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Modeling NIF Experimental Designs with Adaptive Mesh Refinement and Lagrangian Hydrodynamics

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Abstract *Incorporation of adaptive mesh refinement (AMR) into Lagrangian hydrodynamics algorithms allows for the creation of a highly powerful simulation tool effective for complex target designs with three-dimensional structure. We are developing an advanced modeling tool that includes AMR and traditional arbitrary Lagrangian-Eulerian (ALE) techniques. Our goal is the accurate prediction of vaporization, disintegration and fragmentation in National Ignition Facility (NIF) experimental target elements. Although our focus is on minimizing the generation of shrapnel in target designs and protecting the optics, the general techniques are applicable to modern advanced targets that include three-dimensional effects such as those associated with capsule fill tubes. Several essential computations in ordinary radiation hydrodynamics need to be redesigned in order to allow for AMR to work well with ALE, including algorithms associated with radiation transport. Additionally, for our goal of predicting fragmentation, we include elastic/plastic flow into our computations. We discuss the integration of these effects into a new ALE-AMR simulation code. Applications of this newly developed modeling tool as well as traditional ALE simulations in two and three dimensions are applied to NIF early-light target designs.*

I. Introduction

High-powered laser facilities such as NIF and LMJ place new requirements on optics protection from debris and shrapnel created by the laser-induced dismantling of the target and target-related materials in the fusion chamber. Additionally, because these are research facilities, a variety of diagnostic elements are often placed close to target center creating additional sources of debris and shrapnel when they are bathed by x-rays from the primary target. Our goal is to develop a means for modeling these target configurations to minimize the impact on both optics and diagnostics.

Traditionally, Inertial Confinement Fusion (ICF) codes are designed to predict early-time behavior of the hohlraum targets—on the order of the pulse length. In order to calculate chamber effects, we must develop simulation techniques that enable modeling with several different constraints and a different motivation. In particular, we are concerned with the form of the target material as it disassembles and where the material goes rather than predicting the detailed physics during the shot. The basis for our simulations is the ALE method, where the hydrodynamics can be run fully Lagrangian (mesh follows fluid) or fully Eulerian (fixed mesh) or performed on an arbitrary grid that is neither fully Lagrangian nor fully Eulerian. Incorporating this technique alone, our simulations must be able to run out to very late times—on the order of 50 to 100 times the laser pulse length. To mitigate tangling in the ALE mesh, the object or objects being modeled are surrounded with a very low density (or void) mesh. This technique has proved successful in hohlraum simulations [1,2] and in this paper we also discuss its usefulness for thin foils. Additional details of the mitigation of debris damage and relevance to the NIF Early Light (NEL) campaign are given in a companion paper[3].

However, the use of standard ALE alone is not sufficient to model these complex configurations in their inherently three-dimensional complexity. Because a large amount of our problem space consists of "air," it does not make sense to mesh the entire domain with the same resolution and additionally, because of the late-time dynamics, the regions of interest vary during the simulation. For these reasons we are incorporating adaptive mesh refinement (AMR) into our calculations and design tools. In this paper we will also discuss some of the implications of a combined ALE-AMR method.

II. Simulations for the NEL campaign

Late-time debris and shrapnel modeling was important for several of the NEL campaigns. For instance, the "hot holraum" experiments of Schneider et al.[4], posed a potential risk to the optics systems in the case that a jet of hot material might shoot out of the hohlraum's laser entrance hole (LEH) back at the optics. For the hydrodynamic campaign of Robey, et al.[5], the major concern was not damage to the optics, but instead it was important to understand the debris pattern of a pinhole array that was hit by x rays from the primary target.

To simulate these experiments we need to characterize the state of the material and the direction of its expansion. We describe the simulations for these two examples in the next sections.

IIa. Simulations for NEL Hot Hohlraum Campaign

Figure 1 shows a photograph of a NEL hot halfraum target[4] and its corresponding debris simulation in three dimensions is in Fig. 2. The laser beam enters this target from the bottom with the orientation as shown in this figure. Note that hohlraum target has a flange of material at the LEH. Of concern was where this material might go particularly since can contain a significant amount of mass. Additionally, future targets are being designed that include more massive flanges and flanges made of different materials such as Ta.

In order to simulate this target we designed a structured grid in three dimensions and surrounded it in an air/void mesh. One advantage of the air mesh design was that it allowed us to change sizes and design of the flange material with relatively little change to the basic grid as well as the basic parameters of the ALE simulation.

The basic grid used for the simulation is shown in Figure 3, although only the outermost shell of the grid is given. (The full 3D grid is too dense to visualize.) Since the ALE method used for this simulation uses a structured grid, there is a significant amount of extra grid cells that are required to wrap the object in the void mesh while retaining the necessary resolution near the LEH and ALE mandated cell mass-matching criteria.

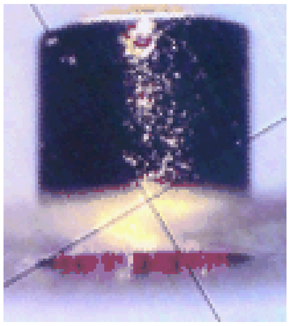

Figure 1. Example of metallic hot halfraum target used in NEL shots [4].

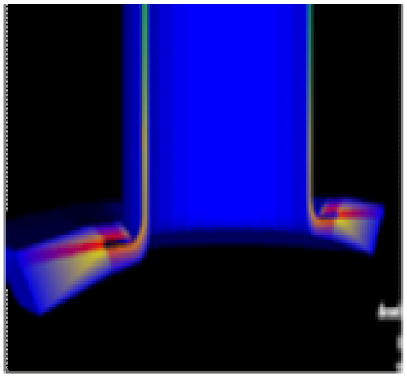

Figure 2. Density isovolumes from halfaum simulation near beginning of pulse.

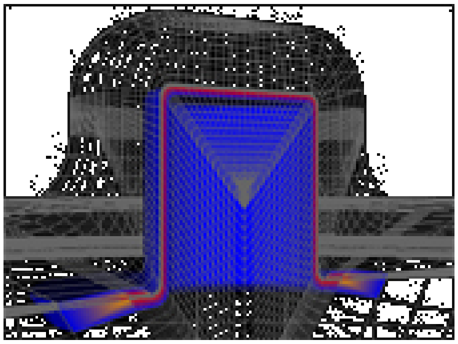

Figure 3. Outermost shell of ALE grid shown surrounding density iosovolumes for NEL halfraums.

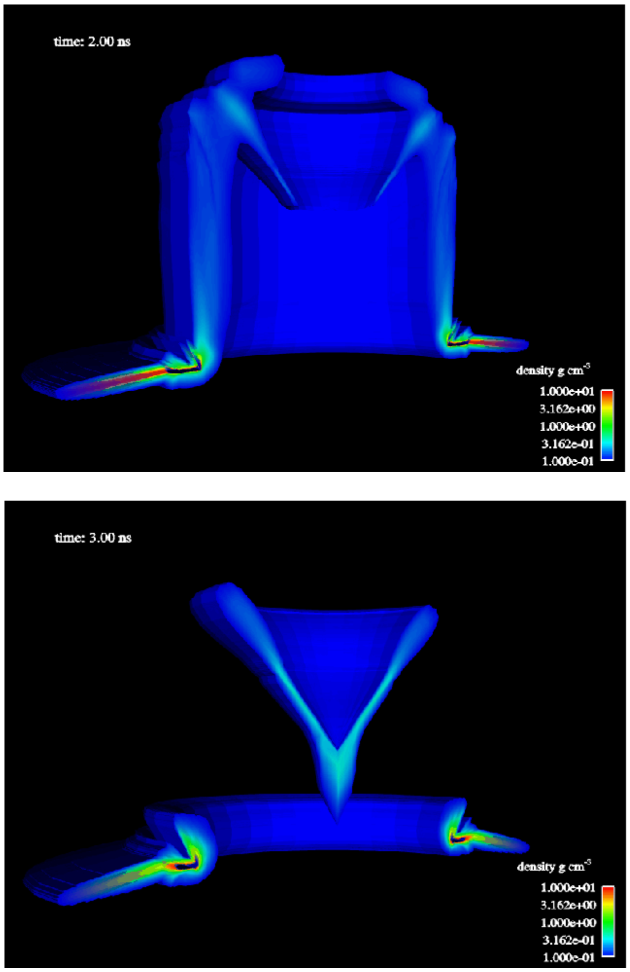

Figure 4. Density isovolumes at 2 and 3, ns are postprocessed to obtain total mass, direction of jets of mass, and temperature/state.

Post-processing of the actual data from the simulation gives the necessary information about potential damage to the optics. Density isovolumes later in time are shown in Fig. 4a,b. For instance in the above simulation, less than 10% of the total mass is in the central jet directed towards the optic. This jet is seen as the funnel-shaped object in the Fig. 4b. The majority of the mass has a velocity in the horizontal direction and avoids the optic completely.

IIb. Simulations for NEL Hydrodynamic Campaign

In the hydrodynamic campaign, a titled pinhole array was used to capture an image of the hydro jet. Details of the experimental setup are given elsewhere [6]. In the first attempt at the experiment, pieces of the pinhole array damaged the imaging camera. To fix the problem, Eder suggested that tilting the pinhole to direct debris away from the camera [3]. Simulations were done to test this hypothesis and then it was also confirmed with experiments on Omega[5]. Figure 5 shows a time progression of the simulation of the tilted pinhole array. The source comes from the horizontal direction, yet the blow-off remains normal to the pinhole surface.

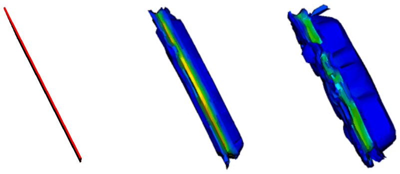

Figure 5. Time sequence showing blow-off of material from a thin Ta foil. An x-ray source hits the back plane of the foil generating the blow-off.

Figure 6 shows the bounding box for the air/void mesh that surrounds the thin foil. Meshing this entire region is necessary for the ALE technique. However, a useful method for reducing the computation as well as doing much more complicated geometries is discussed in the next section. This method consists of combining standard ALE techniques with AMR so that the simulation can use appropriate resolution in the appropriate places.

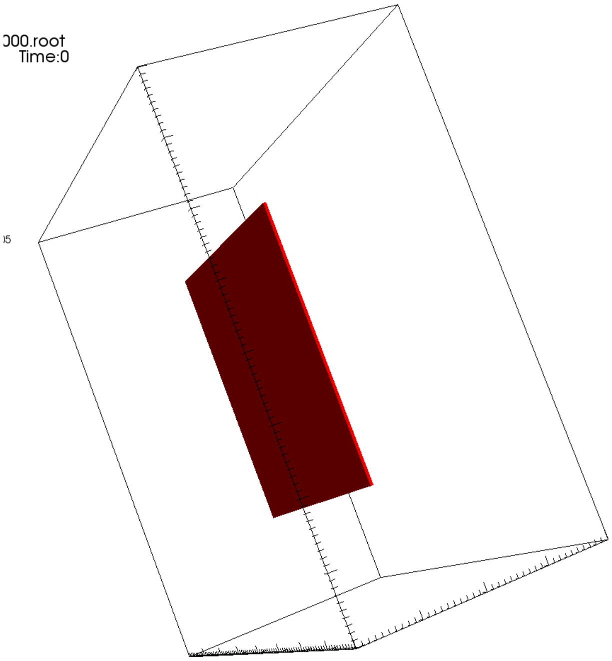

Figure 6. Thin foil surrounded by bounding box of air/void mesh.

III. ALE-AMR Simulation Methods and Future Directions

Both ALE methods and AMR are reasonably well-understood simulations techniques. However the combination of these two is a relatively new development so we describe briefly some of the major issues. Anderson and Pember have done a majority of the pioneering work in this area for gas dynamics [6]. They have developed the necessary concepts including a set of procedures for creating interlevel operators that allow one to smoothly connect data from various levels into a single simulation. With the ALE-AMR technique, we can dynamically drive the simulation through the use of sets of nested grids that automatically coarsen and refine to suit the needs of the simulation. The coarsening and refining is based on a hierarchical grid structure that changes dynamically in time—structured adaptive mesh refinement. The framework that enables this hierarchy is referred to as SAMRAI for structured adaptive mesh refinement application interface. The SAMRAI library maintains patches or combinations of patches on processors and allows the simulation to achieve a high degree of parallelism. This mostly automatic parallelism is an added benefit of this method for complex three-dimensional geometries.

The combination of ALE with AMR or even pure Lagrangian AMR requires new algorithmic developments. Interlevel solution transfer operators are required when new grids are created, for the generation of boundary conditions on finer levels in the hierarchy, for synchronizing coarse and fine data in the hierarchy and finally upon removal of the refined grids when they are no longer needed (coarsening). These difficulties have been mostly solved in the case of gas dynamics, however, adding the new physics models associated with radiation diffusion and material strength and failure is an extremely complicated problem.

The SAMRAI library maintains patches or combinations of patches on processors and allows the simulation to achieve a high degree of parallelism. In the proposed work, at the finest level the material models will also be farmed out to processors using the SAMRAI framework. Sophisticated load balancing techniques will be investigated to allow a highly scalable simulation. The operator splitting with different time scales for the simulation pieces including the implicit radiation transport will allow us to achieve load balancing in a highly complex multiphysics simulation. In other words, the implicit radiation transport and associated solvers could be overlapped with the polycrystal models to create a load-balanced parallel simulation.

In contrast to standard ICF simulations the problem of predicting debris and shrapnel effect often requires detailed modeling of the material behavior under the appropriate loading conditions. Since we are concerned not only with the primary target but also with ancillary components such as shields, pinhole arrays, etc., the material may also be at much lower temperature. Thus the simulation must include an appropriate formulation of elastic-plastic flow and appropriate failure mechanisms in addition to the hydrodynamic flow.

In the context of ALE-AMR, Wang, et al., is developing algorithms to simulate elastic-plastic flow in three dimensions on a moving AMR mesh. [7] Figure 7 gives a sample of the grid for a standard test problem[8] consisting of the impact of an extruded rectangular solid of metal material impacting on a rigid wall. The simulation begins with a uniform grid and as the plastic deformation occurs automatic refinement takes place. In the figure, different patches can be noted corresponding to the SAMRAI patches created during the refinement steps. These patches are automatically and dynamically distributed among the various processors on the parallel computing architecture.

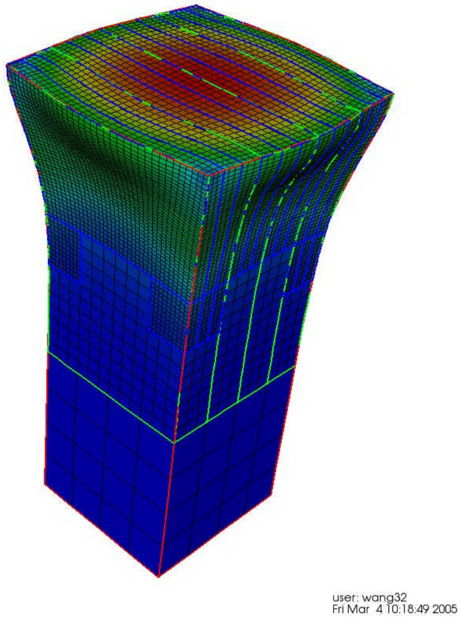

Figure 8. Demonstration of adaptive mesh refinement for elastic/plastic flow.

Additional physics packages are also needed to complete the computational model. Since we are interested primarily in the size, velocity, and material state (solid, vapor, etc.), detailed radiation transport with sophisticated techniques such as S-N or Monte-Carlo transport is not necessarily required, however there must be a means for basic diffusive energy transport between the driving radiation fields and the matter.

We are developing the capability to simulate radiation diffusion effects within the context of the ALE-AMR method. Once the basics of implementing the transport on a moving, non-Cartesian AMR grid are implemented, the next step of improving the transport model will be relatively straight forward. The solution of the radiation diffusion on the moving AMR mesh is based on work by Howell, et al. [9] on a (fixed) Eulerian AMR mesh. We compute the evolution of the radiation field and its interaction with the materials in the domain after each ALE-AMR timestep. The nonlinear equations discretized from the radiation equation are solved using a Newton iteration and the Schur's complement preconditioner. To efficiently solve the resulting linear system of equations, we use the fast adaptive compositie (FAC) approach. FAC is similar to multigrid, which has proven optimal convergence. The coarsest level in the AMR hierarchy does not use FAC, but is instead solved using the Hypre library[10], which also uses multigrid.

Figure 8 shows a standard test problem implemented in the ALE-AMR code. Circular regions of constant opacity are imbedded in an otherwise uniform region of much lower constant opacity. The top of the domain has a Marshak boundary condition with a specified initial flux and the bottom also has a Marshak boundary condition with zero imposed flux. Side boundaries are periodic. The circular regions act like "clouds" in a radiation field that is set up to be decoupled from the fluid energy.

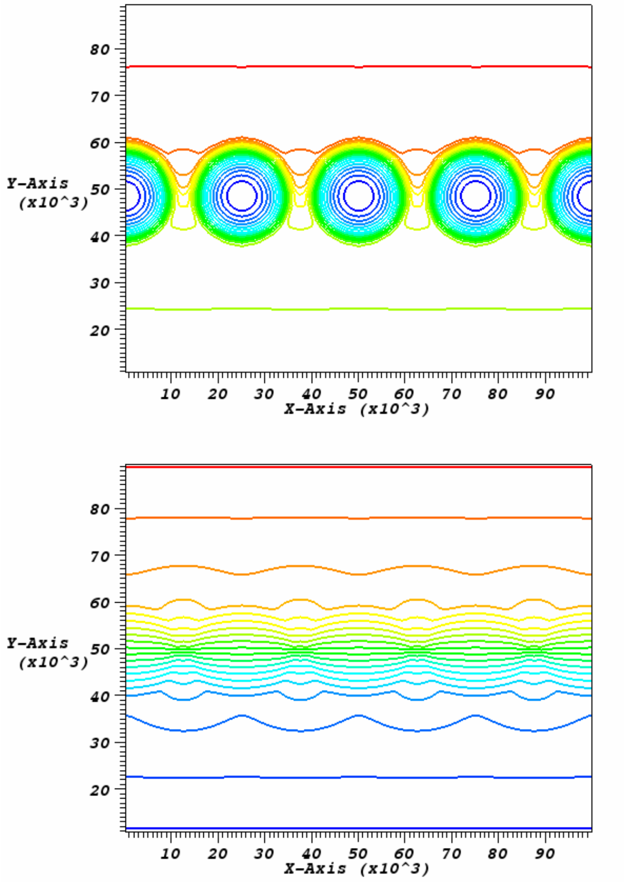

Figure 7. Contour plot of radiation energy density at showing the progression towards equilibrium in a test problem proposed by Howell and Greenough [9].

IV. Conclusions

The problem of predicting the dismantling properties of high-power laser facility targets requires state-of-the-art numerical techniques. Fundamental in our simulations is the ability to surround the objects(s) of interest in a mesh of air/void. New techniques are under development to combine ALE with AMR as a means to handle complex three-dimensional configurations.

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