Numerical Study of Bubble Cloud Dynamics near a Rigid Wall

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ABSTRACT
An Eulerian/Lagrangian two-phase flow model is applied to study the dynamics of a bubble cloud excited by a sinusoidal pressure field near a rigid wall. The effects of key parameters such as the amplitude and frequency of the excitation pressure, the cloud and bubble sizes, and the void fraction on the bubbles' collective behaviors and the resulting pressure load on the nearby wall are investigated. The parametric study addresses nonlinear bubble dynamics, which become more pronounced and result in higher pressure loading at the wall as the excitation pressure amplitude increases. At resonance frequency, corresponding to the highest collective bubble behavior, pressure peaks orders of magnitude higher than the excitation pressure are computed when the amplitude of the pressure excitation is high. This resonance frequency is significantly different from the reported natural frequency of a spherical cloud derived from linear theory which assumes small amplitude oscillations. At high amplitudes of the excitation pressure, the resonance frequency decreases almost linearly with the ratio of excitation pressure amplitude to ambient pressure.

INTRODUCTION
Cloud cavitation is known to be one of the most damaging types of cavitation due to the generated high pressure loading on nearby structures during collective bubble collapse. In naval hydrodynamic applications, cloud cavitation is commonly observed downstream of unsteady sheet cavities (Bark, 2012; de Lange and de Bruin, 1997; Shen and Petersen, 1978) such as on rotating propeller blade surfaces. These clouds are shed from the oscillating cavity and is composed of a myriad of microbubbles interacting with each other and/or trapped in local micro-vortices. The bubble cloud can behave collectively and generate extremely high local pressures resulting in material damage and erosion when it collapses on the blade surfaces. Bent propeller blades have even been reported in the literature in response to the very large loading of the bubble clouds (Chahine, 1983).

Numerical modeling of bubble cloud dynamics near a rigid wall is challenging because it involves bubble-bubble, bubble-flow, and bubble-wall interactions. Many numerical studies have been dedicated to modeling the cloud bubbles dynamics. Among them are asymptotic expansions (Chahine, 1983; Omta, 1987), Boundary Element Method (BEM) simulations (Chahine and Duraiswami, 1992) and Direct Numerical Simulation (DNS) (Esmaeeli and Tryggvason, 1998; Seo et al., 2010). However, due to the computational cost these methods are mostly limited to small scale problems addressed for fundamental study purposes, such as developing subgrid relationships for larger scale models. For practical applications, two-phase bubbly flows are usually modeled using one of several approaches: equivalent homogeneous continuum models, Eulerian two-fluid models, or Eulerian-Lagrangian approaches wherein the bubbles are treated as discrete particles. Homogeneous models are useful for low void fractions, whereas Eulerian-Lagrangian approaches are more appropriate for higher void fractions (Balachandar and Eaton, 2010; Crowe et al., 1996).

In one of our studies (Raju et al., 2011) an Eulerian-Lagrangian two-phase flow model was compared with different numerical models. These models have been assessed for simulation of cloud bubbles interacting with a large exploding bubble in a viscous liquid. It was found that, although all the models capture the average low-frequency dynamics, the microscale response of the discrete bubbles and the resultant high-frequency local fluctuations are properly captured by the Eulerian-Lagrangian solver only. This highlights that a discrete bubble modeling approach is essential to a better description of such problems.
problems since it can resolve the physics down to the single bubble scale, while maintaining computation cost affordability and capturing the overall large scale flow behavior.

The Eulerian-Lagrangian two-phase flow model we consider here treats the two-phase mixture as a continuum and solves the Navier-Stokes equations using Eulerian grids with a time and space varying density (J. Ma et al., 2015; Jingsen Ma et al., 2015; Ma et al., 2012). The microbubbles are modeled as interacting singularities representing moving and oscillating spherical bubbles, which are described by modified Rayleigh-Plesset-Keller-Herring equations and are tracked in a Lagrangian fashion. Higher order bubble deformations can also be included but are not considered here. A two-way coupling between the two-phase medium and the discrete bubbles is realized through the local mixture density deduced from the bubble distribution and volumes and their time and space variations. This model can resolve the physics down to single bubble scales, while maintaining computational cost affordability and capturing large scale pressure and flow field behavior.

In order to contribute to the understanding of the physics involved in collective bubble cloud dynamics and predict the pressure on nearby boundaries, we apply here the Eulerian-Lagrangian two-phase flow model and simulate the dynamics of bubble clouds excited by a sinusoidal pressure field near a rigid wall (J. Ma et al., 2015). A parametric studies is then conducted on key parameters such as the amplitude and frequency of the excitation pressure, the initial cloud and bubble sizes, and the initial cloud void fraction.

**NUMERICAL MODEL**

The Eulerian-Lagrangian two-phase flow model employed in this study has been extensively validated and documented in our previous studies. These included investigations of the effects of a propeller flow on bubble size distribution in water (Hsiao and Chahine, 2012, 2004), modeling of propeller tip vortex cavitation inception (Hsiao and Chahine, 2008, 2004), simulation of bubbly flows in a bubble augmented propulsor (Wu et al., 2010), bubble entrainment in plunging jets (Hsiao et al., 2013) and wave propagation in bubbly media (J. Ma et al., 2015; Jingsen Ma et al., 2015; Ma et al., 2012; Raju et al., 2011), etc. In this two-phase flow approach an Eulerian method is used to solve the continuum-based two-phase medium and is coupled with a discrete bubble model tracking bubble motion using a Lagrangian approach. The two-way coupling between the Eulerian continuum-based model and the Lagrangian discrete bubble model is realized as follows:

- The dynamics and motion of the individual bubbles in the flow field are controlled by the two-phase medium local properties and gradients.
- The local properties of the mixture (void fractions and local densities) are determined by the instantaneous bubble sizes and distribution.
- The mixture flow field has an evolving density distribution, which is space and time dependent, and satisfies mass and momentum conservation.

**Eulerian Continuum-Based Two-Phase Model**

The two-phase medium continuum model uses our viscous flow software, 3DynaFS-Vis5, to solve the Navier-Stokes equations and satisfy the continuity and momentum equations:

\[
\frac{\partial \rho_m}{\partial t} + \nabla \cdot (\rho_m \mathbf{u}) = 0, \tag{1}
\]

\[
\rho_m \frac{D\mathbf{u}}{Dt} = -\nabla p + \mu_m \nabla^2 \mathbf{u}. \tag{2}
\]

where the subscript \( m \) represents the mixture properties. \( \mathbf{u} \) is the mixture velocity, \( p \) is the pressure. The mixture density, \( \rho_m \), and the mixture viscosity, \( \mu_m \), can be expressed as functions of the void volume fraction \( \alpha \):

\[
\rho_m = (1-\alpha) \rho_l + \alpha \rho_g, \quad \mu_m = (1-\alpha) \mu_l + \alpha \mu_g, \tag{3}
\]

where the subscript \( l \) represents the liquid and the subscript \( g \) represents the gas. The equivalent medium has a time and space dependent density since the void fraction \( \alpha \) varies in both space and time. This makes the overall flow field problem similar to a compressible flow problem. In our approach, which couples the continuum medium with the discrete bubbles, the mixture density is not an explicit function of the pressure through an equation of state. Instead, tracking the bubbles and knowing their concentration provides \( \alpha \) and \( \rho_m \) as a function of space and time.

The system of equations is solved by an artificial compressibility method (Chorin, 1967) in which a pseudo-time derivative of the pressure multiplied by an artificial-compressibility factor, \( \beta \), is added to the continuity equation as

\[
\frac{1}{\beta} \frac{\partial \rho}{\partial t} + \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho_m \mathbf{u}) = 0. \tag{4}
\]

As a consequence, a hyperbolic system of equations is formed and can be solved using a time
marching scheme. The solutions are iterated in the pseudo-time until convergence. To obtain a time-dependent solution, a Newton iterative procedure is performed at each physical time step in order to satisfy the continuity equation.

3DYNAFS-VIS uses a finite volume formulation. First-order Euler implicit differencing is applied to the time derivatives. The spatial differencing of the convective terms uses the flux-difference splitting scheme based on Roe’s method (Roe 1981) and van Leer’s MUSCL method (van Leer 1979) for obtaining the first-order and the third-order fluxes, respectively. A second-order central differencing is used for the viscous terms which are simplified using the thin-layer approximation. The flux Jacobians required in an implicit scheme are obtained numerically. The resulting system of algebraic equations is solved using the Discretized Newton Relaxation method (Vanden, and Whitfield 1995) in which symmetric block Gauss-Seidel sub-iterations are performed before the solution is updated at each Newton iteration.

**Lagrangian Discrete Bubble Model**

The Lagrangian discrete bubble model, 3DYNAFS-DSM, uses a discrete singularity model where averaging over the bubble surface is applied to the local fluid quantities (Hsiao et al., 2003; Chahine, 2004, Choi et al., 2004). This model has been shown to produce accurate results when compared to full 3D two-way interaction computations (Hsiao and Chahine 2003) The averaging scheme allows one to consider only a spherical equivalent bubble and use a modified Rayleigh-Plesset-Keller-Herring equation (Plesset and Prosperetti, 1977) to describe the bubble dynamics,

$$
\left(1 - \frac{\dot{R}}{c_m}\right) \dot{R} + \frac{3}{2} \left(1 - \frac{\dot{R}}{3c_m}\right) \dot{R} = \frac{u_s^2}{4} + \frac{1}{\rho_m} \left(1 + \frac{\dot{R}}{c_m} + \frac{R}{c_m} \frac{dR}{dt}\right) \left[ p_v + p_g \left(\frac{R_0}{R}\right)^{3k} - p_{enc} - \frac{2\gamma}{R} - 4\mu_m \frac{\dot{R}}{R}\right].
$$

where $c_m$ is the local sound speed in the mixture. The slip velocity, $u_s = u_{me} - u_e$, is the difference between the bubble encountered liquid velocity, $u_{me}$, and the bubble translation velocity, $u_b$. $R$ and $R_0$ are the bubble radii at times $t$ and $0$. $p_v$ is the liquid vapor pressure, $p_g$ is the initial bubble gas pressure, $k$ is the polytropic compression constant, and $u_{me}$ and $p_{enc}$ are respectively the averages of the liquid velocities and pressures over the bubble surface.

The bubble trajectory is obtained from the following bubble motion equation:

$$
\frac{du_b}{dt} = \left(\rho_i \rho_e^2 \left[\frac{3}{8R}C_D |u_e| u_e + \frac{1}{2} \left(\frac{du_{me}}{dt} - \frac{du_b}{dt}\right)\right] + \frac{3\dot{R}}{2R} u_e - \frac{\nabla p}{\rho_i} + \frac{(\rho_i - \rho_e)}{\rho_i} g + \frac{3C_L \sqrt{\frac{\rho}{\rho_i}}} {4\pi R \sqrt{\Omega}}\right)
$$

where $C_D$ is the bubble drag coefficient given by an empirical equation as in Haberman and Morton (1953). $C_L$ is a lift coefficient and $\Omega$ is the vorticity vector. The 1st right hand side term is a drag force. The 2nd and 3rd terms account for the added mass. The 4th term accounts for the presence of a pressure gradient, while the 5th term accounts for gravity and the 6th term is a lift force (Saffman 1965).

**Void Fraction Computation**

A key of the Eulerian-Lagrangian coupling is the computation of the void fraction from the instantaneous bubble sizes and locations. This is achieved by using a Gaussian distribution scheme which smoothly “spreads” each bubble’s volume over neighboring cells in a selected radial distance while conserving the total bubble volumes (Ma et al., 2014). Figure 1 illustrates the void fraction computation scheme for a representative cell $i$. In this scheme the “void” contribution, $v_{i,j}$, of a bubble $j$ to a nearby cell $i$ can be expressed as:

$$
v_{i,j} = \frac{k}{\hat{R}_j} v_j^b e^{-\frac{\|X_{i,j}\|}{4R}},
$$

where $V_j^b$ is the volume of bubble $j$, $X_{i,j}$ is the position vector between bubble $j$ and cell $i$. However, Equation (7) does not guaranty that the total volume of the bubbles is conserved. Therefore, a cell-volume-weighted normalization scheme is adopted to normalize the “void” contribution such as:

$$
\bar{v}_{i,j} = \frac{v_{i,j} V_i^{cell}}{\sum_k v_{k,j} V_k^{cell}} v_j^b,
$$

where $V_i^{cell}$ is the volume of cell $i$. Since each bubble would only contribute its “void” effects to a limited number of nearby cells due to the Gaussian decay, the normalization is computed only for the $N_{cell}$ cells, which are “influenced” by the bubble $j$. To compute
the void fraction for the cell $i$ we then sum up the “void” contribution from all bubbles within the “influence range” and divide it by the cell volume, i.e.

$$\alpha_i = \frac{\sum_{j=1}^{N_i} V_{i,j}^b}{\sum_{k=1}^{N_{cell}} V_{k,i}^{cell}},$$  

(9)

where $N_i$ is the number of bubbles which are in the “influence range”.

**RESULTS**

Figure 1 shows a cloud of bubbles with an overall initial radius, $A_0$. The cloud has its center initially at a distance $X_0$ from the wall, and is composed of small bubbles having (for simplicity of the study) the same initial radius $R_0$. This bubble cloud is driven by a pressure wave $P(t)$:

$$P(t) = P_0 - P_{\text{amp}} \sin(2 \pi f t) = P_0 \left[1 - \xi \sin(2 \pi f t)\right].$$  

(10)

Here $P_0$ is the initial pressure at $t = 0$, $P_{\text{amp}}$ is the amplitude of the oscillations, $f$ is the frequency, and $\xi = P_{\text{amp}} / P_0$. We assume that the bubbles are randomly distributed in the cloud 3D spherical domain, resulting in a quasi-uniform initial void fraction distribution $\alpha_0$ within the cloud. At $t = 0$ all the bubbles are in equilibrium with $P_0$. Gravity is ignored here for the sake of simplicity.

For this problem we can identify two groups of parameters: one for the imposed pressure field (amplitude and frequency of the driving pressure) and one for the bubble cloud (cloud and bubble sizes, void fraction), which determine the dynamics of the bubble cloud. In the following sections we will investigate the effect of these parameters on the bubble cloud dynamics and the resulting pressures at the nearby wall.

**Effect of Driving Pressure Amplitude**

The effects of the amplitude of the driving pressure are illustrated in Figure 3. This figure shows snapshots of the bubble cloud dynamics at different instants for $P_{\text{amp}} = 4$ atm ($\xi = 0.4$) and $P_{\text{amp}} = 16$ atm ($\xi = 1.6$).

The images from top to bottom are for increasing times during the first cycle of the cloud oscillations. In both cases, the bubbles in the cloud grow first then collapse in response to the driving pressure.

Overall, the bubbles in the cloud collapse in a cascading fashion with the bubbles at the cloud top (farthest from the wall) collapsing first and those on the bottom (closest to the wall) collapsing last. As the amplitude of the driving pressure increases weak bubble oscillations with small amplitudes transform into strong bubble growth and collapse as evidenced by the changes of the bubble sizes visualized by the colors in Figure 3 (red indicates high inner bubble pressure, i.e. very small bubble, while blue indicates low inner bubble pressure, i.e. very large bubble).

This is made further clear in Figure 4, which quantitatively compares, the variations of the radius of a bubble close to the wall for increasing pressure relative amplitudes, $\xi$. For $P_{\text{amp}}= 1$ atm ($\xi = 0.1$), the radius change is negligible. However, for $P_{\text{amp}} = 25$ atm ($\xi = 2.5$), the bubble grows to a maximum radius 2.5 times larger than $R_0$ and then collapses to a minimum of about 0.3 $R_0$. Figure 5 compares the pressure histories monitored at the wall center and shows that the resulting peak increases from 10 atm to about 500 atm for increasing driving pressure amplitudes.
Figure 3: Time sequence of bubble distributions and internal pressures in a bubble cloud driven by pressure excitation with amplitude of 4 atm ($\xi = 0.4$) (left), and 16 atm ($\xi = 1.6$) (right) for $P_0=10$ atm, $R_0=50$ μm, $\alpha_0=5\%$, $f=23$ kHz, and $A_0=X_0=1.5$ mm. The last frame of each row is a view of the pressures at the rigid wall.

Figure 4. Size variations of the bubble closest to the wall for different driving pressure amplitudes ($0.1 \leq \xi \leq 2.5$). $P_0=10$ atm, $R_0=50$ μm, $\alpha_0=5\%$, $f=23$ kHz, and $A_0=X_0=1.5$ mm.

Figure 5: Pressure at the wall center created by the cloud collapse for different excitation pressure amplitudes ($0.1 \leq \xi \leq 2.5$) for $P_0=10$ atm, $R_0=50$ μm, $\alpha_0=5\%$, $f=23$ kHz, and $A_0=X_0=1.5$ mm.

Effect of Driving Frequency

As illustrated in a previous study (Chahine et al., 2014) tuning between the cloud characteristic frequency and the frequency of the excitation pressure field is essential to generating very high collapse impulsive loads. When the driving pressure frequency matches the characteristic frequency of the bubble cloud, strong collective behavior occurs and very high pressures are generated at the wall. We compare in Figure 6, for the same pressure amplitude of 9 atm, the effect of the driving frequency on the pressure at the wall. As the figure shows, the cloud behavior is very sensitive to the driving frequency. The highest collective effects appears to be at 8 kHz and result in a
pressure peak of ~ 300 atm, two orders of magnitudes higher than the excitation pressure. As illustrated in Figure 6, which shows bubble radii versus time for different bubbles in the cloud and the corresponding pressure variations, the optimum occurs when the driving pressure reaches its highest level at the time the individual bubbles start collapsing collectively.

![Figure 6: a) Pressure at the wall center created by a cloud excited at different frequencies and b) maximum pressure on the wall center as a function of the driving frequency for $P_0=10$ atm, $P_{amp}=9$ atm, $R_0=50\mu$m, $\alpha_0=5\%$, and $A_0=X_0=1.5$ mm.](image)

Figure 7 shows bubble radii versus time for different bubbles in the cloud. Collective behavior (i.e. all bubbles collapse almost simultaneously) occurs when the driving pressure reaches its highest level at the time the individual bubbles start their collapse. This highest pressure forces all bubbles to collapse collectively, i.e. simultaneously. For lower driving frequencies, the pressure reaches its peak too early and drops before the bubbles start their collapse. Conversely, for higher frequencies, the driving pressure reaches its highest value too late and the bubble volumes change is not in phase.

![Figure 7: Comparison of bubble radii at different cloud locations for a bubble cloud excited at different pressure frequencies: (a) $f=25$ kHz; (b) $f=8$ kHz, and (c) $f=5$ kHz for $P_0=10$ atm, $P_{amp}=9$ atm, $R_0=50\mu$m, $\alpha_0=5\%$, and $A_0=X_0=1.5$ mm.](image)

**Resonance Frequency of Bubble Cloud**

It is important to note that the resonance frequency of 8 kHz in the cases shown in Figure 6 and Figure 7, is here much smaller than the reported natural frequency of a cloud, $f_{cloud}$, derived for small
amplitude oscillations and linear bubble dynamics theory (Brennen, 1995)

\[ f_{\text{cloud}} = f_0 \left( 1 + \frac{12 \alpha_0^2}{\pi^2 R_0^2 (1 - \alpha_0)} \right)^{1/2}, \]

\[ f_0 = \frac{1}{2\pi} \sqrt{\frac{P_{e\theta}}{\rho \alpha_0 R_0^2 \left( 3 - \frac{2\gamma}{P_{e\theta} R_0} \right)}, \]

which gives a value of \( f_{\text{cloud}} = 23 \) kHz. Two factors may cause this discrepancy: one is due to the wall proximity effects and the other is due to non-linear effects resulting from high excitation amplitude. To investigate which factor contributes to the deviation of the resonance frequency from the linear theory prediction, two additional sets of simulations for a range of frequencies were conducted. The first set of simulations was conducted with the same driving pressure amplitude \( P_{\text{amp}} = 9 \) atm \( (\xi = 0.9) \) but without a nearby wall and the second set of simulations was conducted for a much smaller driving pressure amplitude, \( P_{\text{amp}} = 0.1 \) atm \( (\xi = 0.01) \) without a nearby wall. The resonance frequency for these two set of simulations can be deduced from Figure 8 which shows the comparison of peak pressure at a range of frequencies for different sets of simulations. It is seen that even without a nearby wall, the resonance frequency is only a little higher than 8 kHz while the resonance frequency matches with the linear theory predictions when the driving amplitude is down to 0.1 atm \( (\xi = 0.01) \). This implies the driving amplitude is the key factor which influences here the resonance frequency of the bubble cloud.

To investigate further such dependency, Figure 9 shows the peak pressure as a function of the driving frequency for different values of \( \xi \). From these curves we can deduce the dependency of the resonance frequency on \( \xi \) as shown in Figure 10. It can be seen that when the normalized driving amplitude is less than 0.2, the resonance frequency matches with the linear theory prediction, i.e. 23 kHz. For \( \xi > 0.2 \) the resonance frequency deviate significantly from linear theory, i.e. the non-linear interaction becomes significant. The value of the resonance frequency decreases almost linearly as \( \xi \) increases until \( \xi > 1 \) where the resonance frequency reaches a plateau of 5 kHz.

**Figure 8:** Comparison of the peak pressures in a range of frequencies obtained for both an isolated bubble cloud and for a bubble cloud near a cloud for two driving pressure amplitudes \( (\xi = 0.01 \text{ and } 0.9) \).

**Figure 9:** Peak pressures monitored at the wall center versus driving frequency, for different relative driving pressure amplitude \( (0.01 \leq \xi \leq 1.5) \) for \( P_0 = 10 \) atm, \( R_0 = 50 \mu m, \alpha_0 = 5\% \), and \( A_0 = X_0 = 1.5 \) mm.

It is also interesting to consider the dependency of the peak pressure at resonance frequency on \( \xi \). This is illustrated in Figure 11. It is seen that the peak pressure obtained at the resonance frequency increases from \( 10 \) atm to \( 1,000 \) atm as \( \xi \) increases from 0.01 to 1.5.
Figure 10: Bubble cloud resonance frequency versus $\zeta$ for $P_0 = 10$ atm, $R_0 = 50 \mu$m, $a_0 = 5\%$, and $A_0 = X_0 = 1.5$ mm.

Figure 11: Peak pressure at the wall versus $\zeta$ at of a bubble cloud resonance for $P_0 = 10$ atm, $R_0 = 50 \mu$m, $a_0 = 5\%$, and $A_0 = X_0 = 1.5$ mm.

**Effect of Cloud Size on Resonance Frequency**

Equation (11) implies that the resonance frequency is also function of the initial cloud size, $A_0$, the initial microbubbles size, $R_0$, and the initial void fraction, $a_0$. In this section we investigate the dependency of the resonance frequency on the cloud size. Figure 12 shows the peak pressure as a function of the excitation frequency for different cloud initial radii. As seen in the figure the peak pressure increases with the cloud size while the resonance frequency reduces as the cloud size increase. Figure 13 summarizes the results from Figure 12 and illustrates that the trend in Equation (11) is still valid with the resonance frequency being related to the inverse of the normalized cloud size, $A_0/R_0$.

**Figure 12**: Peak pressure at the wall center versus driving frequency for different cloud sizes. $P_0 = 10$ atm, $P_{\text{amp}} = 9$ atm, $R_0 = 50 \mu$m, $a_0 = 5\%$, and $X_0 = 1.5$ mm.

**Figure 13**: Bubble cloud resonance frequency versus the ratio of initial cloud size to initial bubble size. $P_0 = 10$ atm, $P_{\text{amp}} = 9$ atm, $R_0 = 50 \mu$m, $a_0 = 5\%$, and $A_0 = X_0 = 1.5$ mm.

**Effect of Initial Bubble Size and Void Fraction**

In Figure 14, the peak pressure at the wall is plotted as a function of the initial microbubble size in the cloud. The initial bubble size effect, are considered for $R_0$ between $2 \mu$m and $60 \mu$m while conserving the initial void fraction under the following conditions: $P_0 = 10$ atm, $P_{\text{amp}} = 15$ atm, $A_0 = 1.5 \text{mm}$, $a_0 = 5\%$, $f = 15$ kHz and $X_0 = 1.5$ mm. It is seen that the peak pressure has a sharp maximum for $R_0 = 7 \mu$m. It is noted that the selected driving frequency $f = 15$ kHz is the resonance frequency when $R_0 = 50 \mu$m for this imposed condition according to the results shown in Figure 12. This implies that a
higher peak pressure could be reach for \( R_0 = 7 \mu m \) if a full range of frequencies is interrogated.

CONCLUSIONS

The dynamics of a bubble cloud subjected to a sinusoidal pressure field near a rigid wall is numerically studied. A Eulerian-Lagrangian two-phase flow model is used, where the two-phase medium is modeled using an Eulerian continuum model while the bubbles are considered in a Lagrangian fashion. Simulations involving an initially spherical cloud of bubbles are shown under a wide range of conditions applicable to cloud cavitation configurations.

Simulations to assess the effect of the amplitude of the driving pressure on the bubble cloud behavior indicate strong nonlinear bubble dynamics effects at large amplitudes. Very strong pressure impact can then be generated at the wall while the cloud collapses. In addition, the resonance frequency of the bubble cloud (i.e. the condition that leads to the strongest bubble collective effect and highest pressures at the wall) is strongly affected by these nonlinear effects. The resonance frequency is found to be much lower than that presented earlier in the literature using small oscillations and linearized theory. At high amplitudes of the excitation pressure, the resonance frequency decreases almost linearly with the ratio of excitation pressure amplitude to ambient pressure.

This resonance frequency is also found to be proportional to the ratio of bubble size to cloud size as at low driving pressure amplitudes. Further studies are still required to fully understand the effect of initial bubble size and void fraction on the bubble cloud dynamics.

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