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An Eulerian algorithm for coupled simulations of elastoplastic-solids and condensed-phase explosives

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ABSTRACT

The performance of non-ideal condensed-phase explosives depends on the nature of the confiner material as well as the charge itself, so the accurate modelling of this confiner and its interaction with the explosive allows for improved performance predictions. Traditionally, numerical methods for solving such multi-material problems have used Lagrangian or mixed Eulerian–Lagrangian approaches, but recent advances in numerical methods for coupling CFD (Computational Fluid Dynamics) and CMD (Computational Material Dynamics) algorithms has made such coupled simulations possible in the Eulerian frame of reference. However, to date, the explosive material representation within these simulations has been restricted to the single-phase Euler equations. In the present study we couple a multi-phase chemically-active model for condensed-phase explosives to an elastic–plastic model for inert confiner materials.

In the presented algorithm, the ghost-fluid method is employed to represent the evolving material interfaces as discontinuities on discrete space. The coupling between the materials at these interfaces is achieved by means of a new approximate mixed Riemann solver, developed as part of this research. In addition we present a mixed Riemann solver for a simpler transport model, which ignores compaction effects at the interface. The robustness and accuracy of the developed solvers is demonstrated by comparisons against results from the original ghost-fluid method and exact solutions of model Riemann problems. To allow for more realistic material behaviour, the mixed Riemann solvers are subsequently extended to handle the shock Mie–Grüneisen equation of state, and an iterative procedure is suggested to increase accuracy as required. These mixed Riemann solvers demonstrate their suitability for explosive–solid interactions in two test cases of multi-phase detonations confined by an elastic–plastic solid.

1. Introduction

The accurate numerical simulation of many industrial and defence processes, such as shaped charges, explosive welding or explosive safety assessments, has to take into account the interaction of detonation waves in condensed-phase explosives with a surrounding solid confiner material. In many high-strain-rate applications it is sufficient to describe the solid material solely by its plastic constitutive-law properties, thus allowing the modelling of the solid as a fluid. An application of particular interest to the mining industry is the prediction of the performance of an explosive under solid confinement. This knowledge can be used to improve the fracture and heaving process during blasting. In this paper we are concerned with the development of numerical methods for coupled solid–fluid interaction suitable for the solution of such problems.

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Traditional methods for the numerical solution of these coupled multi-material systems are based on Lagrangian or coupled Lagrangian–Eulerian approaches. However, these methods are likely to encounter problems if there are large distortions of the material interface, due to the corresponding mesh distortion that will inevitably occur. Various methods have been developed to overcome this shortcoming, amongst others arbitrary Lagrangian–Eulerian (ALE) approaches, free Lagrangian approaches and smooth particle hydrodynamics (SPH) [1–3].

In this work we consider an alternative approach, where the entire problem is solved on a fixed, Eulerian, frame. There have been a number of recent advances on this area, which we summarise below. The original Lagrangian solid mechanics formulation was expressed in conservative form within an Eulerian frame first by Godunov and Romenski [4] (see also Plohr and Sharp [5]), providing scope for treating the system using mature high-resolution, shock-capturing methods. Higher-order schemes for the fully conservative system have been developed by Miller and Collela [6], Barton et al. [7] and Gavrilyuk et al. [8]. In the first two studies, linearised Riemann solvers were employed as part of the high-order scheme in order to capture the seven waves of this system. The third employed a HLLC solver, reconstructing the two fastest waves and the contact discontinuity. Comparisons between high-order schemes based on centred discretisations and the linearised Riemann solvers are given by Titarev et al. [9], who advocated the use of GFORCE and GMUSTA schemes as robust and simple alternatives over Riemann solver-based schemes. In addition to the approximate solvers, exact Riemann solvers for the conservative elastic system have been developed by Miller and Collela as well as Barton et al. [10,7].

The elastic system has been extended by a number of researchers to include plastic deformation. One such extension, based on the decay of deviatoric stress via Maxwell's relaxation model, was proposed by Barton et al. [11]. The treatment of plasticity in this form implies a strain-rate-dependent material behaviour governed by the relaxation power law function. Very stiff relaxation laws, physically equivalent to perfect plasticity, are omitted in this plasticity description. A more general approach is the plasticity treatment as suggested by Miller and Collela [6]. This employs a predictor–corrector approach in which a purely elastic predictor update yields states that potentially lie outside of the yield surface and, if so, a return-mapping corrector step is employed to project these states back onto the surface. This plastic deformation and elastic state on the yield surface are determined by the application of the maximum dissipation principle [12].

This system was coupled to the Euler equations for fluid flow by Miller and Collela [13] and more recently by Barton et al. [14]. In both approaches, material interfaces are fitted by a cut-cell approach. An alternative way of coupling the solid and fluid systems was proposed by Favrie et al. [15]. Instead of using an interface tracking method, the interface is represented in a diffuse manner, capturing the solid–fluid interface implicitly.

Although the solid material description in these studies provides an accurate treatment of the solid mechanics up to fracture, the fluid system used to represent an explosive in both [13] and [14] is based on the single-phase Euler equations. This is appropriate for combustion and transition to detonation in a purely gaseous system. However, for the condensed-phase explosives in which we are interested, temperature equilibrium between the explosive's constituents does not hold, and a more sophisticated multi-phase model is required to accurately capture the dynamics. [16,17]. Mechanical relaxation, in contrast, may be reasonably assumed [16–18] hence we employ a single-pressure and single-velocity multi-phase model [17] in this work, which has been successfully validated for modelling mining explosives with high voidage in [18]. The confiner material is governed by the system of equations presented by Miller and Collela [6], which includes elastic and plastic features.

The solid–fluid system is coupled by means of the real ghost-fluid method (rGFM), which has a lower interfacial conservation error and an increase in accuracy as compared to the original GFM and the modified GFM (MGFM) [19]. The rGFM employs a mixed Riemann solver at the interface to capture the interface behaviour. The solid–fluid mixed Riemann problem for the case in which the fluid is represented by the single material Euler equations has been developed previously by Miller and Collela [13] and Barton et al. [14]. In this paper we present the development of an extended mixed Riemann solver that couples the multi-phase model to the elastic–plastic solid system. This solver must be capable of dealing with strong pressure and velocity gradients as experienced under detonation conditions. Furthermore, it must be able to deal with sophisticated equations of state (e.g. Mie–Grüneisen, JWL, WMBG), for more accurate representation of the explosive.

To this end, we derive characteristic equations of the underlying PDE system for the transport model and the single-pressure and single-velocity multi-phase model. These provide the foundation for the subsequent development of the mixed Riemann solvers. The latter are first validated for fluid–fluid applications, by means of comparing against exact solutions and against results obtained using the original ghost-fluid method. The test problems used for this comparison are one-dimensional initial-value problems, representative of detonation conditions, and assess the robustness and accuracy of the algorithm.

We have observed that mixed Riemann solvers for the Mie–Grüneisen equation of state may become unstable under conditions of strong impact if a linearised version of the solver is used. A simple fix is suggested in this work that retains the linearised solver in its explicit form. In addition, a general iterative procedure for linearised mixed Riemann solvers is suggested to reduce the commonly observed density errors in discontinuous initial-value problems.

Further comparison with numerical results from Barton et al. [14] for two solid–fluid test cases are also presented. To demonstrate the applicability of the methods for multi-phase explosives, the iterative solver is used to simulate the one-dimensional impact of a detonation wave onto copper.

Finally, we present results from the simulation of two multi-dimensional real-world applications involving confined multi-phase detonations. The first test case is an extension of that presented by Miller and Collela in [13], with the ideal gas