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A comparative study on interface-capturing models and schemes to solve bubble dynamics and cavitation

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Abstract

In the context of simulation of bubble dynamics and cavitation, even the simple problem of the collapse of a spherical bubble is challenging to compute accurately with general, three-dimensional, interface-capturing schemes. Difficulties arise from both the physical model of the multicomponent fluid and the discretization scheme. Pathologies associated with each factor are identified and solutions to remedy specific issues are proposed.

Introduction

Several applications require a detailed understanding of cavitation and bubble dynamics in and near soft materials, such as biological tissues, polymeric coatings or biofouling. Few preliminary studies highlight the dependence of the bubble dynamics on the material properties and point to the need to develop a comprehensive multiscale theory capable of accounting for physical phenomena not present in traditional hydrodynamic cavitation. However, before modeling viscoelastic effects that would allow to extend our understanding of cavitation in and near soft materials, we focus on developing accurate algorithms for bubble dynamics in water either in free space or near rigid surfaces. Indeed, even the simple problem of the collapse of a spherical bubble is challenging to compute accurately with general, three-dimensional (3D), interface-capturing schemes. Difficulties arise from both the physical model of the multicomponent fluid and the discretization scheme. It can be difficult to isolate the pathology to either factor. Once the pathologies are identified, some solutions are proposed to remedy specific issues.

Multiphase models and numerical methods

A high-order WENO (Weighted Essentially Non-Oscillatory) scheme developed around the mechanical-equilibrium model of Allaire (Allaire et al. 2002) showed good results for shock-induced collapse and droplet atomization (Coralic and Colonius 2014; Meng and Colonius 2014), but failed to maintain sphericity or correctly predict collapse time and minimum radius in the Rayleigh collapse problem. As shown in (Tiwari et al. 2013; Rasthofer et al. 2017) for small initial pressure ratios and in Fig. 1 for small and high initial pressure ratios ($p_{\mathrm{water}}/p_{\mathrm{bubble}} = 10$ and 1427), better results are obtained when the model of Kapila (Kapila et al. 2001) is used. Indeed, there is a term in the volume-fraction equation, not present in the model of Allaire, that accounts for expansion and compression of each phase in mixture regions and is the element that allows good agreement of Kapila's model with analytical, and indirectly experimental, solutions of spherical bubble dynamics.

However, this term relating the volume fraction to the compression rate leads to numerical stability problems during strong compression and expansion. In this work, we propose to use instead a pressure-disequilibrium model (Saurel et al. 2009) that is relaxed, during each time step, to equilibrium so that the additional term on the volume fraction equation is avoided and, at the same time, the results converge to the mechanical-equilibrium model of Kapila. This last model was previously implemented using low-order (MUSCL-type) schemes (Saurel et al. 2009; Schmidmayer et al. 2018a,b). We thus combine the pressure-disequilibrium model with the high-order WENO scheme, and test the resulting model on the spherical bubble problem (Fig. 1). Note that both models (Kapila and Saurel) are hyperbolic, conservative on mass, momentum and total energy, and respect the second law of thermodynamics. Furthermore, in the context of diffuse interface method based on Godunov-type scheme (Godunov 1959), the Riemann problem is solved with an approximate HLLC solver (Toro 1997).

Results

A complete study comparing the models of Kapila and Saurel, and the low- and high-order numerics is provided regarding agreement with analytical solutions and ability of maintaining the sphericity during the collapses and rebounds of the bubbles. Among the observations, the low-order numerics have difficulties, related to analytical agreement and

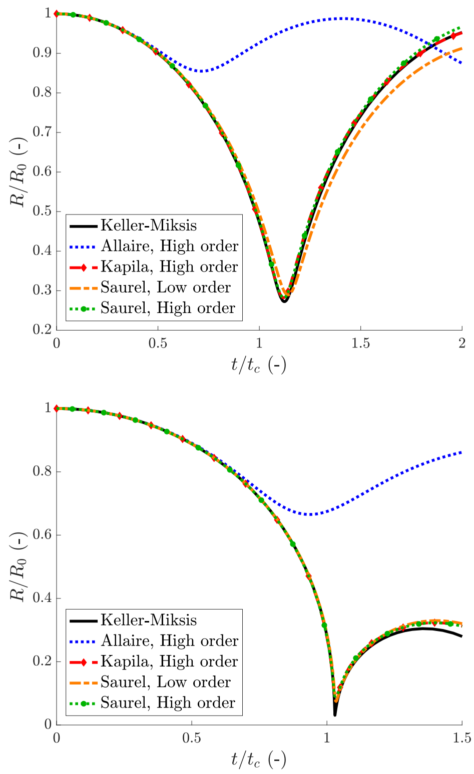

Figure 1: Dimensionless radius function of dimensionless time for the collapse of a gas bubble in water. Analytical solution of Keller-Miksis for spherical bubble collapse and 3D simulations using the models of Allaire, Kapila and Saurel are shown. $p_{\text{water}}/p_{\text{bubble}} = 10$ (top) and 1427 (bottom), and a resolution of 50 (top) and 100 (bottom) cells per diameter is used for the 3D simulations.

sphericity, when considering a small initial pressure ratio while the high-order numerics have difficulties, mainly related to sphericity, for the high ratio. Furthermore, through another Rayleigh-collapse test case but this time with an initial disequilibrium between both sides of the bubble wall, an additional issue is pointed out and is coming from the multicomponent models at the location of smeared interface (mixture region) when pressure discontinuities are encountered. Indeed, one can observe a phenomenon of wave "trapping" from the interface and this last is related to the recovered Wood speed of sound (Wood 1930) in this mixture region.

Solutions using adaptive mesh refinement (Schmidmayer et al. 2018b) and interface-sharpening (Shyue and Xiao 2014) methods are proposed to remedy specific problems.

Conclusions

Pathologies of the physical model of the multicomponent fluid and of the discretization scheme are identified and solutions, such as compute the pressure-disequilibrium model of Saurel et al. to guarantee the robustness of the simulations and the THINC interface-sharpening method of Shyue and Xiao to avoid the phenomenon of wave "trapping", are proposed.

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