Comparison of Penetration Experiments to Equivalent Simulations in Uintah

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Abstract

A simulation of a simple penetration experiment is performed using Material Point Method (MPM) through the Uintah Computational Framework (UCF) and interpreted using the post-processing visualization program VisIt. MPM formatting sets a background mesh with explicit boundaries and monitors the interaction of particles within that mesh to predict the varying movements and orientations of a material in response to loads. The modeled experiment (Piekutowski and Poorman [1] and data therein) compares the effects of an aluminum sphere impacting an aluminum sheet at varying velocities. In this work, the experiment called launch T-1428 (by Piekutowski and Poorman) is simulated using UCF and VisIt. The two materials in the experiment are both simulated using a hypoelastic-plastic model. Varying grid resolutions were used to verify the convergent behavior of the simulations to the experimental results. The validity of the simulation is quantified by comparing perforation hole diameter. A full 3-D simulation followed and was also compared to experimental results. Results and issues in both 2-D and 3-D simulation efforts are discussed. Both the axisymmetric and 3-D simulation results provided very good data with clear convergent behavior.

Introduction

The Material Point Method (MPM) is a modeling and computational simulation approach that sets up a Eulerian background mesh and variably fills that mesh with Lagrangian point masses. Each particle's motion and orientation is updated to the next time step by solving the weak form of the momentum equation on the background grid. At the end of each time step, the background grid is reset to eliminate the effects of "mesh entanglement" (see Banerjee, Guilkey, Harman, Schmidt, McMurty [2] p. 1-2 for a more technical description).

The primary goal of this project was to model an experiment using Uintah and to test the convergence of simulations by decreasing the grid and particle spacing. A secondary goal was to use VisIt to compare the results against measured data. VisIt is a post-processing visualization tool that displays the data Uintah solves and posts it in a way that can be easily understood and manipulated by the user.

The experiment (Piekutowski and Poorman [1] and data therein) involved an aluminum sphere (Al 6061-T6) being launched at a fixed aluminum sheet (Al 2017-T4). The Uintah simulations were modeled assuming a negligible effect of air drag, and gravity. Convergence was tested by comparing the hole diameters of the varying simulations both to the hole diameter measured in physical space and to the hole diameter solved using Richardson Extrapolation (see *Results* section for a further explanation).

Methodology

The experiment being simulated was of a sphere (comprised of Al 6061-T6) being shot at a sheet (comprised of Al 2017-T4) at varying velocities. Both sphere and sheet were modeled as Al 6061-T6 since the emphasis of the simulations was on the effects of penetration on the sphere being launched. Another reason they were both modeled as Al 6061-T6 is due to the physical similarities (see [5] & [6]) between Al 2017-T4 and 6061-T6 (as depicted in Fig. 1 below).

	Aluminum 6061-T6	Aluminum 2017-T4
Young's Modulus	68.9 GPa	73 GPa
Poisson's Ratio	.33	.33
Shear Modulus	32 GPa	36 GPa
Tensile Yield Stress	276 MPa	280 MPa

Fig. 1: Compares basic physical properties of Aluminums 6061-T6 and 2017-T4 to justify modeling both the sphere (6061) and the sheet (2017) as 6061-T6. *Reference: ([5] & [6])*

First an axisymmetric simulation of the sphere impacting the sheet was modeled. An axisymmetric simulation is a one cell thick "wedge-shaped" slice of the impact utilized in order to cut down simulation time and processer use. As is shown in Fig. 2, symmetry is assumed about the y-axis, so the bottom half of the simulation can be modeled and then flipped over to an accurate 2D depiction to the viewer.

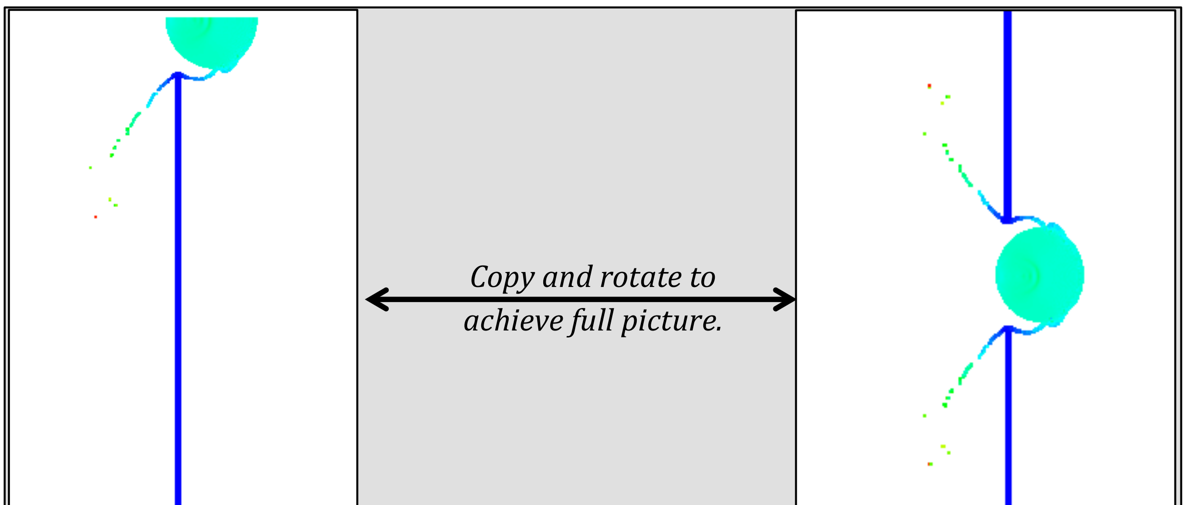


Fig. 2: An example of how computational time was conserved using an axisymmetric assumption while retaining a simple display of results.

Initially, three axisymmetric simulations were run using different spacings and then compared to each other and to the experiment. The first simulation ran with a spacing of 0.2 mm and an average resolution of 4, meaning that every 0.2 mm marked a new cell and each cell contained 4 particles, which are singular objects Uintah tracks both through their effects on other particles and the effects of other particles on them. The next simulations ran with spacings of 0.1 mm and 0.08 mm respectively. As the spacing goes down, the time required to run each respective simulation geometrically increases. The simulations were compared both by running them side-by-side and by overlaying them with differing opacities and color schemes (see Fig. 3).

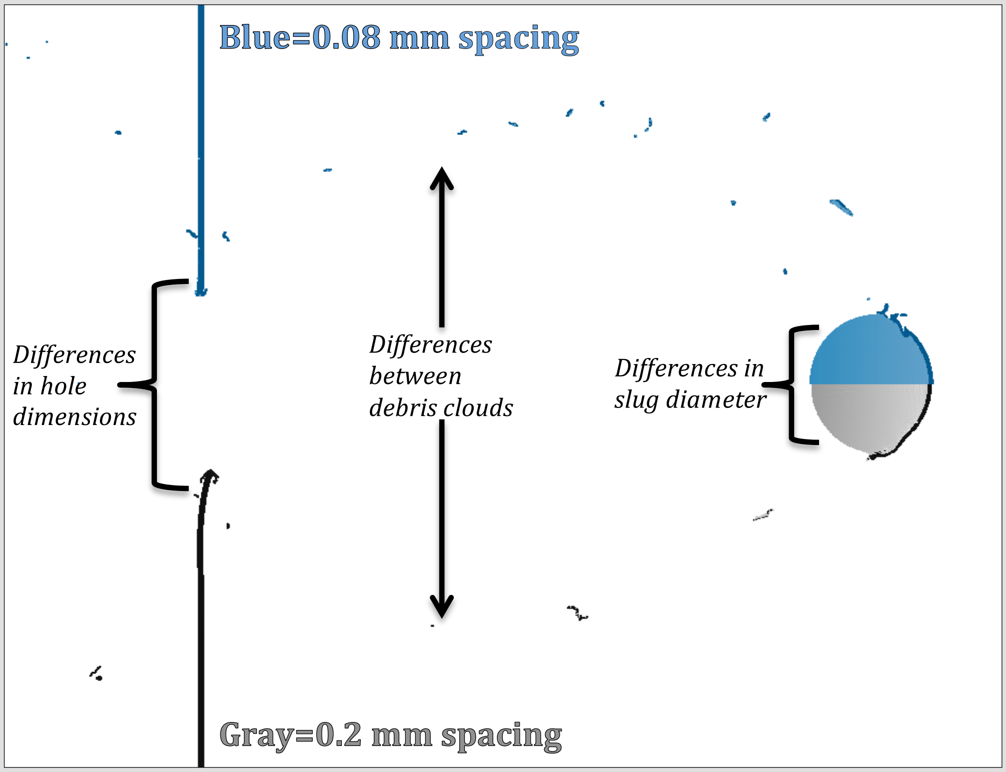


Fig. 3: A side-by-side simulation showing differences between the highest resolution simulation (blue with 0.08-mm spacing) and the lowest resolution simulation (grey with 0.2-mm spacing).

Next a 3-D simulation was run and the 3-D results were compared to both the axisymmetric simulations and to the actual experiment. Since adding so much more volume to the simulation significantly increases run time, the spacing for the 3-D simulation was increased to 0.4 mm with an average resolution of 4. The simulation was also run with only a quarter of the sphere, assuming symmetries about the *x*-axis and then rotated to create a whole sphere and the full simulation of impact. Fig. 4 shows two cross sections of this simulation just as the sphere is penetrating the aluminum sheet.

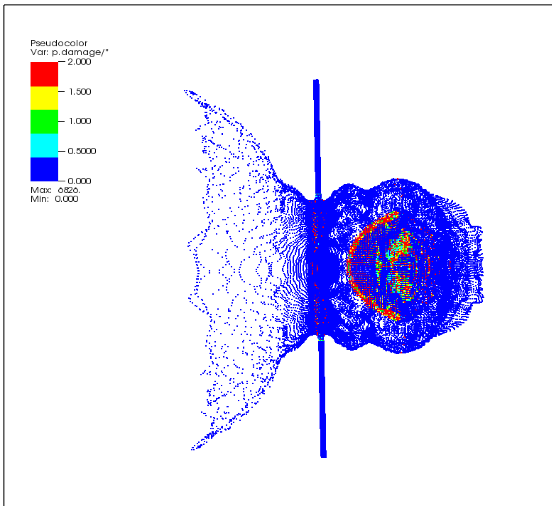
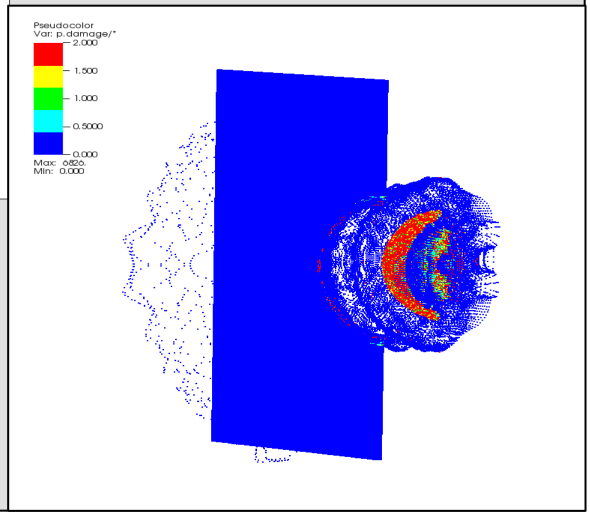


Fig. 4: Shows a side view of the 3D simulation (left) and a view of the 3D simulation from behind (below). In both of these simulations only half of the sphere is being shown in order to afford the viewer a better view of the interior.

The differing colors represent a damage scale, with red being the highest amount of damage and blue being the lowest. The outside of the sphere experiences the most damage following impact, and a damage wave begins to propagate near the front of the sphere.



In each of the simulations, an explicit time integrator calculated each particle's motion and orientation. Since the spall damage of the slug was most emphasized in the original report, (see Piekutowski and Poorman [1] pg. 5 for more detail) the critical stress—or the stress at which damage occurs—was set to be equivalent to the spall strength in the various simulations. According to the literature [3,4], the spall strength of Al 6061-T6 has a value dependent on strain rate ($\dot{\epsilon}$). However, Uintah does not support a strain-rate dependent spall strength. Therefore, a Python code was developed to infer the average strain-rate of a representative particle in a preliminary simulation. The spall strength associated with that strain-rate, as reported in the literature for Al 6061-T6, was used in the subsequent Uintah simulations.

The erosion algorithm "ZeroStress" was run during all of the simulations except the one used to solve for the average strain rate. "ZeroStress"—as its name might suggest—sets the stress on a particle to zero once its stress exceeds the spall strength of Al 6061-T6. The figure (Fig. 6a) below shows an overlay of the most accurate simulation (in comparison to data) versus an illustration of a radiograph taken from the original experiment. The areas of the Uintah simulation that are blue represent where zero stress is present, ergo the blue represents areas in which the spall strength of aluminum has been exceeded and we would expect to see spall damage.

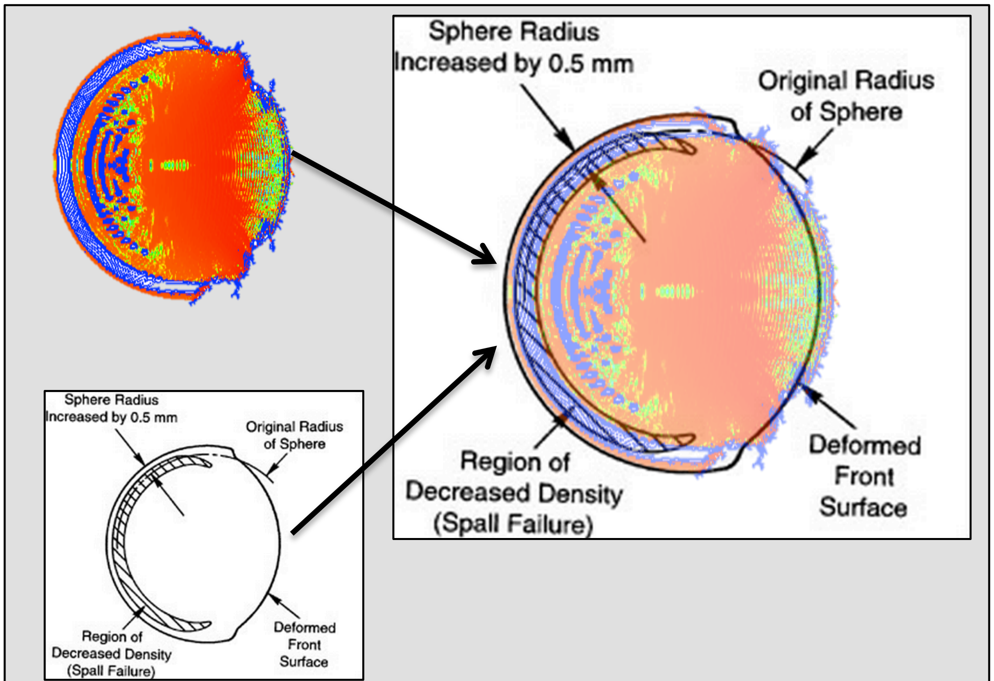


Fig. 6a: The slug from the Uintah simulation (spall damage in blue) overlaid on an illustration of a radiograph taken from the physical experiment. (P. & P. [1] fig. 2)

The below figure (Fig. 6b) compares another Uintah simulated slug to the actual radiograph of the slug taken from the physical experiment.

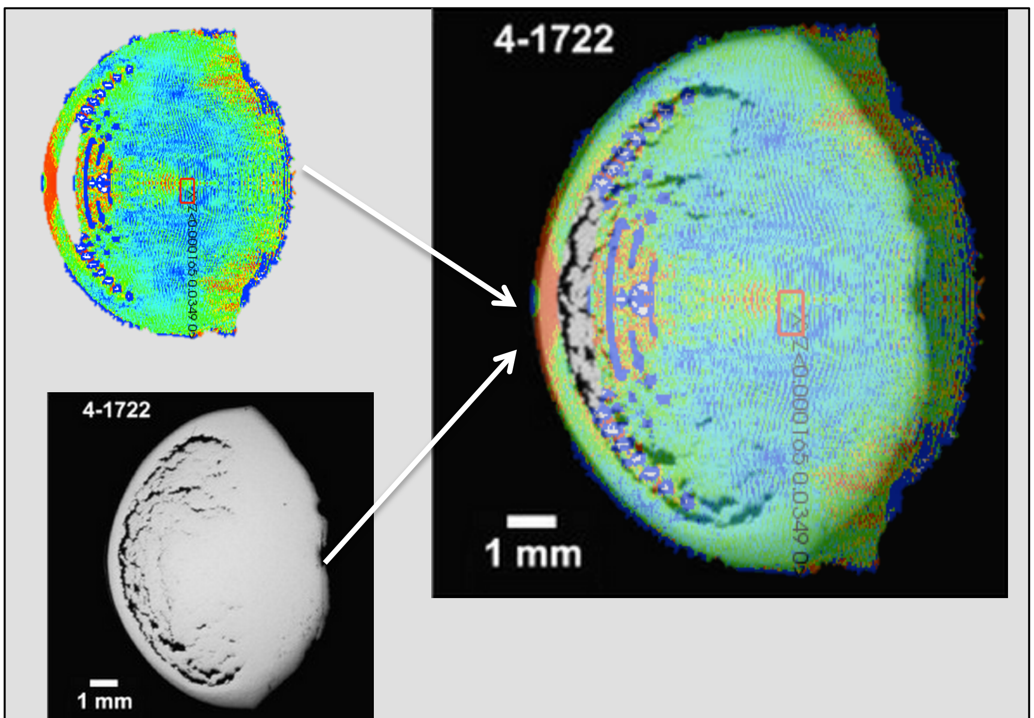


Fig. 6b: Another slug from the Uintah simulation overlaid on a radiograph taken from the physical experiment. (P. & P. [1] fig. 2)

Results

To better solve convergence, a Richardson Extrapolation was performed using the solved Uintah data. The Richardson Extrapolation (Eqn. 3 below) approximates the perforation diameter that Uintah would solve for and eventually converge to with further mesh refinement. The Richardson Extrapolation was applied as follows (See Burden and Faires [7] p. 180-188 for a more detailed description):

$$D = D^{*}(h) + Kh^{p} + O(h^{p+1}) \qquad (1)$$

where D is the true value of the hole diameter, D is the approximation of hole diameter based on h is the spacing and p is the known order of convergence. Rewriting the above equation with a step size that is half as large yields:*

$$D = D^{*}\left(\frac{h}{2}\right) + K\frac{h}{2^{p}}^{p} + O(h^{p+1}) \qquad (2)$$

combining equations (1) & (2) yields:

$$D = \frac{2^{p} * D^{*}\left(\frac{h}{2}\right) - D^{*}(h)}{2^{p} - 1} + O(h^{p+1}) \qquad (3)$$

When the results from the 0.2 mm and 0.1 mm Uintah simulations are used in equation (3) the result is that:

$$D = 10.64 + O(h^{2})$$

Therefore, the converged Uintah diameter would be approximately 10.64 mm. Meaning that after solving for this diameter in Uintah, further mesh refinement would continually yield the same result of 10.64 mm. In the physical experiment however, the measured hole diameter was measured to be 10.49 mm. The discrepancies between Uintah's values and the physical experiment's data will be examined further in the *Discussion* section.

Below is a table comparing the diameter solved from Richardson Extrapolation, the physical experiment and the varying Uintah simulations (fig. 7).

	Slug Diameter d	**Hole Diameter (D_h)**	**% Error from physical experiment**	**% Error from Richardson Extrapolation**
Physical Experiment	9.53 mm	10.49 mm	-----	1.43%
Richardson Extrapolation limit as h→0	9.53 mm	10.64 mm	1.43%	------
3-D Simulation h = 0.4 mm	9.53 mm	11.16 mm	6.39%	4.89%
Axisymmetric Simulation h = 0.2 mm	9.53 mm	11.6 mm	10.58%	9.02%
Axisymmetric Simulation h = 0.1 mm	9.53 mm	11.06 mm	5.15%	3.87%
Axisymmetric Simulation h = 0.08 mm	9.53 mm	10.88 mm	3.58%	2.20%

Fig. 7: Depicts the various Uintah simulation data and the associated error of each simulation relative to physical results and results of Richardson Extrapolation: "*h*" is the spacing of each respective Uintah Simulation.

Figure 8 (below) depicts graphs solving for the rate of convergence of the Uintah simulations relative to Richardson extrapolation and to the physical experiment respectively. In both graphs there is a clear convergent behavior presented as each simulation's cell spacing decreases. As can be seen below, the rate of convergence (the slope) for both graphs is approximately 1. This is the expected rate of convergence for an MPM simulation. (Sadeghirad, Brannon, and Burghardt [*cf.*8])

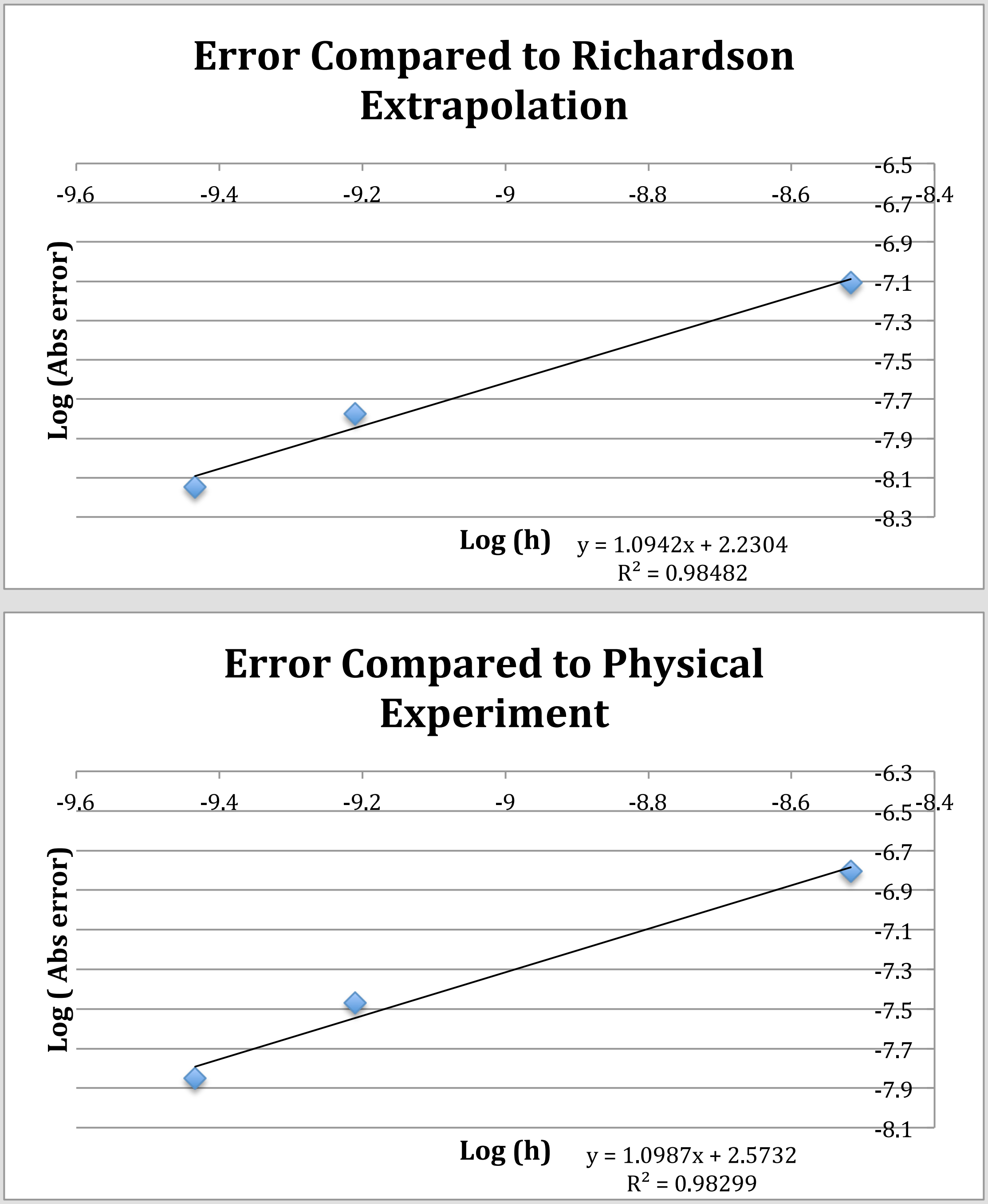


Fig. 8: Represents the MPM convergence to both the solved Richardson Extrapolation value and the physical experiment. Included is each associated line of best fit and R^2 value.

A stress-space plot (fig. 9) was produced for a single particle located near the axis of symmetry within the sphere by extracting the particle's (Cauchy) stress tensor at all time steps using Uintah's data analysis feature and processing the data in Python. This stress history was then plotted as an isomorphic projection onto the meridional plane and is designated below as the *r*-*z* plot. In this plot, *r* is the magnitude of the stress deviator and *z* is the magnitude of the isotropic component of stress. This analysis was done to better understand the nature of the particle's stress state as it undergoes shock loading. To better understand this information, a Python script was also used to animate these plots through time. The red dot depicts the principal stress state at a given point in time while the magenta dot indicates the isomorphic projection of stress throughout time. Upon initial impact, the red dot—which begins in the upper right corner—moves down the line to the bottom left corner (maximum principal stresses. With each successive reflecting of this wave, the red dot moves back and forth on the same line with decreasing intensity until it settles to the starting position of negligible stress. The magenta dot (isomorphic projection) depicts a complicated loading and yield pattern.

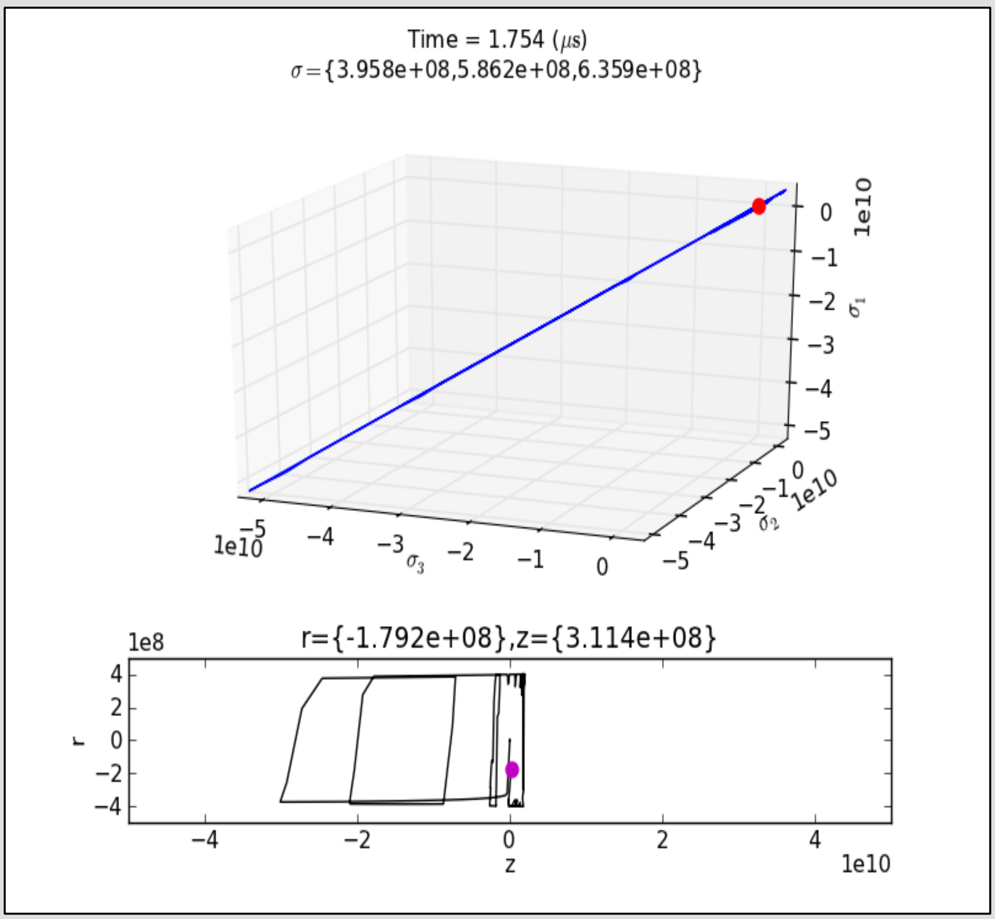


Fig. 9: The stress-space plot (top) and the isomorphic projection (bottom) shown following the sphere's impact into the sheet.

Discussion

As can be seen from the above data (figures 7 & 8), the varying spacings affect the accuracy of the simulations in an expected way. As the cell spacing decreases, the error in the simulations decreases. In the presented data and experimentation, the rate of convergence is approximately 1, which is typical for MPM simulations. It would be expected that with more computational ability and time, further decreasing the spacing of simulations would lead to negligible error in terms of final hole diameter.

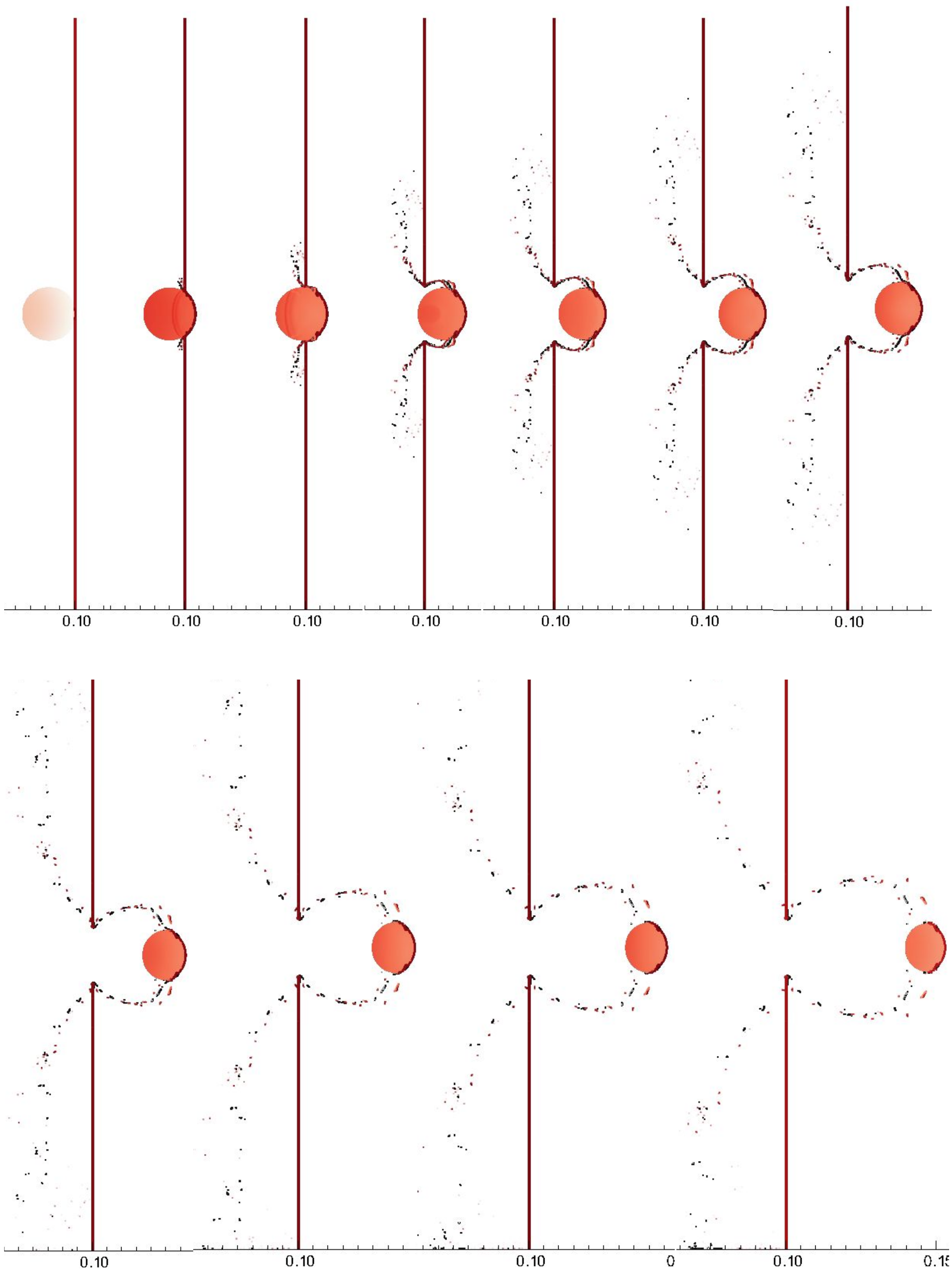
Although the finest resolution has not yet converged, convergent behavior of the simulations is clear and Richardson extrapolation is a useful tool for inferring the converged result from unconverged data. This stands as compelling validation for the usefulness of Uintah as a modeling tool of exceptional accuracy, especially when computational time can be afforded. It should be realized, however, that more kinematic anomalies and errors would be expected as the intricacies of simulations increase, and these anomalies should be thoroughly searched for in future, more expansive simulations.

In order to improve results in upcoming simulations, many different approaches could be made: running more simulations could more obviously present a graphical trend in convergent behavior, taking into account the effects of air drag, and physical differences of aluminum could also increase accuracy, testing against a better documented physical experiment and larger physical data would also be helpful in testing convergence for future simulations. To further increase efficiency of future simulations, data compilation could also be done through a python script rather than being done manually though VisIt and its viewing tools. This would cut down on both human and computational labor required.

Conclusion

The MPM method and implementation through Uintah is a useful tool for simulating complicated physical phenomena. Through a simulation, one can more carefully view the kinematics between particles and objects than could be done in a physical experiment, things can be easily adjusted in simulations whereas entire experiments would need to be repeated in physical space to account for small adjustments, and computation is often much less expensive (and safer) than the physical materials required for physical experimentation. These reasons and many more are the driving force behind the rising demand for accurate simulation programs.

The implementation of Uintah required for this paper and its stated simulations went well. There was a clear convergent behavior and an expected and recognizable pattern between cell spacing and accuracy of simulations. An error of 2.2% in a simulation that ran on 24 cores for approximately 8 hours indicates a very robust process that could easily be improved through more computational power and time. This experiment nicely illustrated the influence that spacing has on simulation accuracy and the competing priorities of maintaining accuracy while conserving computational time.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