NUMERICAL SIMULATIONS OF COLLAPSING CAVITATION BUBBLES ON BLUE WATERS

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EXECUTIVE SUMMARY

The collapse of cavitation bubbles is known to cause damage, ranging from the erosion of naval propellers to soft tissue ablation. While significant attention has been dedicated to investigating this phenomenon in the case of hard materials such as metals, less is known about cavitation-induced damage to soft materials.

In order to elucidate these damage mechanisms, we perform high-fidelity numerical simulations of the collapse of individual and multiple vapor bubbles near both rigid and compliant surfaces. We have developed a computational framework to conduct massively parallel simulations of the three-dimensional compressible Navier–Stokes equations for gas–liquid flows. These simulations provide a clearer image of the detailed nonspherical bubble dynamics, pressure, and temperature fields, and stresses/deformations of the neighboring solid. This knowledge and data enable us to develop numerical models for the collapse of bubble clouds that can be used in biomedical or naval hydrodynamic applications of interest.

RESEARCH CHALLENGE

Cavitation occurs in a wide range of hydraulic applications, such as naval engineering, turbomachinery, and biomedical ultrasound. In contrast with boiling, in which liquid vaporizes as temperature is increased (i.e., a thermally driven phase transition), cavitation occurs when local pressure reductions of a liquid lead to the formation of vapor bubbles. These cavitation bubbles dramatically respond to pressure changes, growing to sizes far greater than their equilibrium radius and undergoing a violent inertially dominated collapse [1]. As a result, shock waves and high-pressure and high-temperature regions are produced, which may damage neighboring solid objects such as propellers or soft tissues [2–5].

While relatively well understood in the context of hard materials (e.g., metals), cavitation erosion to soft matters is not well known [3]. Given the prevalence of cavitating flows in a vast variety of applications, there is an essential need to investigate the detailed bubble dynamics and to predict pressures, temperatures and deformations produced. However, compressibility effects, including the propagation of shock and rarefaction waves in a multiphase medium, result in a complicated nonlinear multi-scale and multi-physics problem that is challenging to solve. Moreover, owing to the wide range of temporal and spatial scales of these flows, precise and accurate measurements are nearly impossible to obtain experimentally. Numerical simulations of effects not available and/or feasible via experimentation have therefore emerged as a powerful tool to complement and enhance our fundamental understanding of these flows [6].

METHODS & CODES

In order to perform high-resolution simulations of the three-dimensional compressible Navier–Stokes equations for a gas–liquid system, we have developed a novel computational algorithm [7]. We used an accurate model of compressible multiphase flows capable of resolving flows around caveating bubbles to correctly compute pressures and temperature across the material interfaces.

The algorithm employs a third-order accurate explicit strong-stability-preserving Runge–Kutta scheme to march in time [8]. For the spatial discretization, we proposed a solution-adaptive, high-order accurate, central difference/discontinuity-capturing method. This method can represent both broadband flow motions and discontinuities accurately and efficiently. The basic idea is that nondissipative methods are used where the solution is smooth, while the more dissipative and computationally expensive capturing schemes are applied near discontinuous regions. For this purpose, a discontinuity sensor discriminates between smooth and discontinuous (shocks, contacts, and interfaces) regions, which all require a different treatment. For large-scale parallel calculations, our in-house petascale production code achieves parallel efficiency over 83% on 4,096 processors using MPI; we have also been exploring alternative approaches such as GPU acceleration. Our code also uses the parallel HDF5 library to manage large and complex data collections.

RESULTS & IMPACT

The current project focuses on two specific problems: the collapse of a single bubble near solid/soft media and the collapse of multiple bubbles near solid/soft media. The first problem provides insight into the detailed dynamics of the collapse, including the nonspherical behavior of the bubble, high-velocity jet formation, propagation of shock waves, and the vortex ring convecting toward the boundary. The simulations provide the flow field pressure and temperature distribution throughout the collapse, which can be used to model cavitation erosion (Fig. 1).

Although studying single-bubble collapse is valuable specifically in exploring the flow physics, the disruptive effects of cavitation erosion are generally caused by the collapse of bubble clouds containing tens of thousands of bubbles. However, resolving every bubble is computationally prohibitive, such that a model representing the collective behavior of the bubble cloud is necessary. Currently, such models are rudimentary [9], as they only account for spherical bubble dynamics. By conducting resolved simulations of individual bubbles, we are investigating the complex interactions within the collapsing bubbles in order to establish a numerical cloud model that includes the bubble–bubble interactions and the nonspherical effects of the collapse.

This project will deepen our knowledge and understanding of the nonspherical behavior of the bubbles in cavitating flows. Developing a comprehensive model for bubble clouds will result in more precise numerical simulations of the collapse of bubble clusters. This will help to reduce the disruptive effects of cavitation erosion in naval applications and turbomachinery. Reducing cavitation erosion will significantly strengthen the structures exposed to deterioration caused by cavitating flows, extend the lifetime of machineries, and has the potential to save billions of dollars each year. Moreover, a well-known treatment in biomedicine utilizes structural damage induced by collapsing bubbles to break apart kidney stones. The same idea has been applied to destroying malignant cells and soft tissue. However, a negative side effect of these medical advancements is the unwanted damage to neighboring cells and tissues. This study delves further into these matters to provide insight into damage mechanisms to better control them in order to minimize the impairment of healthy cells and tissues.

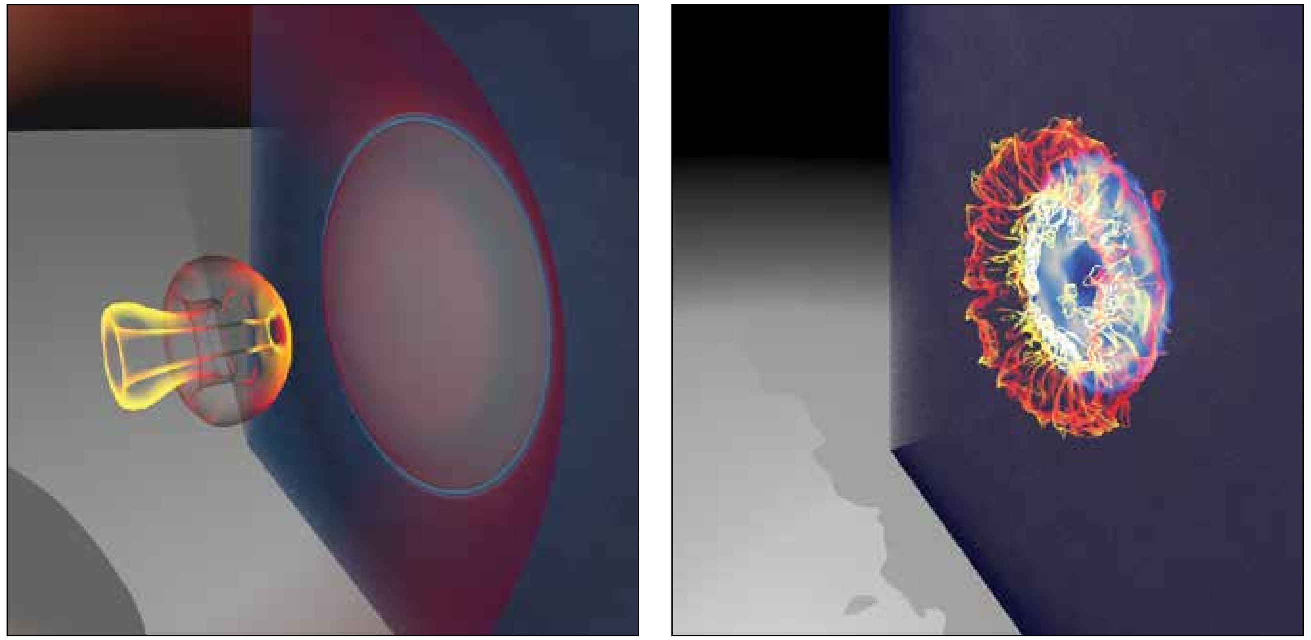

Figure 1: The microjet impacting the distal side of the bubble generates a strong outward propagating shock wave. Later on, this shock hits the wall, reflects back, and eventually interacts with the collapsed bubble which results in a second collapse (left). Thereafter, the bubble takes the form of a convoluted vortex ring, which is convected toward the adjacent wall (right). This image is produced from one of our simulations performed on a different NSF-supported supercomputer, Stampede.

WHY BLUE WATERS

This project utilizes two different in-house codes: our petascale production code for the large-scale simulations (based on MPI) and our next-generation code that enables larger-scale heterogeneous architectures (based on MPI and GPUs). These codes solve the compressible Navier–Stokes equations for multiple gases and liquids. The foundations of both codes are high-order accurate algorithms, explicit in time and in space, thus naturally lending itself to massive parallelization. To carry out accurate simulations of cavitating flows that effectively resolve the small-scale features, extremely high spatial resolution is essential to run even a single simulation over long compute times, which is difficult to achieve on any other NSF computing resource. Given its speed and available computation power, the Blue Waters supercomputer is capable of providing us with this opportunity.