A Novel Approach to Penetrator Calculations

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Summary

I present a novel method for calculating the penetration of soft targets by hard projectiles by using a combination of ALE and contact surface techniques. This method allows the bifurcation in the softer material (at the point of the projectile) to be represented without sacrificing the Lagrangian representation of either the harder material or the contact interface. A series of calculations using this method show good agreement with the experimental data of Forrestal *et al.* [2] This method may prove useful for a range of semi-fluid/structure interactions with friction, including simulations of manufacturing processes.

Introduction

This document describes the SHISM algorithm, which is a novel approach to the simulation of *soft/hard interactions*. By soft/hard interactions, I mean the set of engineering problems in which a rigid body penetrates a softer material. Examples include the penetration of aluminum armor by a hardened projectile or the shaping of plastic or soft metal using a tungsten die. Such problems are often difficult to simulate because of the very different behavior of the two materials.

Consider the penetration of aluminum armor by a conical tungsten projectile. At moderate impact velocities, sliding friction between the projectile and the armor may be significant, and this is difficult to model adequately in an Eulerian framework. On the other hand, there is a bifurcation in the flow field of the armor at the tip of the projectile, which makes a Lagrangian treatment equally difficult. It is the bifurcation in the flow of the softer material that characterizes soft/hard interactions.

Mathematically, the difficulty of simulating a bifurcating flow field using a Lagrangian mesh arises from the topology of the bifurcation. A continuous flow field, free of bifurcations, changes the shape of a body, but it does not change the connectivity of the body. Surface points remain on the surface, interior points remain in the interior, and neighboring points remain close to each other. This implies that an analytic function exists to map the final configuration of the material back to the original configuration. Such functions are easily represented on a discrete mesh. However, a bifurcation produces a discontinuity in the flow field. Neighboring points on either side of the bifurcation are no longer neighbors, and new surface points are created that do not map to any surface in the original configuration. This means that a static Lagrangian mesh, in which the connectivity does not change, cannot capture the behavior. Either the mesh must be Eulerian, for which a mapping between initial and final configurations is not required, or the solution algorithm must be capable of reconnecting the Lagrangian mesh in a way that correctly captures the topology of the bifurcation.

It is theoretically possible to simulate soft/hard interactions with Eulerian meshes, but the results are often disappointing. A large number of computational cells are required to represent thin structures and small components, and sophisticated interface trackers are required to preserve material interfaces. The velocity discontinuity at the interface between the soft and hard materials is not well represented. The resulting simulations are expensive and lack accuracy and robustness. We are thus compelled to seek some sort of hybrid Lagrangian/Eulerian method to simulate soft/hard interactions.

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Candidate Methods

We considered and rejected a number of approaches to solving soft/hard interactions. *A posteriori* methods, such as "pilot hole" approaches, assume that the line of bifurcation is known in advance, which may not be true, and fail to account for the mechanical work required to create the bifurcation. Mesh-based free Lagrange methods, in which the connectivity of the mesh is changed "on the fly", require that the bifurcation point and propagation direction be accurately identified by the algorithm and that new surface faces be accurately created at the bifurcation point, both of which are problematic.

Smooth particle hydrodynamics (SPH) seems like a more promising candidate. The projectile could be modelled using a conventional Lagrangian mesh, while the target could be modelled as a set of SPH particles. Conventional master/slave contact algorithms [1][3] could be used, with the projectile treated as the master and the particles as slave nodes. However, this approach to contact is inconsistent with the mathematical basis of SPH, and there are practical difficulties with coupling SPH and conventional Lagrangian hydrocodes.

Our framework for developing a soft/hard interaction capability is ALEGRA, a solid mechanics framework that supports arbitrarily connected Lagrangian, Eulerian, and ALE meshes [4]. This naturally suggests an arbitrary Lagrangian-Eulerian approach to the soft/hard interaction problem. We chose this approach over the SPH approach in part because much of the necessary computational machinery was already in place.

The SHISM Algorithm

The SHISM algorithm is quite straightforward. The hard projectile is modelled using a Lagrangian mesh, while the remainder of the problem space, including the soft target material, is modelled using an ALE mesh. The two meshes are not connected, but a pair of identical contact surfaces is defined between the meshes. For convenience, we typically choose a reverse ballistic reference frame, in which the velocity of the hard material is initially zero, but this is not strictly necessary.

A single time step begins with a Lagrangian step. The positions of all nodes are calculated based on the internal forces arising from the stresses in each element and any external forces due to gravity or natural boundary conditions. Kinematic constraints are then enforced, particular the contact constraint between the soft and hard meshes. The contact forces may include static or kinematic friction between the soft and hard materials. Finally, the ALE mesh is remapped with the special condition that each node on the ALE contact surface must return to the location of its corresponding node on the Lagrangian contact surface.

The ability of the soft material to flow through the ALE mesh, and, in particular, of soft material to flow along the contact surface, is the key to this method. This flow of material destroys the mapping between the initial and final configurations of the soft material, which permits bifurcation of the flow to take place. However, the target material behaves as a soft solid rather than a fluid because the basic time step, in which all dynamic behavior is modelled, is Lagrangian and includes strength effects. The contact interface is preserved and there is no difficulty about representing the velocity discontinuity across this interface.

Although this method is conceptually simple, the devil is in the details. We find that the best results are obtained if the ALE mesh is initially assumed to be Eulerian except at its contact surface. This minimized the movement of ALE nodes with respect to the Lagrangian penetrator mesh. The ALE mesh nearest the contact surface rapidly becomes distorted, of course, and so the mesh is smoothed in a transition region between the far field of the ALE mesh, which is strictly Eulerian, and the ALE contact surface, which is

remapped to stay with the Lagrangian contact surface. We find equipotential smoothing to be adequate, but it does tend to be a bit aggressive and move nodes more than we would like.

Another difficulty arises when the hard projectile, which is initially at rest in our reverse ballistic treatment, acquires a significant velocity. If the projectile approaches the boundaries of the ALE mesh, large element distortions in the ALE mesh occur and can bring the calculation to a premature halt. We solve this problem by tracking the Lagrangian mesh: the ALE mesh is remapped bodily to keep the Lagrangian mesh centered, and only then is the ALE contact surface mapped back to the Lagrangian contact surface and the transition region smoothed. With this tracking capability, it is not strictly necessary to use a reverse ballistic frame.

Finally, it is essential that the contact algorithm rigorously enforce the contact constraint. Any remaining overlap of the soft mesh with the hard mesh (in violation of the contact constraint) will result in soft material disappearing from the simulation when the soft mesh is remapped. This can be quite significant over the course of a long calculation. In ALEGRA, we apply the contact algorithm iteratively to ensure strict enforcement of the contact constraint.

Results

We have simulated the experiments described by Forrestal *et al.* [2] in which a conical tungsten penetrator is fired into a 12.7mm aluminum plate. Both the aluminum and tungsten were modelled using a Mie-Gruneisen model for the volumetric response, a radial-return elastic-plastic model for the deviatoric response (strength), and a simple pressure-based fracture model for fracture. The results are summarized in Table 1 and illustrated in Figure 1 and Figure 2. All velocities are in meters per second. Experimental data are denoted by circles and SHISM calculated values by squares.

Table 1. Calculated Terminal Velocities (in m/s) for the Forrestal Experimental Data

Shot Number	Initial Velocity	Final Velocity (Measured)	Final Velocity (Calculated)
1829	220	0	0
1840	278	142	161
1831	479	412	419
1820	726	684	683
1819	892	859	854
2048	1195	1156	1161

Figure 1. Final Velocity Comparison

Figure 2. Velocity Delta Comparison

Figure 2 shows the change in velocity (initial minus final velocity) and better displays such disagreement as exists between experiment and calculation. The agreement is actually quite good, especially at higher velocities. However, the calculation just above the ballistic limit definitely shows too small a reduction in velocity. We believe this is due to neglect of friction in these calculations, which Forrestal *et al.* also believe to be significant [2]. These calculations were performed without any "tweaking" of material model parameters, which were taken from our research group's library of material parameters. In principle, the SHISM algorithm could include effects of friction in future calculations.

Conclusions

The SHISM algorithm described in this paper is a very promising approach to simulating the penetration of soft targets by harder materials. Using this algorithm, we were able to closely reproduce experimental data for penetration of aluminum plates by conical tungsten rods, and we believe even better agreement is possible if friction is included in the contact portion of the calculation. This technique may be applicable to a variety of similar phenomena, including metal cutting using dies and other industrial processes, as well as the obvious defense applications.

References

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