All-speed Multi-phase Computational Framework for Simulating the Entire Process of Underwater Explosions: Shocks, Cavitations, and Bubble Pulsations

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Abstract: Underwater explosions contain highly disparate physical phenomena, comprised of three stages: (I) initial shock wave, (II) bulk cavitation, and (III) pulsation of explosion gas bubble. While actual events are sequential and continuous, previous studies have focused on each stage separately, neglecting the possible interactions between each stage. This paper proposes a high-fidelity computational framework that can capture the significant flow physics of the entire process of an underwater explosion. More attention has been put on accurate thermodynamic aspects: sophisticated equation of state and thermodynamic cavitation process. The applicability of this framework is discussed by comparing computations with the field experimental references.

Keywords: Underwater Explosions, All-speed Multi-phase Flows, Shock Waves, Cavitations, Bubble Pulsations.

1 Introduction

Underwater explosions (UNDEX) refer to the detonation of explosive charges immersed in water. While the UNDEX scenario is seemingly simple, actual physical phenomena underneath the water surface are highly complicated and can be categorized into three stages [1]. Massive energy released from the initial explosion induces a spherical blast wave propagation (Stage I). After the shock wave reaches the free surface, rarefaction waves are reflected, while a weak shock is transmitted to the air due to an impedance mismatch between air and water media. As the expansion waves propagate in the water, cavitation bubbles are formed in the low-pressure region beneath the free surface (Stage II). The moment the cavitation bubbles collapse, a bulk cavitation load arises that could reach a comparable magnitude to Stage I. Meanwhile, the explosion gas bubble expands and contracts periodically, emitting a large amount of pressure pulses (Stage III).

Above mentioned phenomena take place consecutively; thus, the possible interactions between stages need to be considered by the continuous simulation of the entire process. Moreover, most of the previous UNDEX studies have been conducted without considering accurate thermodynamic aspects; by adopting the ideal form of the equation of state (EOS) and simple treatment for the phase change. In this study, a high-fidelity computational framework is proposed for simulating the entire process of UNDEX with accurate thermodynamic considerations. Following the proposed framework, an in-house CFD program ACTFlow_MP has been developed and validated by comparing with the field experimental data.

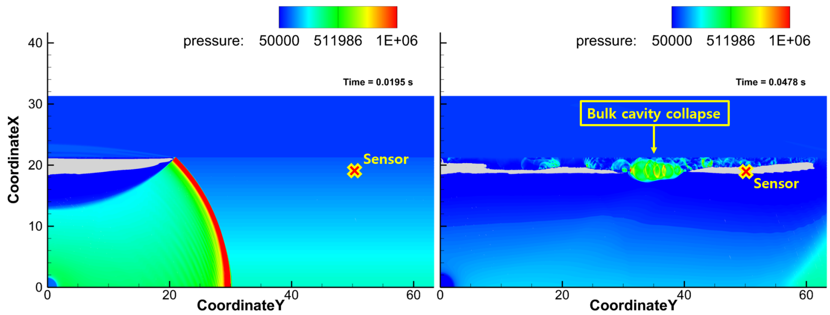

Figure 1: Pressure distributions by time sequence

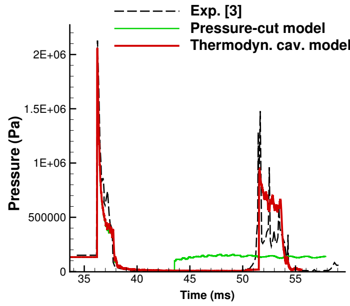

Figure 2: Measured pressure history

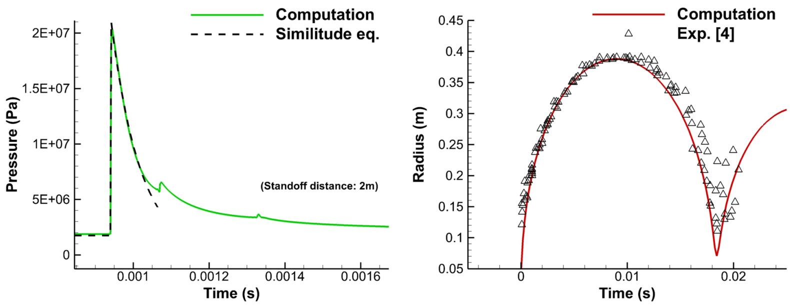

Figure 3: History of shock (left) & bubble radius (right)

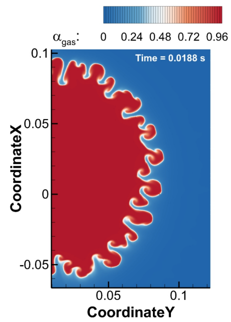

Figure 4: Volume fraction of gas

2 Computational Framework and Validations

The homogeneous mixture model is adopted to describe all-speed multi-phase flows. The governing equations are cast into two-dimensional axisymmetric Euler equations and preconditioned to handle flows spanning subsonic to supersonic. A more sophisticated EOS is adopted for accurate fluid properties: NIST database, Jones-Wilkins-Lee EOS. A thermodynamic cavitation process is employed, which reflects the generation of actual vapor phase with latent heat exchange [2]. The detailed information on the numerical methods will be provided in the full paper.

The first validation case is the field test record on noticeable cavitation load [3], which covers Stages I and II. The gray-colored area in Fig. 1 indicates the cavity region, and it is clear that the secondary shock wave is emitted as the bulk cavity collapses. According to Fig. 2, the thermodynamic cavitation process plays a crucial role in capturing the load in Stage II. This is the first attempt to confirm the efficacy of the thermodynamic cavitation process by comparing it with the experimental reference.

The second case is the measurement of the bubble motion in the deepwater [4]. Figure 3 shows the continuous simulation well captures the representative flow physics of Stages I and III. Right after the bubble collapses (Fig. 4), Rayleigh-Taylor instability is observed at the bubble surface. Compared with UNDEX experiment records, the proposed computational framework can capture the critical physics of the entire process of UNDEX. The full paper will present more detailed information on the simulation results.

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