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The Modified Ghost Fluid Method as Applied to Extreme Fluid-Structure Interaction in the Presence of Cavitation

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Abstract. In this work, the modified Ghost Fluid Method is further developed to apply to compressible fluid coupled to deformable structure, where the pressure in the structure or flow can vary from an initial extremely high magnitude (such that the solid medium can be under plastic compression) to a subsequently very low quantity (so that cavitation can occur in the fluid). New techniques are also developed in the definition of the ghost fluid status when the structure is under plastic deformation or when the flow is under cavitation next to the structure. Numerical results show that the improved MGFM for treatment of the fluid-deformable structure coupling works efficiently for all pressure ranges and is capable of simulating cavitation evolution and cavitation reloading in conjunction with the employment of the isentropic one-fluid cavitation model.

Key words: Ghost fluid method (GFM); modified ghost fluid method (MGFM); one-fluid cavitation model; cavitation reloading; cavitation-structure interaction.

1 Introduction

Cavitation occurs in fluid flow when the low pressure in the liquid reaches the limit of saturated vapour pressure. One example is the flow generated by an underwater explosion near a structure and a free surface, where (bulk) cavitation just below the free surface and (hull) cavitation nearby the structure are usually created and subsequently collapse very violently. As cavitation collapse can induce a strong pressure surge, the loading caused by

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an underwater explosion on the nearby structure physically consists of direct underwater shock loading and cavitation reloading. Traditionally, the shock loading is considered as a major if not the sole contributor to the structural failure. With the advances of experimental and numerical techniques, some recent experiments and numerics have shown that cavitation can affect the pressure loading of the structure significantly [5, 21, 22, 43, 44]. Brett et al. [5] conducted a series of experiments investigating a cylinder deformation associated with underwater explosions. The cavitation reloading on the structure arising from the cavitation collapse can be clearly observed in their experimental results. The underwater experiments and numerical simulations carried out by Wardlaw and Luton [43] in a cylindrical container further showed that the peak pressure caused by cavitation collapse can be up to 40% of the peak pressure associated with the initial/direct shock impact. Recent numerical simulations by Liu et al. [21] and Xie et al. [44] also affirmed that the pressure surge caused by cavitation collapse near a rigid wall can attain up to 40%∼50% of the said peak pressure. Consequently, it is important and perhaps critical to ascertain correctly the possible cavitation reloading on the structure in order to assess accurately the overall loading.

From the viewpoint of numerical simulation, however, it is still extremely challenging to fully simulate the flows generated by an underwater explosion near a deformable structure. There are several difficulties encountered in the modelling and simulating of such unsteady flows. These are summarised as follows

1) The structural deformation and compressibility have to be taken into account. Under the impact of a strong underwater shock, the solid structure can behave like a fluid and strong transmitted compression waves can propagate inside the structure.
2) Fluid phase transition or cavitation has to be modelled in order to capture the possible cavitation reloading on the structure.
3) The fluid-structure non-linear interaction has to be faithfully captured. This is perhaps the most difficult and challenging part in the numerical simulation. The said interaction is usually simplified as in previous numerical works, especially those calculated using commercial software.
4) The treatment of the moving explosive gas-water interface and the free surface is another key challenge.

Some recent analysis and discussions on the influence of a free surface on the structural loading may be found in [22]. The treatment of the moving gas-water interface and discussions on shock wave refraction at a moving gas-water interface can be found in [24, 25]. Discussions on various unsteady cavitation models may be found in [21].

In this work, the focus is on the treatment of the moving fluid-structure interface, which plays a key role in the accurate evaluation of the shock loading and cavitation reloading on the structure. On the other hand, it is well known that the treatment of moving material interfaces is still very challenging, especially if the density ratio of the two media is very large (like air-water flow) or one of the media is constituted with a