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Nonlinear interaction between a gas bubble and a suspended sphere

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ABSTRACT

The fully nonlinear interaction between a gas bubble and a suspended sphere is studied using boundary integral method. The violently expanding and collapsing bubble would cause the sphere to move, in reverse, the sphere response can strongly affect the bubble dynamics. Differing from previous studies, we use the auxiliary function method to decouple the mutual dependence between the force and the sphere motion. To validate our model, two experiments are carried out for a spark-generated bubble interacting with a suspended sphere, captured by using a high speed camera. Our numerical results agree well with the experimental data for both cases, in terms of bubble shapes and sphere displacement. We further conduct convergence and sensitivity studies, in which consistent results have been achieved. Then, the effects of two parameters are investigated, i.e., the stand-off parameter (defined as $\gamma=d/R_m$, where d is the minimum distance between initial bubble center and the sphere surface, R_m is the maximum equivalent bubble radius) and the size ratio (defined as $\theta=R_s/R_m$, where R_s is the sphere radius). The sphere is pushed away by the expanding bubble and gets attracted towards the collapsing bubble. Bubble motion varies greatly with different parameters. We found the maximum jet impact pressure on the sphere is realized when θ is around 2.

1. Introduction

The interaction between bubble and its nearby structure has wide range of applications in engineering: underwater explosion (Kalumuck et al., 1995; Klaseboer et al., 2005; Zhang and Zong, 2011; Zhang et al., 2013a; Wang et al., 2015), cavitation erosion (Hsiao et al., 2014; Hsiao and Chahine, 2015), ultrasonic cleaning (Zong et al., 2004; Wijngaarden, 2016; Chahine et al., 2015; Ohl et al., 2006), some medical applications (Ohl et al., 2006; Calvisi et al., 2008; Curtiss et al., 2013), and so on.

Bubble dynamics are known to be strongly dependent on the nature of boundary conditions. For a cavitation bubble near a rigid wall, a high speed liquid jet forms during the collapse phase and causes a high pressure region on the wall (Naude and Ellis, 1961; Best and Kucera, 1992). When a bubble interacts with the free surface, a downward Bjerknes jet would form, while a spike would form on the free surface (Chahine, 1977). The behaviors of a bubble near other kinds of boundaries are also studied, such as an elastic boundary (Gibson and Blake, 1982; Brujan et al. 2001; Turangan et al. 2006), a closed spherical free surface (Obreschkow et al., 2006), a curved rigid surface (Tomita et al., 2002), and a floating structure

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(Klaseboer et al., 2005; Kim, 2013). It is thus an interesting idea to study the interaction between a bubble and a suspended object, which is associated with applications in underwater explosion, cleaning and medical treatment.

In present study, we employ boundary integral method (BIM) to simulate the coupling process between a bubble and a suspended object. BIM is an efficient way to study bubble dynamics and it has been validated by many experiments (Blake and Gibson, 1981; Tong et al., 1999; Brujan et al. 2002; Tomita et al., 2002; Turangan et al., 2006; Dawoodian et al., 2015; Li et al., 2015; Han et al., 2015), which will not be reviewed in detail. Here, we focus on the nonlinear interaction between a gas bubble and a suspended object in an infinite medium of liquid. To simplify the problem, we assume the suspended object is a sphere with the density equal to the liquid, thus the sphere can stay at rest in the flow unless acted upon by an external unbalanced force. During the bubble-sphere interaction, the violent bubble motion would cause the sphere to move, in reverse, the sphere response can strongly affect the bubble dynamics. In a word, the bubble dynamic behavior is coupled with the sphere motion. Prediction of these effects thus requires fully coupled bubble-sphere modeling.

According to Newton's Law, we need to know the force acting on the sphere if we want to predict the transient motion of the sphere. In potential flow, the force is usually obtained by integrating the pressure got from the Bernoulli equation over the sphere wetted surface. However, we face a difficulty associated with the nonlinear interaction between the sphere motion and the bubble caused force, i.e., the force relies on the acceleration and the acceleration, in turn, relies on the force. In numerical calculation, the difficulty lies in the calculation of the partial derivative of the potential with respect to time, or ϕ_t. Duncan and Zhang (1991) employed the finite difference approximation to calculate ϕ_t, in which the small time steps used for violently collapsing bubble often result in numerical instabilities. Moreover, due to the motion of the boundary, the result got from the finite difference approximation is the material derivative rather than the partial derivative. A large deviation will be imported when the object velocity is high. Given this, Duncan et al. (1996) used the relation between material derivative and partial derivative to correct the finite difference approximation. In present study, an auxiliary function is defined to avoid calculating the direct solution of ϕ_t. This method decouples the mutual dependence between the force and the sphere motion. This method is similar to that widely used for simulation of body motion in water waves (Wu and Hu, 2004).

Few studies on fully coupled bubble-sphere modeling have been undertaken to date, with exception of Kalumuck et al. (1995), Li et al. (2013), and Zong et al. (2015). This study differs from previous studies in the following three ways. Firstly, the auxiliary function method is used to decouple the mutual dependence between the force and the sphere motion, which improves the accuracy and stability of the model.

Secondly, the simulations in previous studies were restricted just before jet impact. Bubble transforms from a singly-connected into a double-connected form after the jet threading the opposite bubble surface, and there exists a velocity potential jump at the impact point. In present study, the vortex ring model (Wang et al., 1996b) is adopted to handle this problem and the subsequent toroidal-bubble-sphere interaction is simulated. In some cases, the toroidal bubble would split into two, then we use the multiple vortex rings model (Zhang et al., 2015) to simulate the interaction between two toroidal bubbles and the sphere.

Thirdly, when the bubble is initiated very close to the sphere, the bubble surface would contact the sphere during the expansion phase of the bubble, causing a stronger coupling effect and numerical instabilities at the same time. Inspired by the work of Ni et al. (2015), the instabilities are handled by removing the thin water layer between them and joining the bubble surface with the sphere surface. This allows the subsequent numerical simulation.

To validate the numerical model, we carry out two experiments for bubble-sphere interaction. The bubble is generated by an electric spark generator (Turangan et al., 2006; Zhang et al., 2013b). In the first experiment, the maximum bubble radius is approximately equal to the sphere radius and there is no contact between them before jet impact. In the second experiment, the maximum bubble radius is larger than the sphere radius and the bubble contacts with the sphere during its expansion phase. The bubble dynamic behaviors in the two cases have quite different features. Our numerical results agree qualitatively with the experimental data for both cases, in terms of bubble shapes and sphere motion. In addition, convergence and sensitivity studies of our model are conducted, in which consistent results have been achieved.

With the validated model, the effects of some dimensionless parameters on bubble dynamics and the pressure features on sphere surface are investigated. The pressure contours and the velocity fields of the flow are also provided for better analysis of the coupling effect between bubble and sphere.

2. Theory and numerical model

2.1. Basic formulas for bubble dynamics

A cylindrical coordinate system $O-r\theta z$ is defined, with the origin at the initial bubble center and z axis pointing towards the opposite direction of the gravity acceleration. In present study, we consider bubble-sphere interaction in an axisymmetric configuration. The liquid viscosity is ignored because the large Reynolds number associated with the experiments in this study can be estimated as $O(10^6)$ using the maximum bubble radius (20 mm) and jet speed (200 m s^{-1}) as character length and velocity. The fluid is further assumed incompressible and the flow irrotational. Thus the velocity potential φ can be introduced and satisfies the following boundary integral equation (Blake et al., 1986; Wang et al., 1996a):