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The simulation of compressible multi-fluid multi-solid interactions using the modified ghost method

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ABSTRACT

Based on the Modified Ghost Fluid Method (MGFM) and Modified Ghost Solid Method (MGSM), the Modified Ghost Method (MGM) is developed to deal with the combined compressible multi-fluid multi-solid interactions. The exact solution for 1D fluid-elastic-plastic solid Riemann problem is derived, which is subsequently used to verify the validity of the MGM as applied to fluid-elastic-plastic solid interaction. Using MGM, we construct a coherent and consistent approach to simulate truly compressible multi-medium problems as for gas-water-solid-solid interaction. Similar to the 1D cases, several 2D multi-medium cases are simulated to show the versatility and ease of application for the MGM. Finally, a multi-medium case with a complex geometry in solid domain is simulated, which shows that the proposed approach can be effectively used to study the response of the various structure domain.

1. Introduction

Systems with multi-medium interaction are important in various fields. They cover acoustics [1], offshore oil and gas [2,3], underwater explosion [4], bursting of fluid-filled containers [5], aerospace industries [6], and many others. These multi-medium interactions involve materials ranging from liquid to gas to solid. Various approaches have been attempted to develop numerical methods which can simulate the multi-medium interaction [7–17]. Most of these methods, however, only focus on the interaction between two media, like gas-liquid, fluid-solid or solid-solid interaction. There is a dearth of work considering all the three media of gas, liquid and solid or more. A mathematically consistent approach which can effectively deal with the mentioned interaction problem will likely be significant. This paper attempts to address this challenge based on the Modified Ghost Method (MGM) and a robust, consistent and coherent numerical approach is proposed for the simulation of truly compressible multi-medium materials/flows in which various waves (pressure, acoustic, and shock waves) propagate and interact with the different interfaces.

The original Ghost Fluid Method (GFM) was proposed by Fedkiw et al. [18] and applied to the fluid-fluid interaction problem and subsequently to Fluid Structure Interaction (FSI) problem [19]. Thereafter, several variants of the GFM [20–24] have been developed to make the approach more robust and accurate. In particular, Liu et al. [22] proposed the solution of the approximate Riemann problem at the fluid-fluid interface for calculation of the appropriate ghost cell properties and hence enable the method to take on very strong shockwave impacting on the said interface, and termed as the Modified Ghost Fluid method (MGFM). This is broadly adopted in the present work both for the fluid-fluid interaction and fluid-solid interaction problems. Very recently, Kaboudian et al. [8,25] developed and applied the MGFM to solid-solid interaction problems where elastic-elastic, elastic-plastic and plastic-plastic deformations take place; they termed it as the Modified Ghost Solid Method (MGSM).

For simplicity and ease of referral, we shall use the term Modified Ghost Method (MGM) to refer to MGFM and MGSM since they shared essentially the *same* approach of solving the Riemann problem applicable at the interface to arrive at the ghost cell properties for use in the respective media (whether solid, liquid or gas). Thus far, it appears that there is no attempt in using the MGM to solve a truly multi-medium problem which encompasses different media, like gas-water-solid-solid interaction. This provides largely the motivation of the present work. Meanwhile, in particular for the 1D FSI problem, we extend the method [9] originally intended for elastic solid so that it can deal with the solid undergoing elastic-plastic deformation. For FSI problem, the structure initially is under compression, and after long-time computation, tension waves may develop in solid and fluid which can cause fluid cavitation at the

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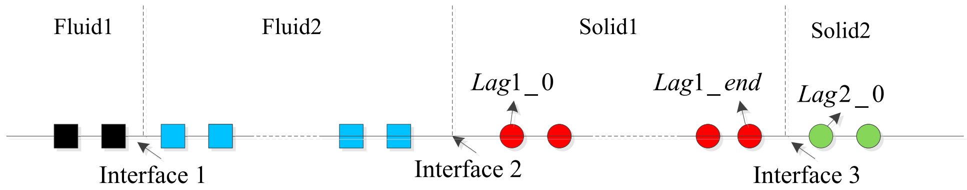

Fig. 1. Schematic illustration of 1D multi-medium interaction.

interface. It is not our intent to solve the FSI problems under the presence of cavitation in this paper. We may focus on this problem in the future. Therefore, we only compute for a short time before the cavitation occurred, when the solids are under compression.

Since Eulerian numerical methods are usually employed for the simulation of fluid and Lagrangian numerical methods for the simulation of solid, we shall use Eulerian numerical methods for fluid-fluid interaction, Eulerian–Lagrangian coupling for FSI and Lagrangian framework for solid-solid interaction. The paper is organized as follow. Sections 2 and 3 discuss the basic equations and details about the MGM for 1D and 2D multi-fluid multi-solid interaction problems, respectively. Section 4 presents the results for some interesting 1D and 2D numerical cases. The concluding remark is given in Section 5.

2. The MGM for 1D multi-medium interaction

In this section, the formulation for the 1D multi-medium interaction under the framework of MGM is provided. Fig. 1 provides a schematic of the problem at hand.

As MGFM has been successfully applied to different extreme cases of fluid-fluid problems, it is chosen to deal with fluid-fluid interaction which correspond to the 'Interface' 1 in Fig. 1. Similarly, we adopt MGSM to deal with the interaction between the solid-solid interface ('Interface 3' in Fig. 1). Next, the MGFM in [9] is modified and applied to the 1D fluid-solid interaction ('Interface 2' in Fig. 1) to take on both elastic and plastic deformations in the solid.

2.1. Governing equations

2.1.1. Governing equations for the 1D fluid

The governing equations for 1D compressible fluid are the Euler equations:

$$\frac{\partial U}{\partial t} + \frac{\partial F}{\partial x} = 0 \tag{2.1}$$

where $U = (\rho, \rho u, E)^T$, $F(U) = (\rho, \rho u^2 + p, u(E + p))^T$, $E = \rho e + 0.5\rho u^2$.

A general equation of state (EOS) can be used to close the system (2.1), like $e = e(p, \rho)$ [26]. Without loss of generality, the consistent form $p = (\gamma - 1)\rho e - \gamma p_\infty$ is used as the EOS for compressible gases and water in this work, where γ is the specific heat ratio and p_∞ is a material dependent constant. Here $\gamma_g = 1.4$ and $p_{\infty g} = 0.0\,Pa$ are set for gas (idea gas equation), and $\gamma_w = 7.15$ and $p_{\infty w} = 3309 \times 10^8\,Pa$ are set for water (Tait's equation). It may be noted that Tait EOS corresponds to the particular case of isentropic Stiffened Gas EOS (SGEOS), which has the form of $p = (\gamma - 1)\rho e - \gamma p_\infty$. How the Tait EOS is related to the SGEOS can be found in [14,27], which is not repeated here. The sound speed can be written in a unified form $c = \sqrt{\gamma \frac{p + p_\infty}{\rho}}$.

2.1.2. Governing equations for the 1D solid

The governing equations for the 1D isotropic linear elastic-plastic solid [28]:

$$\frac{\partial U}{\partial t} + \frac{\partial F}{\partial x'} = 0 \Rightarrow \frac{\partial U}{\partial t} + A\frac{\partial F}{\partial x'} = 0 \tag{2.2}$$

where $U = (u \quad p)^T$, $F = (\frac{c^2}{E'}p \quad E'u)^T$, $A = \begin{bmatrix} 0 & \frac{c^2}{E'} \\ E' & 0 \end{bmatrix}$ and x' represents the Lagrangian coordinate, which is different from the x used in the Eulerian coordinate system. Here, $p = -\sigma$, $c = \sqrt{\frac{E'}{\rho}}$, $E' = \begin{cases} E when |\sigma + d\sigma| \le \kappa \\ E_p when |\sigma + d\sigma| > \kappa \end{cases}$, where κ is the current yield stress, E is the Young's modulus, E_p is the modulus of the plasticity. We shall use $p = -\sigma$ for the solid, unless otherwise stated.

A linearly elastic, power-law work-hardening plastic stress-strain relationship is given by

$$\frac{1}{E_p(\kappa)} = \frac{\alpha}{E}\left(\frac{\kappa}{\kappa_0}\right)^{\alpha - 1}, \tag{2.3}$$

where κ_0 is the reference yield strength of the solid, κ is the current yield strength of the solid, and α is a constant for a particular material; or, a linearly elastic, linearly plastic, work hardening stress-strain relationship given by $E_p = \text{const}$ is applied to the elastic-plastic material for solid.

System (2.2) can be rewritten in the characteristic form as

$$du = -\frac{dp}{\rho c(\kappa)}, \text{ along } \frac{dx'}{dt} = c \tag{2.4}$$

$$du = \frac{dp}{\rho c(\kappa)}, \text{ along } \frac{dx'}{dt} = -c. \tag{2.5}$$

The governing equations for each of the medium in multi-medium problems involve the different (mathematical) variables, e.g. pressure, velocity, stress, density etc. Two types of variables can be identified in multi-medium interaction problems viz. (a) coupled and (b) uncoupled variables. Coupled variables are those which at the interface can be uniquely determined by using the characteristic information from both sides of the interface and the boundary conditions at the interface. Uncoupled variables cannot be uniquely determined at the interface. For 1D problems, the normal velocity and pressure at the interface are coupled as they can be determined using the characteristic from the two sides of the interface and the boundary conditions across the interface. The modulus (E and E_p), density (ρ), the current yield (κ) and all the material properties are uncoupled variables.

2.2. 1D MGM-based algorithm

2.2.1. Prediction of the interfacial status for the MGM

For MGM-based algorithm, one of the key problems is to predict the interfacial status. We need to solve an approximate Riemann problem (ARPS) at the interfaces via the method of characteristics. To illustrate, assuming that the interface lies between the nodes i and $i+1$. We shall use the C^+ characteristic line from the left side of the interface and C^- characteristic line from the right side of the interface side as shown in Fig 2.