Arbitrary Lagrangian Eulerian Simulations of High Speed Particle Impacts Encountered During Hypersonic Flight

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Abstract: Particles, particulates, and small debris present in the atmosphere are known to cause substantial progressive damage to leading edges and control surfaces on hypersonic vehicles. This study seeks to predict the material responses (mechanical and thermal) to high-speed impact loading during hypersonic flight. To address such challenges, a multi-material fluid-based approach for modeling problems in this regime is examined. This method combines Arbitrary Lagrangian Eulerian (ALE) hydrodynamics with Adaptive Mesh Refinement (AMR) and multi-zone physics. The method is tested for particles (5-10 μm and 2-6 mm diameter) impacting a material surface at high speeds (1-6 km/s).

Keywords: Numerical Algorithms, Computational Fluid Dynamics, Hypersonics, Impact Mechanics, Shock Physics, Arbitrary Eulerian Lagrangian

1 Introduction

The abundance of particles in the atmosphere and the potential for a vehicle to fly through precipitation at low altitudes is known to cause severe degradation and erosion to leading edges and control surfaces of high-speed flight vehicles. An ALE hydrocode called PISALE (Pacific Island Structured-AMR with ALE) is used to characterize the high-speed impact event to gain an increased understanding of progressive material degradation due to particle impingement.

2 Problem Statement

A qualified code for this problem must be able to handle large deformations and maintain proper internal pressures within the materials. PISALE achieves this by computing field variables based on a staggered grid Lagrangian formulation, where kinematic quantities are computed at grid nodes and thermodynamic/kinetic quantities are computed at the cell-centers. The code then follows a traditional ALE approach.

The governing fluid equations that PISALE solves are in a Lagrangian formulation (in both vector and index notation $i, j, k = 1, 2, 3$)

$$\frac{\mathrm{D}\rho}{\mathrm{D}t} = -\rho\nabla\cdot\vec{U} = -\rho U_{i,i} \tag{1}$$

$$\rho\frac{\mathrm{D}\vec{U}}{\mathrm{D}t} = \frac{1}{\rho}\nabla\cdot\boldsymbol{\sigma} = \frac{1}{\rho}\sigma_{ij,j} \tag{2}$$

$$\frac{\mathrm{D}e}{\mathrm{D}t} = \frac{1}{\rho}V\boldsymbol{s}:\dot{\boldsymbol{\varepsilon}} - P\dot{V} = \frac{1}{\rho}V\left(s_{ij}\dot{\varepsilon}_{ij}\right) - P\dot{V} \tag{3}$$

where ρ is the density, $\vec{U} = (u, v, w)$ is the material velocity, t is time, $\boldsymbol{\sigma}$ is the total stress tensor, P is the pressure, e is the internal energy, V is the relative volume ($\rho V = \rho_0$ where ρ_0 is the reference density), $\boldsymbol{s}$ is the deviatoric stress, and $\dot{\boldsymbol{\epsilon}}$ is the strain rate tensor.

The pressure is determined by a user-defined equation of state (EOS), which evaluates pressure as a function of density and internal energy/temperature while the deviatoric stresses are determined by constitutive relations.

3 Results and On-going Work

An initial study of high-speed particle impact has been performed using the PISALE code [3]. A parameter study was performed and particle penetration depths were compared to theory. An example simulation result is shown in Fig. 1. Simulations predicted significantly less penetration compared to theory, however, theory does not account for dissipative effects due to plastic deformation, among other assumptions. This paper will analyze particle impacts for a range of velocities (0.5 - 6 km/s), particle sizes (5 - 10 μm and 2-6 mm), and impact angles. Results will not only be compared with theory, but will ultimately be compared with new experimental data from the University of Minnesota involving well-characterized particles (size, composition, impact velocity) impacting material samples that are characterized pre- and post-impact.

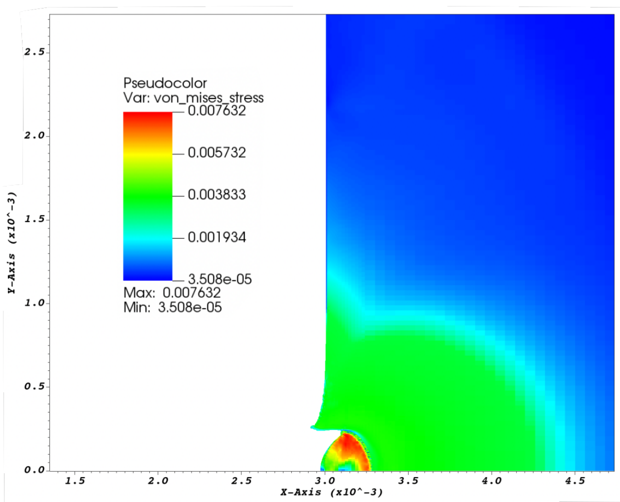

Figure 1: Normal impact of an iron sphere (4 μm diameter) on a thick aluminum plate at 700 m/s: Von Mises stress (MBar). Plot dimensions are in cm.

References

[1] Walker, J.D. *Modern Impact and Penetration Mechanics*. Cambridge Univeristy. 2021.

[2] Wu, Li, Thornton *Rebound behaviour of spheres for plastic impacts*. International Journal of Impact Engineering 28 (2003) 929–946

[3] Yip, P., Torres, E., Nompelis, I., Schwartzentruber, T.E., Fisher, A., Eder D.C., Koniges A. *Adapting a Multi-Material ALE with AMR Method for Physics of High-Speed Material Interactions*. AIAA SciTech 2022 Forum. 2022.