NUMERICAL SIMULATIONS OF A COLLAPSING CAVITATION BUBBLE NEAR AN ELASTICALLY DEFORMABLE OBJECT

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EXECUTIVE SUMMARY

The aim of this work is to understand the structural damage to nearby objects as a result of cavitation (the formation of small vapor-filled cavities). In extreme cases, cavitation gas bubbles collapse into small volumes that produce high pressures and temperatures and generate strong shock waves that interact with the surroundings. When adjacent to a neighboring elastically deformable object, the collapse becomes asymmetric and a re-entrant liquid jet forms within the bubble. The jet hits the opposite side of the bubble and generates an outwardly propagating water-hammer shock that then interacts with neighboring object(s). To determine the effect of confinement and of an elastically deformable object, the research team conducted two high-resolution numerical simulation studies of the collapse of: (1) a single bubble near a viscoelastic object undergoing elastic deformations, and (2) a single bubble in a channel composed of rigid walls. These simulations will be used to understand damage mechanisms in elastic objects and to potentially mitigate erosion.

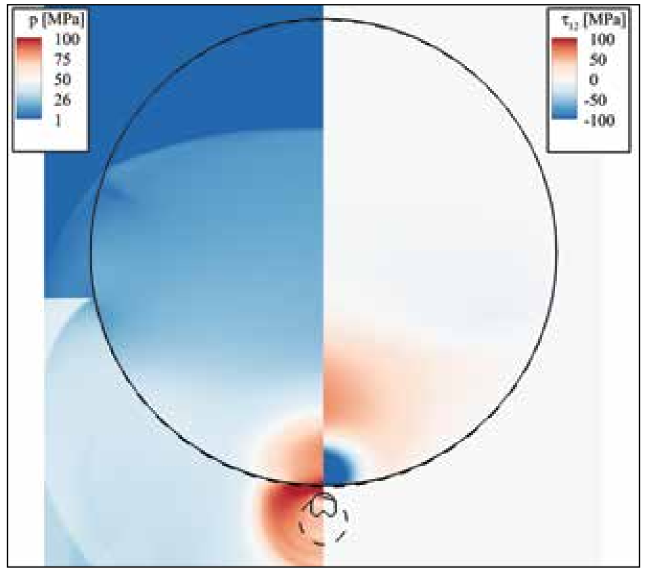

Figure 1: Pressure (left) and elastic shear stress component (right) contours of a shock-induced collapse-induced gas bubble (bottom outline) near a finite-sized elastic (calcium) stone. Isolines denote the approximate location of the bubble's and calcium stone's interface.

RESEARCH CHALLENGE

Cavitation bubble dynamics appear in a wide range of hydraulic applications such as turbomachinery, naval structures, biomedical ultrasound, and combustion. Cavitation happens owing to the reduction in local pressure beyond the tensional threshold in the surrounding liquid, thereby incurring a mechanically driven phase change in the liquid and leading to the formation of vapor bubbles. Vapor bubbles collapsing near surfaces/objects form a re-entrant jet that impacts on the distal bubble wall, generating a water-hammer shock wave that interacts with the surroundings. The high pressures and temperatures as well as the corresponding shock waves produced by the collapse of cavitation bubbles can damage nearby objects [1–4]. 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. In naval applications, engineers still struggle to cope with the deleterious effects of cavitation erosion on surfaces and hydraulic machinery, which lead to degradation in performance and need for repair and/or replacement. In the context of therapeutic ultrasound, the pressure pulses from the collapse of cavitation bubbles are employed to fragment kidney stones and pathogenic tissues.

Understanding the collapse dynamics and the associated damage mechanisms will enable researchers to develop techniques to control (either by mitigation or enhancement) cavitation erosion. However, the wide range of temporal and spatial scales of these flows significantly limits the ability to obtain precise experimental measurements. As a result, numerical simulations serve as a valuable complementary tool to further our understanding of the physics, alongside analytical and experimental efforts. For this reason, the research team has developed a novel numerical framework to investigate the detailed dynamics of nonspherical bubble collapse near viscoelastic objects using high-resolution simulations [5–8]. These simulations will be used to develop a comprehensive model of the collapse dynamics and corresponding damage mechanisms of nearby objects, leading toward developing strategies to better control cavitation-induced erosion.

METHODS & CODES

The team used its in-house petascale production code for the large-scale simulations based on MPI. This code solves the three-dimensional compressible Navier–Stokes equations with thermodynamically consistent evolution equations for the elastic contribution of the stress to represent multiple gases, liquids, and viscoelastic solids [5–8]. The code is based on high-order accurate (in smooth regions), nondissipative schemes with discontinuity detectors to apply high-order numerical dissipation at shock wave and material interfaces. Thus, the code can accurately solve problems involving broadband features, *e.g.*, turbulence, and discontinuous features such as material interfaces, shock, and shear waves. 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 has been verified and validated against a series of theoretical and experimental results.

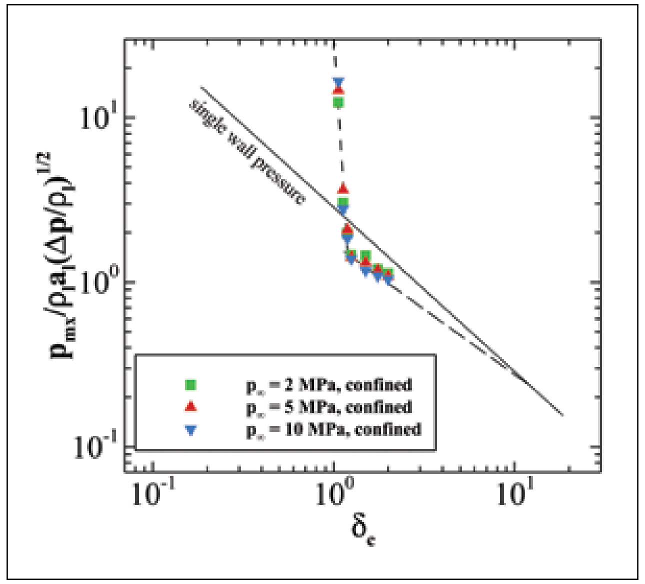

Figure 2: Scaling of maximum pressure measured along a confined channel from the collapse of a bubble centered in a channel at stand-off distance from the surface and the collapse driving pressure. Solid line: scaling for a bubble near a single wall; dashed line: scaling for a bubble centered in a channel.

RESULTS & IMPACT

To better understand the detailed bubble collapse dynamics near an elastically deformable object or in confinement, two problem configurations were considered: (1) shock-induced collapse of a single bubble near a finite-sized (spherical) calcium stone, and (2) collapse of a single bubble in a confined channel. When a cavitation bubble collapses in these configurations, the collapse becomes nonspherical, leading to the formation of a high-velocity re-entrant liquid jet(s) (Fig. 1). The impact of the jet upon the opposite side of the bubble generates a water-hammer outwardly propagating shock wave, and thus can create high-pressure regions on the surface of the neighboring surfaces/objects (Fig. 2). Scaling laws of the maximum pressures (and resulting impact loads) exhibited on these surfaces based on important collapse parameters (*e.g.*, driving pressure, bubble location) were developed to predict the single-bubble dynamics.

In the first study, the synchronization of the shock wave with the bubble collapsing near the stone depends on the initial bubble size–stone size ratio for maximizing the tension inside the stone that could lead to its comminution. These results will enable further optimization and development of ultrasound therapy tools used to fractionate elastic stones. Scaling results from the second study showed that for significant confinement, the bubble collapse jet formation dynamics change with the re-entrant jet forming in the direction parallel to the channel. This then further strengthens the collapse of the remaining bubble remnants. As a result, the channel-scaling relationship deviates from the scaling for a single bubble collapsing near a single wall.

These results enable the team to predict and quantify the damage mechanisms involving the nonspherical bubble collapse near a finite-sized elastic object in confined geometries to develop cavitation mitigation/enhancement strategies.

WHY BLUE WATERS

The three-dimensional high-resolution simulations (requiring more than one billion grid points) that can effectively resolve the necessary small-scale features of the flow for high-fidelity results for over 36-hour simulation wall-times, as well as postprocessing and visualizations of large data files, require substantial computational power and resources. The Blue Waters petascale computing and simulation wall-time capabilities make such simulations possible and were essential for the success of this study.

PUBLICATIONS & DATA SETS

M. Rodriguez, S. Alahyari Beig, E. Johnsen, and C. Barbier, "Inertially-driven gas bubble collapse in a channel," in preparation, 2019.

M. Rodriguez and E. Johnsen, "Numerical investigation of a shock-induced bubble collapse near an elastic, rigid object," in preparation, 2019.

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, "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.