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A front tracking algorithm for hypervelocity impact problems with crack growth, large deformations and high strain rates

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Dedicated to the 70th birthday of Professor NK Gupta.

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ABSTRACT

In the present paper, a front tracking algorithm, which includes a front tracking part and a specified crack growth scheme, is proposed for tracking material interfaces and describing the formation and propagation of a crack. Combined with an improved space–time Conservation Element and Solution Element (CE/SE) scheme, the algorithm can simulate high-velocity impact problems with crack growth, large deformations and high strain rates. The present front tracking algorithm shows high accuracy in the numerical test of a single vortex problem. Numerical simulations are also presented for spall fractures in a plate when impacted by a spherical projectile and perforation of a cylindrical Arne tool steel projectile impacting a plate target. The numerical results are in good agreement with the corresponding experimental observations. It is demonstrated that the present algorithm is feasible and reliable for analyzing fractures.

1. Introduction

The computer codes which are used in the study of high-velocity impact problems can broadly be classified as Eulerian or Lagrangian descriptions, depending on whether the material flows through a fixed mesh, or the mesh follows the deformation of solid. Anderson [1] summarized the advantages and disadvantages of both Lagrangian and Eulerian descriptions. Lagrangian schemes work well at multimaterial interfaces, but have shortcomings in problems with large deformations. One extreme case is that the simulation fails when a grid cell folds over itself. In recent decades, many Lagrangian meshless/mesh-free and particle methods [2,3] have been proposed to solve problems with large deformations. These methods also present some intrinsic limitations including lower computing speed than other modern grid-based methods and difficulties in the treatment of boundary conditions. Eulerian codes, which allow the boundaries to flow through a fixed mesh, can solve arbitrarily large distortions. When combined with efficient numerical methods for describing moving interfaces, Eulerian methodology is a promising alternative.

Traditional Eulerian codes have low accuracy and cannot capture strong shock waves very well. In the recent years, some researchers have applied high-resolution techniques which are used in the field of modern computational fluid dynamics (CFD) to elastic–plastic flow problems. Udaykumar et al. [4] presented a technique for the numerical simulation of high-speed multi-material impact. A high-order accurate ENO scheme was adopted along with the interface tracking technique to evolve sharp boundaries. After that, their methodology was updated by substituting the hybrid particle level set method [5] for the interface tracking algorithm. Sambasivan et al. [6,7] proposed a three-dimensional, Eulerian, sharp interface, Cartesian grid technique for simulating the response of elasto-plastic solid materials to hypervelocity impact, shocks and detonations. Barton et al. [8] developed an Eulerian adaptive numerical method for high-velocity impact problems in two- and three-dimensions. Wang et al. [9] have proposed an improved space–time Conservation Element and Solution Element (CE/SE) scheme and extended it to the community of high-speed impact dynamics in solids. The CE/SE method is a novel numerical scheme for solving hyperbolic conservation laws. It has several attractive features: (a) being mathematically simple; (b) a unified treatment of both space and time and enforcement of flux conservation in both space and time; (c) very little or almost no numerical dissipation; (d) the lack of

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directional splitting for flows in multiple spatial dimensions, resulting in a truly multidimensional scheme. The features mentioned above make the method substantially different from traditional well-established methods such as the finite difference and the finite volume methods. Chen and Liu [10] proposed an Eulerian scheme combined with the hybrid particle level set method for the numerical simulation of spall fracture due to high-velocity impact. These efforts have not only improved the accuracy of the numerical results for the problems of elastic–plastic flow, but also shown a remarkable direction in the field of computational mechanics.

Numerical methods for describing moving interfaces can be grouped into Eulerian and Lagrangian approaches. Eulerian schemes distinguish phases by characteristic functions defined on the computational grid. For example, volume-of-fluid (VOF) method uses a marker function to identify material interfaces; Level-set method represents the phase boundary implicitly as the zero level-set of a scalar grid function. A review of the VOF method can be found in Scardovelli and Zaleski [11]. The level-set method is reviewed by Osher and Fedkiw [12] and by Sethian [13]. Traditionally, the main difficulty in using these methods has been the maintenance of a sharp boundary between different fluids. The so-called front-tracking methods which represent the interface explicitly by a set of marker particles are included in the second group. Front tracking has many advantages, such as high accuracy and its lack of numerical diffusion. It is found that front tracking often does not require such highly refined grids, and that grid orientation does not affect the numerical solution (no grid anisotropy). Front tracking enables a precise description of the location and geometry of the interface. As a Lagrangian scheme, front tracking method is quite successful in conserving mass since it preserves material characteristics for all time as opposed to regularizing them out of existence, which may happen with Eulerian front-capturing methods. Front tracking also has shortcomings, such as its difficulty in robustly handling interface merging and breakup. Especially, in high-velocity impact problems it cannot describe the fractures in a straightforward manner.

Many numerical methods for crack problems have been devised in recent years. Tvergaard [14] proposed an element vanishing technique which removes elements that meet a failure criterion. Xu and Needleman [15] developed a mesh splitting method to simulate crack branching. Camacho and Ortiz [16] developed a cohesive-law model, in which adaptive meshing technique was employed to provide a rich enough set of possible fracture path. More recently, cohesive finite elements have been used to simulate dynamic fragmentation [17–19]. This technique is naturally more realistic than element deletion for modeling discrete cracks. Many Lagrangian meshless/meshfree and particle methods [2,3,20–22] have been proposed to solve challenging dynamic crack propagation problems. Clayton [23] developed a method that combines generalized particle algorithm (GPA) with energy balance to simulate fragment size distribution. Wang et al. [24] presented a predictive method based on the theories of continuum damage mechanics and mechanics of micro-crack development, in order to simulate fragments of masonry wall to blast loading. A few years ago, Stolarska et al. [25] introduced the Level-set method to the field of the numerical simulation of crack propagation in solids. Lately, Duflot [26] reviewed in detail the update techniques of the crack representation by level set functions and proposed several new techniques. In these methods, a crack is an open curve (an open surface in three dimensions) that grows from its tip (its front in three dimensions), and two level set functions are necessary to represent a crack. When it comes to the spall fracture, however, this kind of crack representation becomes inappropriate. The crack appearing in the spall fracture opens wide with the motion of the scab. If the crack is modeled as a curve, the scab will never separate. In addition, it is unreasonable to put an initial crack in the target plate before simulation. Chen et al. [27] proposed a new representation of crack by level-set method and extended the methodology proposed by Wang et al. [9] to simulate the spall fracture by introducing the idea of “element erosion” from the FEM. In Chen's method, the crack is represented as a two-dimensional narrow region which can be in any shape according to the specific problem. As the element, whose damage factor reaches a critical value, is deleted in this method, it will cause mass loss. In Chen's method, the loss of mass may be severe when there are many fractures. One of the advantages of level-set method is that it can handle interface merging automatically. When two surfaces are close enough, they will merge and the two surfaces will disappear. It is helpful in the simulation of fluid dynamics. But in the simulation of hypervelocity impact problems, it is a disadvantage as it may cause facture to disappear.

In the present paper, we propose a new front tracking method to construct a front tracking algorithm for the 2-dimensional simulation of hypervelocity impact problems with crack growth, large deformations and high strain rates. The algorithm includes a front tracking part which describes moving interfaces with high accuracy, and a newly proposed automatic crack growth scheme which can describe cracks very well by marker particles. The algorithm can be easily combined with the improved CE/SE scheme for the simulation of hypervelocity impact problems. In the study, a single vortex problem is used to investigate the grid dependence and the accuracy of the front tracking algorithm. Then simulations are presented for spall fracture in a plate when impacted by a spherical projectile and perforation of a cylindrical Arne tool steel projectile impacting a plate target. To demonstrate the feasibility and reliability of our front tracking algorithm, the numerical results are carefully compared with the corresponding experimental observations.

To the authors' knowledge, it is the first time to apply the front tracking method in describing the fractures. Since the front tracking method has higher accuracy than the level-set method, the methodology presented here has advantages in simulating dynamic fracture such as fractures in ductile materials caused by hypervelocity impact.

2. Governing equations

Using cylindrical coordinates (r, θ, z), the Eulerian governing equations for the homogenous media without heat conducting, thermal diffusion and external forces can be written in the form of conservation laws as

$$\frac{\partial \mathbf{Q}}{\partial t}+\frac{\partial \mathbf{E}(\mathbf{Q})}{\partial r}+\frac{\partial \mathbf{F}(\mathbf{Q})}{\partial z}=\mathbf{S}(\mathbf{Q}), \qquad (1)$$

where $\mathbf{Q}$ is the vector of conserved variables, $\mathbf{E}$ and $\mathbf{F}$ are the conservation flux vectors in r and z directions respectively, and $\mathbf{S}$ is the source term vector. In Eulerian representation, these vectors are

where ρ is the density, u and v are the r and z components of the velocity respectively, E is the total energy per unit volume, s_{rr}, s_{zz}, $s_{\theta\theta}$