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Modified Ghost Fluid Method as Applied to Fluid-Plate Interaction

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Abstract. The modified ghost fluid method (MGFM) provides a robust and efficient interface treatment for various multi-medium flow simulations and some particular fluid-structure interaction (FSI) simulations. However, this methodology for one specific class of FSI problems, where the structure is plate, remains to be developed. This work is devoted to extending the MGFM to treat compressible fluid coupled with a thin elastic plate. In order to take into account the influence of simultaneous interaction at the interface, a fluid-plate coupling system is constructed at each time step and solved approximately to predict the interfacial states. Then, ghost fluid states and plate load can be defined by utilizing the obtained interfacial states. A type of acceleration strategy in the coupling process is presented to pursue higher efficiency. Several one-dimensional examples are used to highlight the utility of this method over loosely-coupled method and validate the acceleration techniques. Especially, this method is applied to compute the underwater explosions (UNDEX) near thin elastic plates. Evolution of strong shock impacting on the thin elastic plate and dynamic response of the plate are investigated. Numerical results disclose that this methodology for treatment of the fluid-plate coupling indeed works conveniently and accurately for different structural flexibilities and is capable of efficiently simulating the processes of UNDEX with the employment of the acceleration strategy.

AMS subject classifications: 65M06, 65N85, 74F10

Key words: Fluid-structure interaction, modified ghost fluid method, compressible flow, thin elastic plate, underwater explosions.

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1 Introduction

Research on the interaction between fluid and structure, especially for the problem of strong shock impacting on the interface, has a number of important applications in mili-

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tary technology, homeland security and engineering. Shock waves generated by underwater explosions (UNDEX) would cause damage to vessels including hull deformation or even fracture. Generally speaking, UNDEX tests are costly and hazardous, and even may not be repeatable. Validated numerical approaches to faithfully simulate such problems are essential. The accurate numerical solution, however, may be extremely difficult to obtain due to complicated nonlinear interaction. Usually, a fluid-structure interaction (FSI) problem can be solved in a monolithic or partitioned way. The monolithic approach, where the flow and structural equations are solved simultaneously, requires a purpose-designed procedure and large computational cost. Comparatively speaking, the partitioned approach, where the flow and structural equations are solved separately, allows us to use the already existing solvers or highly developed software to treat respective media. For example, currently popular high-resolution fluid solvers, such as the discontinuous Galerkin (DG) schemes [1, 2] or the (weighted) essentially non-oscillatory ((W)ENO) schemes [3, 4], and high-order finite element method (FEM) can be conveniently applied in the calculation of flow and structure, respectively. The loosely-coupled method [5–9], categorized as one partitioned approach, treats the coupling conditions in an explicit manner at each time step, which means that the flow does not change while the solution of the structural equations is calculated and vice versa. This is often the method of choice, usually in most commercial software, due to its simplicity and low computational cost. But it does not enforce the equilibrium on the fluid-structure interface because the interaction is achieved by applying respective boundary conditions to the individual solver separately. Thus, the numerical instability is induced, especially when the structure is under a strong shock wave impact. On the other hand, an additional mesh deformation algorithm or remeshing technique at least in the vicinity of the interface may be required. Furthermore, it is also a challenge to conservatively map quantities from Eulerian boundary nodes to nearby Lagrangian boundary nodes, and vice versa.

Recently, a ghost fluid method (GFM) has been employed to model fluid-fluid or fluid-structure interaction in a simple and flexible way by Fedkiw et al. [10, 11]. One does not need to remesh the fluid domain using this method because the moving interface is treated as an invisible internal boundary. The boundary condition is simply imposed by extrapolating specific variables from one medium to another. This treatment is classified as a partitioned approach but different from the above loosely-coupled method and, therefore, can also be regarded as a half-way-coupled method. However, it is found to be inaccurate in some situations such as high-speed jet impacting [12, 13]. To overcome this problem and combine the advantages of partitioned loosely-coupled method, a modified GFM (MGFM) was proposed and developed by Liu et al. [12]. The MGFM, when used to handle fluid-fluid interaction, employs a double-shock approximate Riemann solver to determine the interface states. The predicted interface states are then used to define the fluid states in a narrow band of ghost fluid cells near the interface. The MGFM-based techniques, including its varieties like RGFM [14], have been shown to be robust and less problem-related and successfully applied to various gas-gas, gas-water coupling problems [12–16] or even solid-solid contact problems [17]. Furthermore, it has been proved