain. On the free surface s_f, the fully nonlinear kinematic and dynamic boundary conditions can be written below in the Lagrangian framework:

$$\frac{Dr}{Dt} = \frac{\partial\Phi}{\partial r}, \quad \frac{Dz}{Dt} = \frac{\partial\Phi}{\partial z}, \tag{3}$$

$$\frac{D\Phi}{Dt} = \frac{1}{2}|\nabla\Phi|^2 - gz, \tag{4}$$

where D/Dt is the substantial derivative following a fluid particle, g is the acceleration due to gravity. Bernoulli equation and constant pressure on the free surface have been used in Eq.(4). The boundary condition at infinity s_∞ is based on the assumption that the fluid there is undisturbed. One has

$$\nabla\Phi \to 0. \qquad \sqrt{r^2 + z^2} \to \infty \tag{5}$$

Green's third identity with the Green function and boundary-element method will be adopted to solve Eq.(1) with boundary conditions in Eqs.(2)-(5).

Based on the derivation of Ni & Wu (2016), when the body density ρ_B is smaller than a critical density $\rho_{B,c}$, the fully submerged light body will burst out of water totally under net buoyance force after release. Otherwise, if $\rho_{B,c} < \rho_B < \rho$, the body will exit water partially before it falls down. In this paper, we consider the latter case. To simulate the whole process continuously, care must be taken for free-surface breakup and rejoining as body rises and falls. The relevant numerical treatment for free-surface breakup has been introduced and discussed by Ni et al. (2015). Following the numerical procedure in Ni et al. (2015), the free-surface rejoining is solved in this paper. As Fig.2 (a) shows, after the body nose falls back to water, an air column is usually seen to be attached to the body surface. It is assumed when the radius of the air column is smaller than $\Delta\bar{S}_c$, free-surface rejoining will occur in the numerical simulation at the next time step. And the free surface is sewed up by allocating the free end of the segment at the free surface on the symmetry axis and a very small distance above the body nose, which is also adopted as $\Delta\bar{S}_c$ in this paper. Ni et al. (2015) have undertaken extensive numerical investigations and found that the results of interest are not sensitive to the choice of $\Delta\bar{S}_c$ when it is sufficiently small. It is taken as 10% of the element size on the body in the present work.

As discussed in Ni & Wu (2016), the motion of the body and fluid flow is decoupled by introducing auxiliary functions (Wu & Eatock Taylor, 2003). Nondimensionalisation is applied based on the length of the body $L = 2b$, the acceleration g due to gravity, and the density of the fluid ρ. The dimensionless parameters will then be denoted by a bar. Besides, $\lambda = h/L$ is defined as the initial submergence parameter.

3. RESULTS AND DISCUSSIONS

We undertake water exit and re-entry of a body at a density close to water $\bar{\rho}_B = 0.96$, whose dimensionless minor axis $\bar{a}$=1/8. The initial submergence parameter is taken as $\lambda = 0.91$. Based on the critical density equation in Ni & Wu (2006), one can predict $\bar{\rho}_{B,c} = \lambda/(\lambda + 0.5) \approx 0.645$, so the body will exit water partially before it falls down as $\bar{\rho}_{B,c} < \bar{\rho}_B < 1$. The initial total number of elements on the body surface in the meridian plane is taken as $N_b = 40$. Elements of equal size $\Delta\bar{l}_b$ are used on the body surface and on the free surface within a prescribed radius from the axis of symmetry. Beyond the prescribed radius, element size increases gradually until it reaches a maximum.

On the other hand, we did a series of experiments to validate the numerical model here. A hollow metal spheroid with *L*=245mm and *a*/*b*=1/4 is amounted at the end of an L-type connecting rod by using an electromagnet. It would be released underwater when the electromagnet is switched off by a control system. High speed photography system is used to capture the motion of the model and the deformation of the free surface. The average density of the body is $\bar{\rho}_B = 0.96$ and the submergence parameter is $\lambda = 0.91$, same as those in numerical simulation.

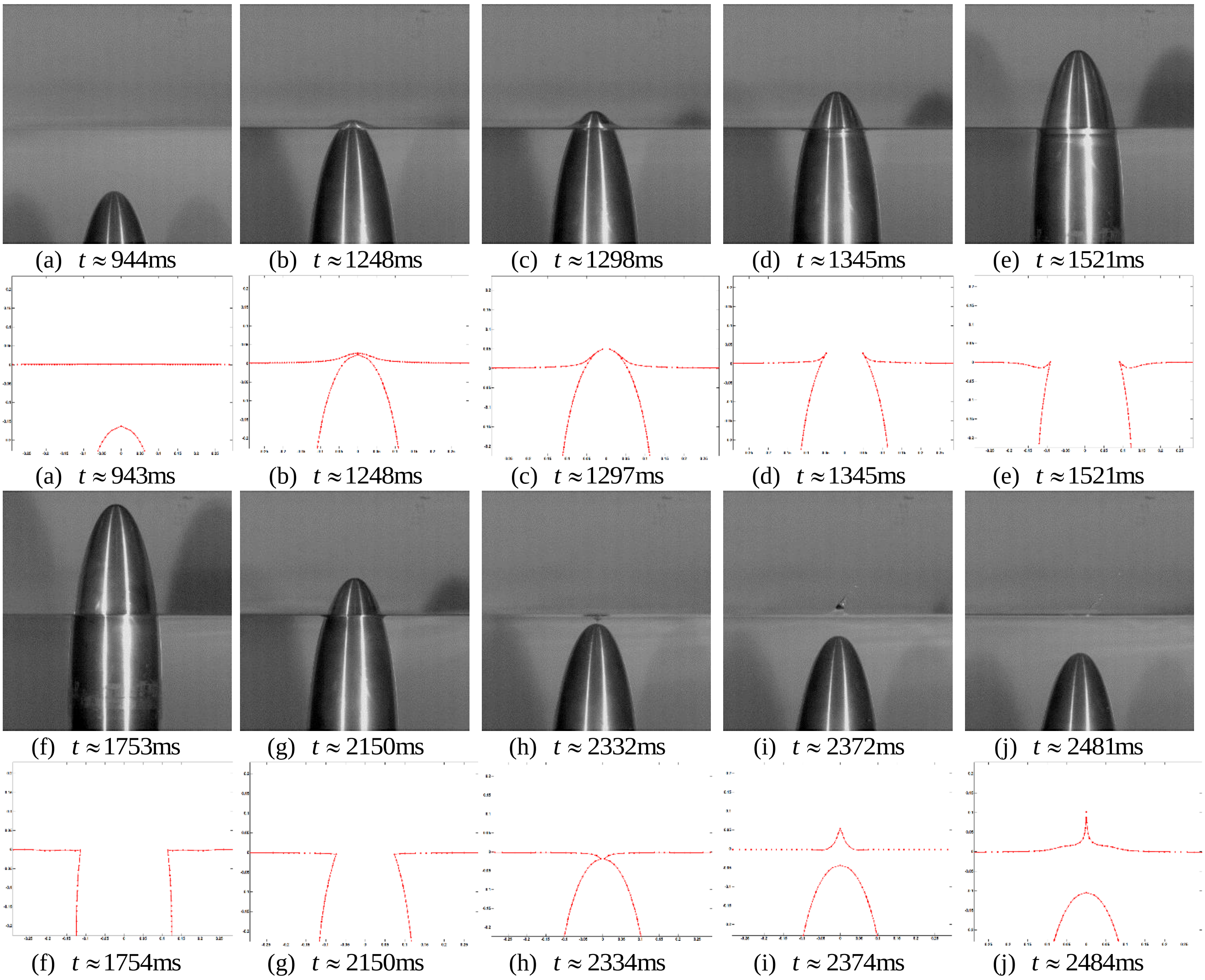

Fig.3 Comparison between experimental and numerical results of water exit and re-entry of a light body

Fig.3 provides the comparison between numerical results and experimental data on body motion and free-surface deformation, where the corresponding time is marked below each figure. It can be seen numerical results agree well with experimental data during the whole process, which validates our numerical model. During Fig.3 (a)-(f), it is a water exit stage. It can be seen that the fully submerged body rises under net buoyance, pushes free surface up and breaks it up as shown in Fig.3 (c). Then a thin layer of water is attached on the body surface and moves along body surface as shown in Fig.3 (c)-(e). As the body exits water, the net buoyance is getting smaller until to zero before minus, which decelerates the body until its velocity approaches to zero when its height peaks, as shown in Fig.3 (f). Afterwards the water exit turns into re-entry stage. Because the body speed is small during this re-entry stage and the slender body has a reducing cross area with free surface, the deformation of the free surface is quite small and keeps almost flat as shown in Fig.3 (f)-(g). After the body nose is lower than initial undisturbed free surface, under inertia, a small air column is attached on the body surface and presents a concave on the free surface, as shown in Fig.3 (h). As the air column is getting thinner and thinner, it will break and the free surface will rejoin. In the numerical simulation, the treatments as described in the introduction are used. Then the body continues to move downwards but interestingly the local free surface splashes a small jet upwards, as shown in Fig.3 (i). As the jet moves upwards its tip may breaks into a string of water drops as shown in Fig.3 (j), when the numerical simulation terminates. In the experiments, the jet is very easy to incline due to a small disturbance but it is expected to be straight up in the numerical simulation. It can be predicted that the body would rise up and fall down again and oscillate by penetrating free surface many times before it achieves motionless finally, which is beyond the scope of this paper.

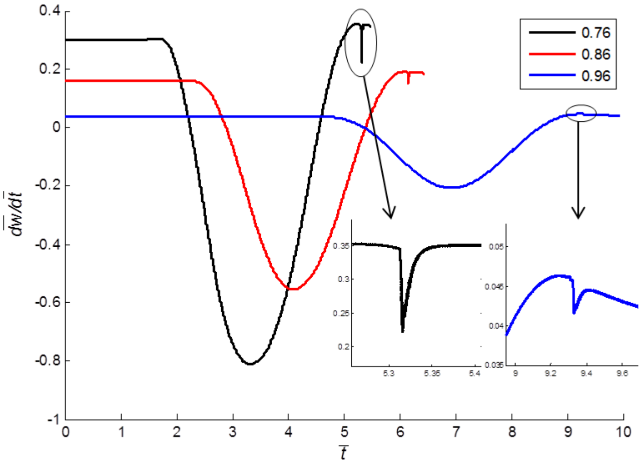

Fig.4 Acceleration of the light body with different density

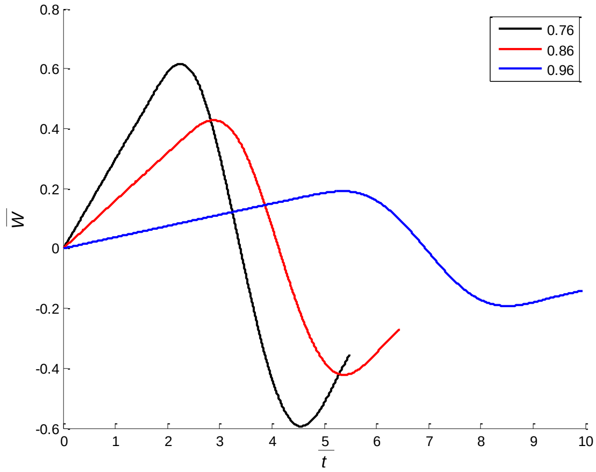

Fig.5 Velocity of the light body with different density

Fig.4 and Fig.5 provide the acceleration and velocity of the light body with different density $\bar{\rho}_B$, taking as 0.76, 0.86 and 0.96, respectively. It can be seen that the body with a smaller density has a larger acceleration and velocity, thus exit and re-enter water earlier. The free-surface break up would not influence the continuity of acceleration and velocity of the body. What is interesting is that, after free-surface rejoining, the acceleration declines sharply before rises again (see the magnifying figure in Fig.4), and the smaller the density is, the larger the decline is. The sharp decline is mainly because the rapid rejoining of free surface will form a very local high pressure region just under free surface, which is also observed in the bubble bursting at free surface (Ni, 2015). This transient local high pressure region will push the body downwards and the free surface upwards simultaneously, which is also why the jet forms as Fig.3 (i) shows. But the local high pressure region vanishes very soon, so the acceleration returns very quickly and the velocity is hardly influenced as Fig.5 shows.

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