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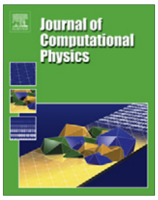

Simulation of high speed impact, penetration and fragmentation problems on locally refined Cartesian grids

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ABSTRACT

Techniques are presented to solve problems involving high speed material interactions that can lead to large deformations followed by fragmentation. To simulate such problems in an Eulerian framework on a fixed Cartesian mesh, interfaces (free surfaces as well as interacting material interfaces) are tracked as levelsets; to resolve shocks and interfaces, a quadtree adaptive mesh is employed. This paper addresses issues associated with the treatment of all interfaces as sharp entities by defining ghost fields on each side of the interface. Collisions between embedded objects are resolved using an efficient collision detection algorithm and appropriate interfacial conditions are supplied. Key issues of supplying interfacial conditions at the precise location of the sharp interface and populating the ghost cells with physically consistent values during and beyond fragmentation events are addressed. Numerous examples pertaining to impact, penetration, void collapse and fragmentation phenomena are presented along with careful benchmarking to establish the validity, accuracy and versatility of the approach.

1. Introduction

The phenomena of high speed impact, penetration and fragmentation arise in many applications including munition–target interactions [1,2], geological impact dynamics [3,4], shock-processing of powders [5,6], formation of shaped charges [7,8], etc. The hydrodynamic pressures realized in such problems often overwhelm the strength of the material, leading to short transients of elastic deformation followed by drastic plastic flow of the material. Wave propagation in the interacting media is highly nonlinear and may result in localized phenomena such as shear bands, crack propagation, fracture and/or complete failure of the material. The fundamental challenges to a simulation capability designed to solve problems involving the physical phenomena listed above arise from the large deformations, culminating in total fragmentation of materials, occurring under high strain-rate conditions [9]. Traditionally, the tools that have been used to solve such large deformation, transient problems have been called hydrocodes [10]. The broad range of available hydrocodes has been reviewed by Anderson [11], Benson [10] and others.

Hydrocodes may be based on a Lagrangian formulation, such as in EPIC and DYNA, where a moving unstructured mesh is used to follow the deformation, or an Eulerian formulation, such as in CTH, where a fixed mesh is used and the boundaries are tracked through the mesh [11,12]. An intermediate approach, ALE (Arbitrary Lagrangian Eulerian) [10], permits the mesh

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to move so as to conform to the contours of the deforming object, but the mesh is not necessarily attached to material points. Modern variants of the ALE approach include ReALE [13], and other approaches formulated on strict geometric conservation principles [14], cell-centered ALE [15] and hybrid ALE approaches [16]. In the Lagrangian and ALE-type moving mesh methods, considerable complexity is enjoined by the need for mesh management [17] to accommodate the large distortion of the embedded boundary. Therefore periodic re-meshing operations are required so that an adequately refined mesh with good mesh quality is maintained. In three dimensions and in the event of large interface distortions such as fragmentation these issues can present challenges. In some cases, in a Lagrangian framework, it is advantageous to use meshless methods such as Smooth-Particle Hydrodynamics (SPH) to cope with severe deformations [18].

Both Lagrangian and Eulerian frameworks have been identified with certain issues [19,20] and take different paths in formulating large deformation problems in elasto-plastically deforming materials [21,22]. Lagrangian methods adopt a multiplicative decomposition of deformation gradients [23] and a hyperelastic model for the elastic deformation [24]. Due to the presumed existence of a mapping to the undeformed state through the flow process, they operate on the Piola–Kirchhoff stress tensor. For the severe deformation cases of interest in this paper Xiao et al. [22] point out that the multiplicative model assumes the presence of an ''intermediate'' configuration which can be mapped on to the original undeformed state. However, such an intermediate configuration may not satisfy geometric compatibility [22]. Furthermore, it is not clear how a mapping to the original geometry is relevant following complete fragmentation and ejection of debris. The Eulerian methodology is typically based on an additive decomposition of the strain rate tensor [24]. In terms of constitutive laws, the elastic part of deformation is governed by hypoelasticity in the Eulerian framework. There is an issue of non-integrability in the hypoelastic model which results in elastic dissipation by not fully recovering the elastic part of strain [22]; however, in simulations involving high speed impact and penetration elastic strains are rather negligible and of little interest when compared to the plastic strain. Another concern with Eulerian formulations is with regard to oscillatory solutions for a simple shear problem [25]; this problem has been shown to be resolved by using the Jaumann rate [24] for stress update. Despite these issues, Eulerian methods are attractive due to the simplicity accruing from use of a fixed global grid, use of true stress state represented by the Cauchy stress tensor, ease of handling of contact and penetration using embedded interfaces. However, an intrinsic limitation of adopting a fixed global grid is that local small-scale features cannot typically be adequately resolved without demanding global refinement; to circumvent this problem local adaptivity is necessary, which engenders a significant transformation of an Eulerian solver. On the other hand, locally refined, dynamic meshes complicate parallel implementation [26,27] in that domain decomposition amongst many processors must occur in a dynamic fashion as the mesh evolves along with the field solution and interfaces.

In this work, a sharp interface Cartesian grid-based hydrocode is developed to solve problems involving high speed impact, collision, penetration and fragmentation. There are two main objectives; first, calculations are to be followed past complete fragmentation while still maintaining sharp interfaces, and second, resolution should be directed to spatially and temporally localized events. Both of these demands present rather stiff challenges. In contrast to the previous Cartesian grid approaches [9,12], the present paper advances computational schemes for high-speed multimaterial interaction problems in the following ways:

1. The interfaces are tracked and represented via the traditional level set approach as opposed to the hybrid particle level set technique employed in [9] or the marker particles approach employed in [12]. This improves the efficiency of the calculations, obviating search procedures associated with particle-based approaches on an unstructured mesh in the quad-tree format. While simpler from an implementation standpoint, the grid-based levelset approach is adequate to capture sharp corners and slender features due to resolution augmented by local refinement [28].
2. Traditionally, Eulerian methods have evolved from work that adhered to the idea of fractional cells as implicit in the marker and cell approach [29]. This antecedent has evolved a mixture model treatment for cells where interacting materials coexist, which poses problems in defining mixture properties (and constitutive relations such as equations of state) for materials with large disparity in material properties [30]. In contrast, the present work develops the idea of treating all interfaces as sharp entities [9,31–36], with fields on either side treated as comprised of distinct materials. A modified Ghost Fluid Method (GFM) [37] is applied to treat the embedded interface. In contrast to [12], where the discretization scheme was modified to incorporate the boundary conditions at the interface, the present method decouples the discretization scheme from interface capturing. However, it raises the issue of the appropriate and accurate way to populate the ghost field to obtain physically consistent solutions in the context of elasto-plastic material interactions, particularly when interfaces are stretched into slender structures prior to disconnecting to form discrete fragments. The present work addresses this issue by evaluating techniques to infuse the boundary conditions into the ghost cells. The interaction of the embedded boundaries with each other and the evolution of free boundaries is treated by applying appropriate boundary conditions at the resulting material–material and material–void boundaries. The proposed method carefully takes into account the subcell position and topology of the interface.
3. A simple and robust algorithm for tracking and detecting collision is developed. As opposed to the limited number of applications reported in [9,12], several numerical examples encompassing a broad spectrum of speeds of interaction are presented, including calculations well past fragmentation. In addition, the results obtained from the present approach are shown to be superior to previous work [9,12]. Although the numerical examples demonstrated in this work are