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Oscillation and breakup of a bubble under forced vibration

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ABSTRACT

Coupled shape oscillations and translational motion of an incompressible gas bubble in a vibrating liquid container is studied numerically. The bubble oscillation characteristics are mapped based on the bubble Bond number (Bo) and the ratio of the vibration amplitude of the container to the bubble diameter (A/D). At small Bo and A/D, the bubble oscillation is found to be linear with small amplitudes, and at large Bo and A/D, it is nonlinear and chaotic. This chaotic bubble oscillation is similar to those observed in two coupled nonlinear systems, here being the gas inside the bubble and its surrounding liquid. Further increases in the forcing, results in the bubble breakup due to large liquid inertia.

1. Introduction

Oscillations and translational motion of gas bubbles in a host fluid under forced vibrations are encountered in many two phase flow applications. For instance, in mixers and reactors (Ni and Gao, 1996; Krishna and Ellenberger, 2002; Knopf et al., 2006), and in thermal management systems in microgravity (Gaul et al., 2010; Zhang et al., 2009; Weislogel et al., 2009). In most such devices, bubbles enhance the heat and mass transfer coefficients and reaction rates in the mixture.

Depending on the imposed amplitude and frequency of the vibrations, bubble oscillations range from small amplitude and linear to large amplitude and nonlinear oscillations. Further increase of the amplitude and frequency of the vibration results in bubble breakup.

Experimental study of the bubble oscillation under forced vibration requires a reduced gravity condition to trap the bubble and study its motion. As a result, there are very limited studies using forced vibration. The available studies have shown that the bubble undergoes an oscillatory translational motion at the same frequency as the forcing (Ishikawa et al., 1994; Friesen et al., 2002; Farris et al., 2004). Vibration amplitude and frequency were kept small in these studies resulting in a small deviation of the bubble from the spherical shape. Since the oscillation frequencies were orders of magnitude lower than the Minnaert frequency (Devaud et al., 2008), no volume oscillations were considered.

Several studies have investigated bubble oscillation by acoustic levitation, where an acoustic force was used to trap a bubble and modulate its oscillation. Eller and Crum (1970) found a threshold for the beginning of large amplitude shape oscillations of a gas bubble as a function of the bubble radius. Their results showed that the pressure threshold for the beginning of shape oscillation decreases with increasing bubble radius, since surface tension force decreases as the bubble size increases. In the case of large amplitude oscillations, it was shown that the interaction among volume oscillations, shape oscillations, and translational motion results in a chaotic bubble response (Akhatov and Konovalova, 2005; Watanabe and Kukita, 1993). Chaotic response is because of the coupling of large amplitude and nonlinear shape and volume oscillations, and the translational motion. Due to the coupling, excitation of any of these motions, e.g. the translational motion, can excite the rest (Doinikov, 2004; Mei and Zhou, 1991; Benjamin and Ellis, 1990).

If the acoustic forcing is strong enough, and if the shape of the bubble is distorted from the spherical shape due to the asymmetries in the flow field, a liquid jet can form which penetrates into the bubble and pierces it (Crum, 1979). The impact of this high velocity liquid jet is the dominant mechanism leading to cavitation damage. Bubble breakup has also been studied in the context of sonoluminescence, where bubbles violently collapse. Calvisi et al. (2007) and Blake et al. (1999) showed that in the case of surface instabilities which can be induced by rigid boundaries, neighboring bubbles, flow disturbances, and asymmetric flows around a bubble, a breakup liquid jet can form within the bubble core as the bubble collapses. In a recent study by Yoshikawa et al. (2010) large amplitude shape oscillations of a bubble in response to forced vibration was studied experimentally in a parabolic flight. Results suggested that as the forcing increases, bubble undergoes large amplitude shape oscillations and breakup.

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In a previous work, the authors studied regular and chaotic response of a bubble to the forced vibrations in 2D (Movassat et al., 2012). In the present study, the dynamics of a single bubble in response to forced vibration is studied using a 3D numerical scheme. As mentioned, available studies on the bubble oscillation under forced vibration are limited to small amplitude oscillations where the bubble shape remains spherical. The focus of the present study is to understand the coupling between shape oscillations and translational motion and characterize the nonlinear large amplitude and chaotic bubble motion, and bubble breakup in frequencies which are orders of magnitude lower than those in acoustic levitation. Since the imposed frequency in this work is lower than Minnaert frequency and also because isothermal and adiabatic conditions are assumed, no volume oscillation is considered and the bubble response is limited to the shape oscillations and the translational motion.

2. Numerical model

The equations governing the motion of an incompressible bubble in a liquid domain are the mass and momentum conservation equations,

$$\nabla \cdot \vec{V} = 0 \tag{1}$$

$$\frac{\partial \vec{V}}{\partial t} + \vec{V} \cdot \nabla \vec{V} = -\frac{1}{\rho}\nabla p + \frac{1}{\rho}\nabla \cdot \tau + \frac{1}{\rho}\vec{F}_{SF} + A(2\pi f)^2 cos(2\pi f t) \tag{2}$$

where $\vec{V}$ is the velocity vector, p is the fluid pressure, ρ is the fluid density, τ is the shear stress tensor, $\vec{F}_{SF}$ represents the surface tension force per unit volume, which is applied on the interface between two fluids. The last term on the right hand side of Eq. (2) is the imposed oscillation force as a result of the forced vibrations, in which A and f are the amplitude and frequency of the vibration, respectively. Since the fluids are Newtonian,

$$\tau = \mu(\nabla \vec{V} + (\nabla \vec{V})^T) \tag{3}$$

where μ is the fluid dynamic viscosity.

The TransAT software was used for the simulations. The simulations were run on 32 processors on SciNet clusters at University of Toronto. The Level Set (LS) method was used to capture the interface between the two fluids. If the interface is defined by Γ, a function, φ, is defined as $\varphi > 0$ in the liquid, $\varphi < 0$ in the gas, and $\varphi = 0$ on the interface, Γ. Since the interface moves with the fluids, φ must be advected by the following equation,

$$\frac{\partial \varphi}{\partial t} + \vec{V} \cdot \nabla \varphi = 0 \tag{4}$$

In the LS method, the interface is assumed to have a finite thickness. Thus a smoothed density and viscosity, denoted as $\rho_\varepsilon(\varphi)$ and $\mu_\varepsilon(\varphi)$, are defined in each computational cell as,

$$\rho_\varepsilon(\varphi) = \rho_g + (\rho_l - \rho_g)H_\varepsilon(\varphi) \tag{5}$$

$$\mu_\varepsilon(\varphi) = \mu_g + (\mu_l - \mu_g)H_\varepsilon(\varphi) \tag{6}$$

where subscripts g and l represent gas and liquid, respectively. The modified Heaviside function, H_ε, is defined as, $H_\varepsilon(\varphi) = 0$ for $\varphi < -\varepsilon$, $H_\varepsilon(\varphi) = 1$ for $\varphi > \varepsilon$, and $H_\varepsilon(\varphi) = 0.5[1 + \varphi/\varepsilon + 1/\pi sin(\pi\varphi/\varepsilon)]$ for $|\varphi| \leqslant \varepsilon$. At each time step the LS function is reinitialized without changing its zero level set. This is achieved by solving the following partial differential equation,

$$\frac{\partial d}{\partial \tau} = sign(\varphi)(1 - |\nabla d|) \tag{7}$$

with initial condition of, $d(x, 0) = \varphi(x)$, where $sign(\varphi) = -1$ for $\varphi < 0$, $sign(\varphi) = 1$ for $\varphi > 0$, and $sign(\varphi) = 0$ for $\varphi = 0$. In Eq. (7), d is the distance function representing the interface between the two fluids and ε is the integration variable representing time step. The major drawback of Level Set method has been its ability to conserve mass. In TransAT, this error is minimized using a correction factor in the solver settings. This correction factor is applied locally, for each cell, and globally, for the whole domain, to assure that the mass is conserved from one time step to the next. Comparing to other interface capturing methods such as Volume of Fluid, Level Set provides a sharper property change across the interface.

The surface tension force is modeled as $\vec{F}_{ST} = \sigma\kappa\delta\vec{n}$, where σ is the coefficient of surface tension, κ is the interface curvature, and δ is the Dirac delta function, which is defined as, $\delta(\varphi) = dH_\varepsilon/d\varphi$. Unit normal vectors and Curvature are calculated based on the level set function as,

$$\vec{n} = \frac{\nabla \varphi}{|\nabla \varphi|}\bigg|_{\varphi=0} \tag{8}$$

$$\kappa = \nabla \cdot \left(\frac{\nabla \varphi}{|\nabla \varphi|}\right)_{\varphi=0} \tag{9}$$

The surface tension force is then discretized as a volume force using a modified CSF method. CSF was first introduced by Brackbill et al. (1992). This model has been modified in TransAT to overcome the shortcomings of the original model and minimize smoothing of this force across the interface (Lakehal et al., 2002; Liovic et al., 2006; Liovic and Lakehal, 2007). In TransAT the governing equations are discretized on a collocated mesh in which velocities are defined at cell centers. Adaptive time stepping is controlled by specifying the following limits: $CFL = max(|u_{ijk}|\Delta t/\Delta x, |v_{ijk}|\Delta t/\Delta y, |w_{ijk}|\Delta t/\Delta z) < 0.3$, $DIFF = max(\mu\Delta t/\rho\Delta x_i^2) < 0.3$, and $STN = max(\Delta t\sqrt{\sigma|\kappa|\delta n_i/\rho\Delta x_i}) < 0.3$, which are time restrictions for the convective, viscous, and surface tension terms, respectively.

As mentioned in the introduction, experimental studies for bubble oscillation under forced vibration is limited to small amplitude oscillations in which shape of the bubble remains spherical. In a previous paper (Movassat et al., 2012), authors showed that simulation results for translational motion of the bubble match well with experimental data. As frequencies applied in forced vibration are orders of magnitude smaller than acoustic frequencies, no comparison can be made to acoustic studies where bubble undergoes large amplitude shape oscillations. Also, experimental studies involve multi bubbles and the interaction force among the bubbles is an effective force. The focus of this work was to understand the large amplitude shape oscillations and translational motion, and chaotic interaction of these two motions, for a bubble under forced vibration.

To identify the non-dimensional numbers, bubble diameter, D, vibration frequency, f, and surface tension coefficient, σ, are used to non-dimensionalized the governing equations. Resulting non-dimensional numbers are Bond number, $Bo = \rho(Af^2)D^2/\sigma$, Reynolds number, $Re = \rho(Af)D/\mu$, and the ratio of the vibration amplitude to the bubble diameter, A/D. It will be shown that at large amplitude oscillations, the viscous forces play a smaller role, and Bo and A/D are sufficient to predict the bubble behavior. One can use Weber number, We, as a non-dimensional number to characterize this flow. However, the Weber number in this case is written as $We = \rho(Af)^2D/\sigma$, which is a multiplication of Bo and A/D: $We = Bo \times A/D$, and it is not an independent non-dimensional number in this problem. Therefore, it is sufficient to describe the problem in terms of Bo and A/D.