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A 3D combined particle-element method for intense impulsive loading computations involving severe distortions

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ABSTRACT

This article presents a Combined Particle-Element Method (CPEM) for 3D intense loading computations that include severe distortions. It includes the numerical algorithms and example computations. The advantages of this method are that the lower-strained particles (stress points) are computed with a fast and accurate finite-element formulation, and the higher-strained particles are computed with a meshless-particle formulation that can handle severe distortions. Furthermore, the meshless-particle algorithm (with MLS strain rates and weak-form forces) is consistent and does not exhibit tensile instabilities. It is also well suited for conversion of finite elements into variable-connectivity meshless particles because the conversion does not require deletion of elements and addition of particles. Instead there is simply a branch point based on equivalent plastic strain. The basic approach can also be used for the element algorithm only or the particle algorithm only.

1. Introduction

During the past decade there has been an increase in the development of Lagrangian algorithms for high-velocity impact and other intense loading conditions, as various techniques have been developed to handle the high distortions that often result from these conditions. There has always been a desire to use Lagrangian codes, instead of Eulerian codes, as there is no dispersion of internal variables and the interfaces are well defined. They also require less CPU time and less memory (especially if large voids are included in the computation). The historical problem with Lagrangian codes for these problems is that highly distorted elements lead to very small integration time increments, and the computations cannot continue in an efficient manner. In the late eighties two 3D algorithms [1,2] were presented for the automatic erosion of distorted finite elements. Here, highly distorted elements are automatically removed from the computation and the contact interfaces are automatically updated. This allows Lagrangian formulations to be used for very large distortions, although some inaccuracies are introduced when the elements are discarded, as they cannot develop any stresses. The masses can be retained however.

Also, in the late eighties, some meshless-particle algorithms began to appear. These algorithms are Lagrangian (as the mass is attached to the particle nodes which move with the material), but large distortions are achieved by allowing the particle nodes to have new neighbor nodes as the computation progresses. An early (particle) NABOR algorithm attempted to allow for severe distortions by using variable nodal connectivity, and it also included a link between the NABOR nodes and finite elements [3]. Soon after, Libersky and Petschek introduced a Smoothed Particle Hydrodynamics (SPH) algorithm that included material strength [4]. This was the beginning of a vast movement of meshless-particle research that was prevalent during the nineties.

A desirable feature of the SPH algorithms is that all of the cycle-to-cycle variables (mass, position, velocity, stress, strain, damage, internal energy, etc.) are carried at the nodes, and this co-location characteristic allows for a relatively simple algorithm that can include very large distortions. Unfortunately, this co-location approach has some problems that involve tensile instabilities and a lack of consistency. Even though the original SPH algorithm has been improved, the general co-location approach has some limitations. It also became evident that the meshless-particle algorithms for high-velocity impact require considerably more CPU time than finite-element algorithms, at least until the finite elements become highly distorted. This increased CPU time is

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generally due to the search routines that are required to determine the nearest neighbors, and to the greater number of neighboring particles (when compared to nodes per element).

An obvious approach is to link the elements and particles such that the elements represent the mildly distorted material and the particles represent the highly-distorted material, with some early applications provided by Johnson and others [3,5,6]. These early applications included predetermining the distribution of particles and elements, as well as automatically converting distorted elements into particles. Since then a Generalized Particle Algorithm (GPA) has been developed [7,8], and it has been used together with improved conversion (of elements into particles) algorithms [9,10].

A hybrid particle-finite element method is another approach that uses both elements and particles. This method was initially presented by Fahrenthold and Horban [11], and has undergone additional development by Fahrenthold and others since then [12]. This hybrid algorithm computes the compressive pressure at the nodes (particles), with the strength and tensile pressure computed in the elements. This approach allows large distortions and fragmentation to be represented, it eliminates tensile instabilities in the particles, and it allows the contact to be performed within the particle algorithm. Another approach for a hybrid algorithm was recently presented by the authors [13], and it was determined that there are both advantages and disadvantages for the conversion and hybrid algorithms.

In 2000 Randles and Libersky [14] presented an algorithm that introduced (massless) stress points, together with velocity points (that include mass), and this algorithm exhibited consistency and did not develop tensile instabilities. Their formulation included stress points on the outer boundaries, and a Moving Least Squares (MLS) determination of the strain rates (spatial derivatives of the velocity fields) and the forces (spatial derivatives of the stress fields) from the strong form. Unfortunately, a robust interface algorithm was not developed with this approach, and it could not be used effectively for a wide range of high-velocity impact problems. More recently, Li et al. [15] presented an Optimal Transportation Meshfree (OTM) method that is also based on material points and nodal points. Here the nodal forces are determined from a weak formulation and the algorithm appears to be more robust.

The previous references [1–15] provide a sequential trail of research and development that has led to the work presented here. However, there has been a vast amount of other work performed for both meshless particles and for coupling between finite elements and particles. In one approach, co-location meshfree methods are developed by strain-smoothing stabilization of the nodally integrated weak form [16–18]. These have been adapted for impact and penetration by integrating robust contact algorithms [19,20]. In another approach, the ease of enriching meshfree shape functions is exploited for the purpose of modeling cracks [21,22]. Enrichment allows the introduction of discontinuities into the continuum and the simulation of multiple randomly oriented and propagating cracks, which are essential features of impact and penetration events.

One practical distinction between the various coupling schemes that have been introduced is whether the meshfree methods are implemented adaptively. Early schemes generally lack adaptivity, and require embedding the meshfree discretization into the initial meshes in the regions where large deformations are expected. More recent contributions, such as the one introduced here, generally offer an algorithm for adaptively replacing finite elements with meshfree methods when a deformation criterion is met.

Another distinction between the schemes is the means by which the two methods are coupled. Many schemes enforce compatibility of the displacements and velocities along the interface between the methods, along with a suitable means of transmitting forces, with the details having direct bearing on accuracy. One approach uses master-slave coupling of the nodes along the interface, such as the aforementioned non-adaptive scheme of Johnson et al. [5,6], and the subsequent adaptive version [9,10]. Another approach imposes compatibility of the displacements and velocities by defining a ramp function to transition linearly between the finite-element and meshfree fields across a region where the two methods overlap [23]. Hegen [24] enforced compatibility by introducing a Lagrange multiplier to the potential energy functional, and this approach was generalized by Rabczuk and Belytschko [25]. Sauer [26] devised a similar scheme to enforce compatibility of finite elements and smooth-particle hydrodynamics.

While enforcing compatibility of the displacements and velocities is a common approach to coupling, it is not the only one. In the bridging-domain method [27], ramp functions are defined in regions where the two methods overlap for the purpose of transitioning linearly between the finite-element and meshfree discretizations of the integrands in the weak form. This approach was devised as a multiscale method, but it also serves to distinguish regions of high and low deformations. Chuzel-Marmot et al. [28] introduced a similar formulation and demonstrated it for deep penetration of concrete targets. In the aforementioned hybrid method of Fahrenthold and co-workers [11,12], the interface between the particle and element methods is essentially distributed throughout the domain, with shared dependence on the same displacement and velocity fields. A good summary and comparison of some of these coupling schemes is provided by Rabczuk et al. [29].

This article presents numerical algorithms and example computations for a 3D Combined Particle-Element Method (CPEM) that is intended for problems involving severe distortions. It is based on some of the concepts in these aforementioned articles [8,14,15], and an extension of the author's initial CPEM work for 2D plane strain geometry [30]. Both the 2D and 3D algorithms are incorporated into the EPIC code [31]. Although it is not practical to make direct comparisons with all of the aforementioned approaches the CPEM has some very positive characteristics: It will be shown that it is easy to generate the initial mesh (as it is identical to a finite element mesh), the computational method runs fast (as most of the region is composed of finite elements), both the element and meshless-particle algorithms are accurate (they converge, fulfill the patch test, and do not form tensile instabilities), there is no need to add particles during the conversion process (but rather there is a straightforward transition from the element formulation to the particle formulation), and the method is robust (for severe strains, fragmentation, and contact).

2. The combined particle-element method (CPEM)

For this new approach the initial mesh is input as solid finite elements (constant stress), and then it is put into a meshless-particle structure in the preprocessor. Triangular and quadrilateral elements can be used for 2D geometry, and tetrahedral and hexahedral elements can be used for 3D geometry. The integration points of the original elements are transformed into massless stress points, and the nodes from the elements carry the mass and accept forces from the stresses. CPEM uses a particle structure, rather than an element structure, with the element's stress point being a particle that initially has a fixed number of neighbor (particle) mass nodes. In contrast, the GPA and SPH algorithms carry all the variables on all the nodes [7].

When the equivalent plastic strain in a stress point is less than a user-specified value ($\varepsilon_{\mathbf{crit}}$) a finite-element algorithm (formulated within a particle structure) is used to update the strain rates and strains at the stress point, and to compute forces for the (fixed connectivity) particle nodes. When the equivalent plastic strain in a