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Extended Abstract+

Validation of an Improved Contact Method for Multi-Material Eulerian Hydrocodes in Three-Dimensions

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1. Introduction

Realistic and accurate modeling of contact for problems involving large deformations and severe distortions presents a host of computational challenges. Due to their natural description of surfaces, Lagrangian finite element methods are traditionally used for problems involving sliding contact. However, problems such as those involving ballistic penetrations, blast-structure interactions, and vehicular crash dynamics, can result in elements developing large aspect ratios, twisting, or even inverting. For this reason, Eulerian, and by extension Arbitrary Lagrangian-Eulerian (ALE), methods have become popular. However, additional complexities arise when these methods permit multiple materials to occupy a single finite element.

Multi-material Eulerian formulations in computational structural mechanics are traditionally approached using mixed-element thermodynamic and constitutive models. These traditional approaches treat discontinuous pressure and stress fields that exist in elements with material interfaces by using a single approximated pressure and stress field. However, this approximation often has little basis in the physics taking place at the contact boundary and can easily lead to unphysical behavior. This work presents a significant departure from traditional Eulerian contact models by solving the conservation equations separately for each material within each computational element and then imposing inequality constraints associated with contact to the solutions for each material with the appropriate tractions included. The advantages of this method have been demonstrated with several computational examples which are fully detailed in [6] and only partially described here. These examples are limited to contact between two materials. Future work will examine contact between three or more materials within an element. This work concludes by drawing a comparison between the method put forth in this work and traditional treatment of multi-material contact in Eulerian methods.

2. Research Approach

The theory developed in this work represents a significant departure from traditional treatment of contact in an Eulerian framework. It essentially represents a generalization of a technique used in Lagrangian formulations and implements it in an Eulerian framework in order to avoid the mesh distortion drawbacks of a Lagrangian method while also removing issues related to mixture theory associated with an Eulerian approach. In this work, mixed cell thermodynamic and constitutive models traditionally used in an Eulerian framework are not used. Rather, the governing equations are solved for each material individually and then specific contact constraints are imposed. After these constraints are enforced the traction, which is traditionally handled implicitly in Eulerian methods, is determined explicitly. This results in a set of coupled equations that can be approximated using an uncoupled system. The following sections briefly describe the finite element formulations and contact constraints used in this work. Readers can reference the article by Walls and Littlefield in [6] and a dissertation by Walls [1] for more complete descriptions of the conservation equations, interface tracking formulation, finite element formulation, contact constraints, and other background information about the work presented here. The formulations developed in this work

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+ Full paper can found at https://www.sciencedirect.com/journal/international-journal-of-impact-engineering/special-issue/10MTGP5W4VJ

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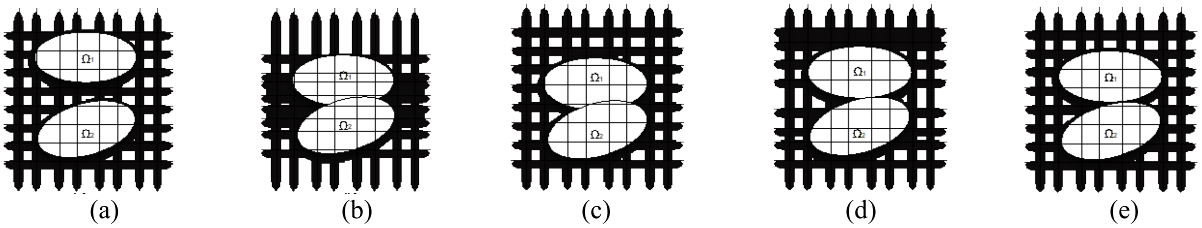
have been implemented in the multi-material finite element code ALEAS (Arbitrary Lagrangian-Eulerian Adaptive Solver) in order to examine the advantages of this approach.

In this work, the conservation equations are solved using a finite element formulation that makes use of two operator splits. The first operator split is traditionally performed in Eulerian formulations and is solved without accounting for the traction, **t**. The second operator split is unique to this work and enforces contact by determining the traction and applying the Signorini contact constraints. This second operator split is valid everywhere, but since the traction is zero except in elements where contact occurs it is only performed in elements where the contact constraints are not identically satisfied. In this work the values for density, ρ, and specific internal energy, *e*, are considered to be piecewise constants, while the velocity function, **v,** is a piecewise linear function. A visual representation of the finite element approach used in this work is shown in Figure 1.



(a) (b) (c) (d) (e)

Figure 1: Representation of the finite element formulation implemented in this work. (a) Initial condition, (b) Lagrangian step, (c) first remap step, (d) contact enforcement step, and (e) second remap step. Steps (d) and (e) are unique to this work.

3. Discussion

There are several advantages to using the form of the conservation equations described in this work. Since this formulation treats each material separately, and there are no quantities associated with the whole cell, such as temperature, pressure, or strain rate; there is no need for the use of traditional cell mixture theory involving mixed cell thermodynamic, strength, and fracture algorithms, all of which typically contribute to significant amounts of error in simulations where contact is important. Additionally, the form of the conservation equations used in these formulations guarantees element-level conservation of mass, momentum, and energy. This allows for the amount of material being transported between adjacent elements to be determined easily. One other feature that distinguishes the approach used in this work is that each material has its own momentum balance and, consequently, separate densities, velocities, energies, and stresses are updated for each material.

The main complication of this method is a result of the ability of each material to have its own velocity field. Because of this property it is possible for advection volumes to become complicated in shape or even disjoint. This difficulty is accounted for by using interface tracking, however not in the traditional sense. In a typical multi-material Eulerian contact formulation interface tracking is used to determine the contents of an advection volume whose shape is known. However, in this formulation the contents of the advection volume are known, and thus the shape of the advection volume can be determined.

The advantages of using the formulation presented in this work over traditional Eulerian methods for classes of problems where large deformations and high strains are present, but contact is important are evident and can be seen in the results of a set of validation problems described below.

4. Results

In order to demonstrate the effectiveness of the method presented in this work, a set of validation problems have been developed. These test cases have been developed to demonstrate the superiority of the method described in this work to a traditional Eulerian formulation as well as determine the applicability of the newly developed method in cases that are handled well by traditional Eulerian methods with mixture theory. The simulations presented here were carried out in the multi-material hydrocode ALEAS. Simulations using the method developed for this work were carried out using the multi-material momentum (MMM) option, while comparison runs using mixture theory were run using the single-material momentum (SMM) option. Two validation cases are described in this extended abstract. Interested readers should refer to [1] and [6] for a more complete validation of the method presented here.

Validation 1: Long Rod Penetration of Oblique Plates

As a means of validating the advantages of the method implemented in ALEAS MMM this work used the three test conditions presented by Cagliostro, et al. [4] which utilized data from Fugelso and Taylor [3] to validate the MESA code. A more complete description of the problem setup can be found in [6]. The initial velocities and orientations of the rods and plates were designed in such a way that the rod impact velocity relative to the plate was 1.29 km/s at an obliquity of 65º for yaws of -9.3º, 0º, and +10.3º. The penetration of oblique plates by projectiles of various yaw serves as a means of demonstrating the shortcomings of traditional Eulerian formulations with mixture theory. Due to the increased interaction between materials as the rod passes through the plate an artificial slowing of the rod compared to experimental data is often seen due to material bonding when mixture theory is employed. This result is not desirable, especially for applications such as multi-layered armor or other events where the ability to accurately model a secondary or further subsequent impact is important.


(a) (b)

Figure 4: Results of -9.3º yaw case for (a) ALEAS MMM and (b) ALEAS SMM at 100μs

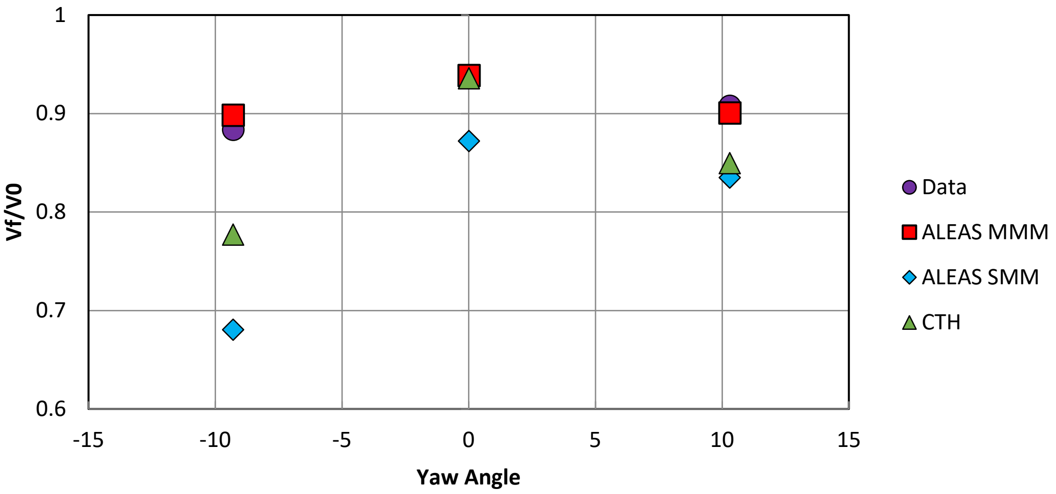


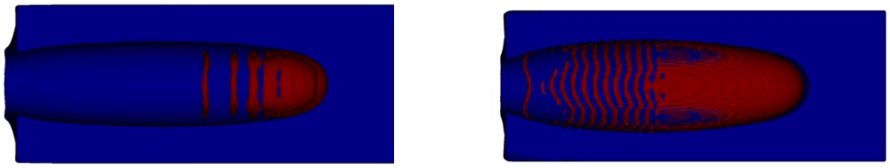
Figure 5: Comparison of normalized exit velocity versus yaw angle

Results of the -9.3º yaw case is shown in Figure 4 and the relative exit velocity versus yaw angle is summarized in Figure 5 for all cases. ALEAS MMM showed significant improvements over ALEAS SMM and CTH which use mixture theory. Both of the mixture theory runs show a significant artificial slowing of the penetrator due to material bonding. In the CTH runs this effect is mitigated by the use of an ad hoc fracture model, which has not yet been implemented in ALEAS. Figure 4 (b) illustrates the shortcomings of the mixture theory formulation. As the penetrator passes through the plate large chunks of plate material bond to the rod. This is non-physical and is not seen in the ALEAS MMM formulation shown in Figure 4 (a).

Validation 2: Long Rod Penetration of Semi-infinite Targets

Another class of impact and penetration events considered for the validation of ALEAS was the penetration of tungsten alloy long rod projectiles into semi-infinite steel targets. This class of problems is frequently used as a validation of hydrocodes. The setup for the simulations consists of a tungsten-heavy-alloy cylindrical penetrator with diameter of 0.5 cm and length of 5 cm impacting a semi-infinite hardened steel target at initial velocities of 500, 1000, 1500, 2000, and 3000 m/s.

The role of contact in this class of problems is less important due to hydrodynamic erosion, so traditional Eulerian formulations that use mixture theory often perform very well. As such, it was desirable to ensure that the new method developed in this work was capable of obtaining reasonable results. As can be seen in Figure 6, the depth of penetration for the 3000 m/s impact case showed good agreement between both methods, however, the ALEAS SMM case showed greater amounts of erosion of the impactor along the crater wall, while material continued to slide down the wall and collected at the base of the crater at late time in the ALEAS MMM case. Due to the hydrodynamic erosion that takes place in the rod at this velocity a trail of material should be present along the length of the crater and is seen experimentally. This serves to demonstrate a limitation of the method developed in this work. Since contact is not an important factor in long rod penetration of semi-infinite targets the method developed for this work was not expected to provide perfect agreement, however, when comparing penetration efficiency, the primary measure for assessing these simulations, the agreement between the new contact method and mixture theory proved to be adequate, however the added computation cost makes the method developed in this work less appealing for this type of problems where sliding contact is not a significant factor.



(a) (b)

Figure 6: Results of the penetration of L/D=10 tungsten alloy rod into steel target with V_0=3000m/s at 50 μs for (a) ALEAS MMM and (b) ALEAS SMM

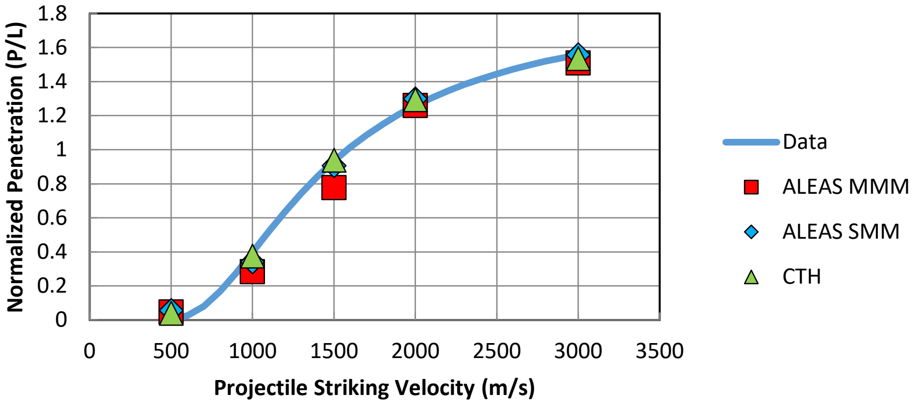


Figure 7: Comparison of normalized depth of penetration (P/L) for ALEAS MMM, ALEAS SMM, CTH, and fit to experimental data [5] for L/D=10 tungsten alloy rods into steel targets

5. Conclusions

This study has validated a new method for the treatment of multi-material contact-impact problems in Eulerian hydrocodes used for computational structural mechanics. Contact constraints have been added to a multi-material Eulerian formulation using numerical approximations to impose the contact inequalities using a finite element model. The conservation equations have also been solved separately for each material in the problem space. As a result, a separate velocity field is assigned to each contacting body, leading to a tremendous improvement over traditional Eulerian contact methods that make use of mixture theory for problems where large deformations are present, but contact is an important factor. The advantages of using the method presented in this work have been shown in a series of validation problems, introduced here and fully described in [6].

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