INERTIAL COLLAPSE OF INDIVIDUAL BUBBLES NEAR SOLID/FREE BOUNDARIES

Allocation: GLCPC/350 Knh
PI: Eric Johnsen[1]
Co-PIs: Shahaboddin Alahyari Beig[1], Mauro Rodriguez[1], Minki Kim[1]

[1]University of Michigan

EXECUTIVE SUMMARY

Inertial collapse of cavitation bubbles is a particularly complicated multiscale (ranging from micro- to macrobubbles in space, and microseconds to hours in time) and multiphysics (compressible fluid mechanics, multiphase flows, heat transfer, and solid mechanics) problem with a range of applications from naval hydrodynamics to biomedical ultrasound.

One of the main consequences of cavitation is structural damage to nearby objects. Collapse of cavitation bubbles can concentrate energy into a small volume, produce high pressures and temperatures, and generate strong shock waves. When they are adjacent to a neighboring interface such as another bubble, a solid object, or a free surface, the collapse becomes asymmetric and a re-entrant liquid jet penetrates the bubble. This jet hits the opposite side of the bubble and generates a radially propagating water-hammer shock.

To investigate this phenomenon, the research team carried out high-resolution numerical simulations of the collapse of: (1) a single bubble near an interface, and (2) multiple bubbles near a solid surface. These simulations yielded the detailed nonspherical bubble morphology as well as the pressure and temperature fields based on the relevant nondimensional parameters entering the problem. These simulations will be used to model the collapse of bubble clouds, to comprehend the damage mechanisms, and potentially to mitigate erosion.

RESEARCH CHALLENGE

Cavitation research is essential to a variety of applications ranging from naval hydrodynamics to medicine and the energy sciences. Vapor cavities can grow from submicron-sized nuclei to millimeter-sized bubbles, and they collapse violently in an inertial fashion [1]. This implosion, which concentrates energy into a small volume, can produce high pressures and temperatures, generate strong shock waves, and even emit visible light [2]. It is known that high pressures and temperatures as well as the corresponding shock waves produced by the collapse of cavitation bubbles are capable of damaging nearby objects. This damage is recognized as one of the main consequences of cavitation and is an essential research topic in a variety of hydrodynamic and acoustic/biomedical applications [3–5].

The combination of compressibility effects of high-impedance fluids (liquids), the propagation of shock/rarefaction waves in a multiphase medium, and their interactions with material interfaces and nearby solid/free boundaries results in a complex multiscale problem that ranges from micro- to macrobubbles in space and microseconds to hours in time and a multiphysics problem dealing with compressible fluid mechanics, multiphase flows, heat transfer, and solid mechanics. Laboratory experiments of such flows are challenging owing to the wide range of spatial and temporal scales, difficult optical access, and limitations of measurement devices. Thus, highly resolved numerical simulations have emerged as an alternative tool to complement experimental studies. However, the most commonly used algorithms are incapable of simulating the flow around the cavitating bubbles and treating the material interfaces correctly. To overcome these issues, the research team developed a novel numerical model to carry out accurate and efficient simulations of compressible multiphase flows [6,7]. These simulations provide valuable insight into the detailed dynamics of inertial collapse of individual bubbles near solid/free boundaries.

METHODS &CODES

To carry out the simulations, the team developed a novel numerical framework to solve the compressible Navier–Stokes equations for a binary, gas–liquid system [6,7]. This numerical approach prevents spurious pressure and temperature oscillations across the material interfaces. For discretization, the group developed a solution-adaptive central-differencing/discontinuity-capturing approach. The basic idea is to use a high-order accurate, nominally nondissipative central difference scheme in smooth regions, and to apply a more dissipative, computationally expensive, high-order accurate, shock- and interface-capturing approach only to the regions with discontinuities. For this purpose, a discontinuity sensor discriminates between smooth and discontinuous (shocks, contacts, and interfaces) regions. The time marching is handled with a third-order accurate TVD Runge–Kutta scheme. To perform the three-dimensional numerical simulations of the problems of interest, an in-house code was developed in C++, which was parallelized using the MPI library and implemented the parallel HDF5 library for I/O. The code was verified and validated against a series of theoretical and experimental data. To better understand the detailed collapse dynamics, as well as to comprehend the damage mechanisms and potentially mitigate erosion, the team studied the collapse of individual bubbles near solid/free boundaries.

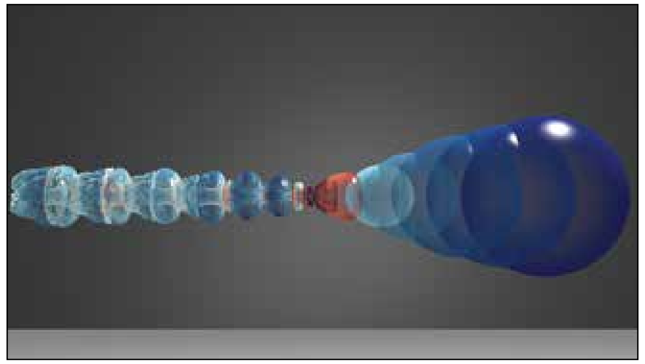

Figure 1: Volume rendering of the bubble interface colored by its temperature showing the re-entrant jet formation and vortex ring convection during the collapse of a single bubble near a solid surface.

RESULTS & IMPACT

When a cavitation bubble collapses near an interface, the collapse becomes nonspherical, leading to the formation of a high-velocity re-entrant liquid jet (Fig. 1). The impact of the jet on the opposite side of the bubble can generate a water-hammer shock wave that propagates in the surrounding media and thus can create high-pressure regions on the surface of neighboring solids (Fig. 2). Simulating the collapse of a single bubble near an interface delves into the details of the re-entrant jet formation and the corresponding shock propagation. The results will be used to provide scaling laws for important collapse parameters (*e.g.*, jet velocity, bubble nonsphericity, collapse time, and shock pressure) that can be used to predict the single-bubble dynamics.

However, the disruptive effects of cavitation erosion in real flow problems are generally caused by the collapse of bubble clouds that include thousands of bubbles. To simulate such flows where resolving every bubble is numerically impossible, a robust cloud model is required. Current models are typically based on spherical bubble dynamics, and thus neglect the nonspherical effects of the collapse owing to bubble–bubble/bubble–boundary interactions [8], which leads to an inaccurate estimation of the impact loads on nearby surfaces. To address this, the team simulated the collapse of a bubble pair near a solid surface to investigate and quantify the bubble–bubble/bubble–boundary interactions and their effects on the collapse dynamics. The simulation showed that such interactions intensify the overall collapse nonsphericity and may increase or decrease the collapse intensity depending on the initial flow configuration.

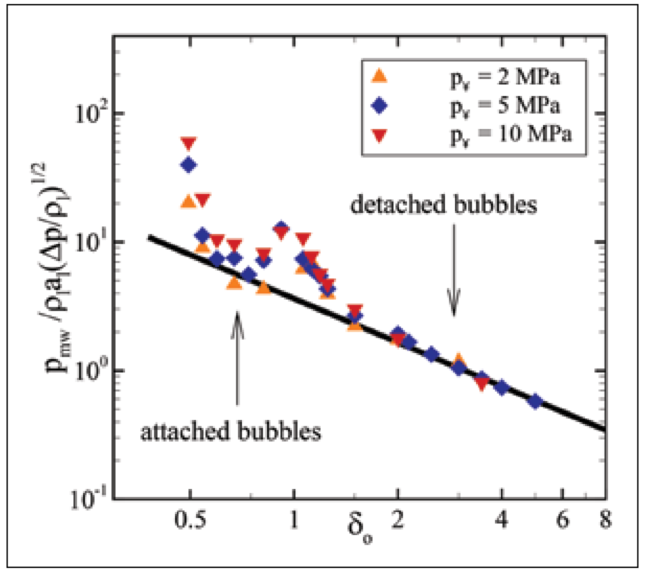

Figure 2: The scaling of the maximum pressure measured along a solid surface caused by the collapse of a nearby single bubble as a function of the initial standoff distance from the surface and the collapse driving pressure.

These results can be used to develop a more reliable cloud model that includes the nonspherical effects of the collapse, providing a more accurate prediction of the cloud dynamics and potential cavitation-induced erosion.

WHY BLUE WATERS

Performing three-dimensional high-resolution simulations of up to 3.6 billion gridpoints that can effectively resolve the small-scale features of the flow, as well as handling postprocessing and visualizations of large data files, requires substantial computational power. A petascale computing resource such as Blue Waters makes these simulations possible and has been essential for the success of the present study. This project will help researchers to gain valuable insights and understanding of these complex flows, which was not previously possible.

PUBLICATIONS & DATA SETS

S. A. Beig, B. Aboulhasanzadeh, and E. Johnsen, "Temperatures produced by inertially collapsing bubbles near rigid surfaces," *J. Fluid Mech.*, vol. 852, pp. 105–125, 2018.

S. A. Beig, M. Kim, and E. Johnsen, "The role of compressibility in energy budget of spherical collapse of an isolated bubble," *Phys. Rev. Lett.*, in preparation, 2019.

S. A. Beig and E. Johnsen, "Inertial collapse of a gas bubble near a rigid boundary," *J. Fluid Mech.*, in preparation, 2019.

S. A. Beig and E. Johnsen, "On the effects of bubble–bubble interactions in inertial collapse of a bubble pair near a rigid wall," *J. Fluid Mech.*, in preparation, 2019.

S. A. Beig, "Inertial collapse of individual bubbles near a rigid surface," presented at the 10th Int. Conf. Mult. Flows, Rio de Janeiro, Brazil, May 19–24, 2019.

S. A. Beig and E. Johnsen, "Bubble–bubble interactions and wall pressures/temperatures produced by the collapse of a bubble pair near a rigid surface," presented at the 10th Int. Cav. Sym., Baltimore, MD, U.S.A., 2018.