Modeling Armor Penetration

by Ed Cort

Armor and anti-armor technology is becoming increasingly complex, forcing weapons designers to rely more and more on computer modeling. For years, computer simulations of armor penetration contributed only modestly to armor development compared, say, to the role of computational fluid dynamics in the aircraft and aerospace industries. However, computer modeling is becoming a major tool in the study of armor-penetrator interactions by offering weapons designers a number of distinct advantages in their quest of an essential understanding of the processes.

For example, the destruction and the speed of ballistic penetration make experimental diagnostics expensive, difficult to interpret, and, in many cases, impossible to gather. In comparison, a computer simulation, when benchmarked against even limited test data, can “replay” the experiment in slow motion. Computer modeling can also resolve velocity and stress and strain components in the target and penetrator in fine detail and pinpoint the relative interaction between armor components. The role of penetrator velocity, plate spacing in multilayered armor, and yaw (the angle of the penetrator’s axis with respect to its velocity vector) can be assessed easily, and armor designers can test their understanding and arrive at new insights by changing and optimizing such parameters. The results of a computation. done *before* the experiment can be used to guide test design by answering questions about the most advantageous locations for the instruments, the proper scale ranges for recording data, and the important experimental variables.

The goals of the computational research being carried out under ATAC’s direction are to validate and benchmark codes and methods, to pinpoint areas of needed research, and to improve existing codes-especially the ability to deal with a three-dimensional modeling of impact and penetration.

The *hydrocodes* used in the simulations are grounded in classical continuum mechanics, which attempts to describe the dynamics with a set of differential equations bed on the conservation of mass, momentum, and energy. An equation of state relates the material’s density, internal energy, and pressure. Finally, a constitutive equation describes the stress-strain relationship in the material and reflects changes in the properties of the material, such as work hardening that result from severe distortion. In fact, there is a frequent need to model the material *after* it has failed, a need that may sometimes distort the usual assumptions of continuum mechanics beyond simple extrapolation.

From a practical point of view, the ideal design code should have a user interface that allows problems to be set up conveniently, standardized material models and properties that can be expanded or modified easily, and powerful graphics and post-processing that can depict results quickly and in a manner that is easy to interpret. The code should be accurate in the physics and material behavior it intends to model as well as in the numerical implementation and programming that translate equations into code. The code must be adaptable to a wide variety of problems, efficient in memory use and running time (although, here, the definition of what is unacceptable constantly changes), and robust enough that the code does not fail when it encounters an unexpected situation.

The bulk of the computer codes used on a production basis fall into two categories: Eulerian and Lagrangian. Simply stated, Eulerian methods move the material through a fixed mesh as the problem progresses whereas Lagrangian methods have a computational grid attached to the material that distorts with movement of the material. (Eulerian codes are frequently used in fluid dynamics whereas Lagrangian methods are more often used in structural analysis,) Each method has its peculiar advantages and disadvantages. For instance, Lagrangian methods tend to be faster, can implement sophisticated material models more easily, are efficient with large problems, and treat material interfaces accurately. However, they also deal inaccurately with large shear flows, are more complex to set up, and are not robust with large distortions such as those that occur when armor penetration is significant. Eulerian methods are almost a mirror image of Lagrangian methods since they are robust, easy to set up, and capable of handling large shears and distortions. On the other hand, Eulerian codes tend to be less accurate in the treatment of material interfaces, inefficient in the use of computer memory, difficult to implement with more sophisticated material models, and generally slower in running.

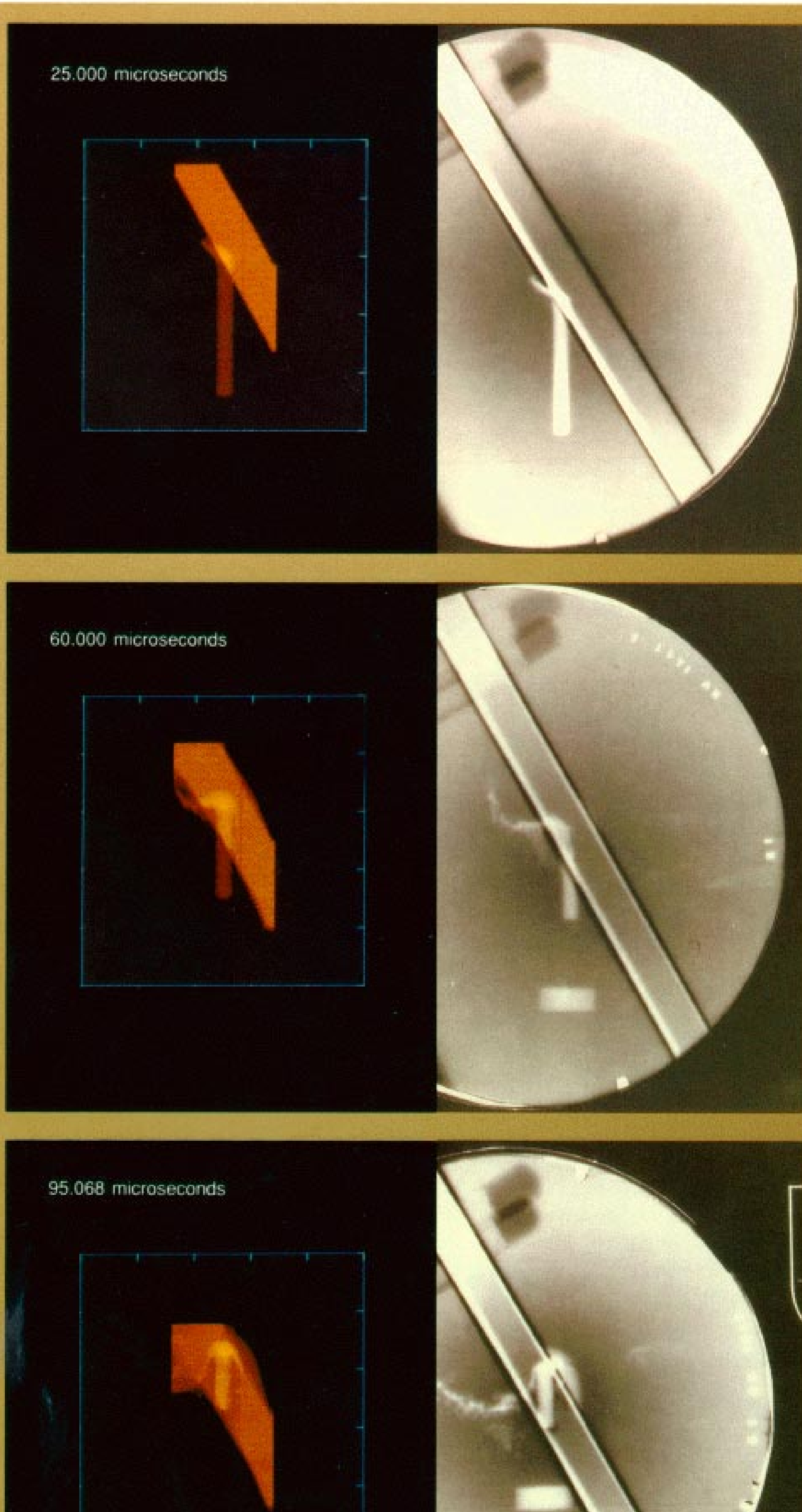
In our work at Los Alamos, we first explored an existing three-dimensional Eulerian code, HULL. We wanted to test its ability to accurately predict penetration of *spaced* armor, which has multiple layers of armor separated by gaps and set at oblique angles to the penetrator's line of flight. The intent of such a configuration is for the obliquity of the plates to deflect, bend, or break the long rod so that later plates can stop the residual pieces more easily. Reactive armor is another type of multilayered armor that also attempts to interfere with the rod's trajectory. In this case yaw is created on impact when a layer of explosive ignites, shoving a plate of armor toward the penetrator to knock it askew.

A computer simulation of the penetration of spaced armor plate will be realistic only if the code deals accurately with (1) the erosion of the front of the rod as it penetrates a plate, (2) the loss in velocity of the residual rod, (3) any changes in the orientation of the rod, and (4) the yielding and failure in the plate. We tested the ability of HULL to model armor penetration accurately by having it simulate a set of experiments carried out in the late 1970s using the PHERMEX machine. In these experiments, long-rod uranium-alloy Penetrators impacted steel-alloy plates set at various angles to the flight of the rod. Comparison of a PHERMEX radiograph and the corresponding computer simulation (Figure) illustrates how well the code predicted the interaction between penetrator and target.

These benchmark experiments gave us confidence that the code had the potential to provide useful information about similar experiments with more complex targets, such as ceramics, whose interaction with the penetrator was more difficult to model, But a computation of this type pushed HULL to the limit of its capability—it had a running time in a CRAY X-MP computer of 11 hours, and the computer memory would not hold enough information to model a second target plate with an intervening space. Even if larger computer memories were available, realistic targets-up to 10 times as thick as the preliminary example—would require considerably more computer time to model. Our evaluation was that HULL is a useful but limited code.

The evaluation, coupled with many other code comparisons, motivated us to develop a new three-dimensional code designed specifically for simulations of armor and anti-armor systems. The code, called MESA, is Eulerian and treats hydrodynamic flow and the dynamic deformation of solid materials. Because it uses state-of-the-art numerical methods, it runs faster and is less affected by spurious numerical problems than existing Eulerian codes. The version of MESA now being tested incorporates several of the standard strength models that take into account both the elastic and the plastic regions of the stress-strain relationship of the materials. There is also a programmed-bum model for the explosives. We have developed ‘a number of such models, which should increase our ability to simulate a variety of interactions for modern armor systems. In future versions of MESA we will include more advanced materials models.

One such model, called the Mechanical Threshold Stress model, will incorporate the physical deformation mechanisms needed to simulate conditions not easily achieved in the laboratory but important to this type of research. Specifically, the model will allow us to extrapolate better into regimes of high deformation rate, high temperature, and large amounts of strain. The model separates the kinetics of strain hardening (that is, dependencies on temperature and strain rate) from the kinetics related to the strength at a given instant. So far we have demonstrated the model only for certain well-characterized metallic systems, but we are extending it to the more complicated materials used in armor and anti-armor applications. We also hope to combine the defor-



**BALLISTIC IMPACT—
SIMULATED AND ACTUAL**

The penetration of steel plate by a kinetic-energy rod as photographed with x rays generated by PHERMEX (right) and as simulated by the HULL hydrocode (left). Time increases from 25 microseconds after impact at the top to about 95 microseconds at the bottom, and the impact velocity of the rod is 1000 meters per second.

Table

Current application of MESA (funded by the Department of Defense and the Army Missile Command as well as DARPA, the Defense Advanced Research Project Agency).

Nonaxisymmetric shaped-charge generators of explosively-formed jets.

Penetration of reactive armor by jets.

Effects on jet formation in TOW missile when:
- two warheads are fired side-by-side, and
- passive materials are placed nonaxisymmetrically adjacent to a single warhead.

Penetration of armor by long rods with:
- the rod trajectory impinging obliquely,
- the target moving, and
- various degrees of pitch and yaw.

mation kinetics of this model with the anisotropic deformation incorporated in some of the other models we are developing. Such a marriage has already been demonstrated in specialized problems, but we need to do further work to reduce the computational burden that accompanies the full analysis.

Another major application area for MESA is the reactive-armor problem. We foresee a need to model in some detail the interaction of projectiles with these sandwiched layers of metal plate and explosive. When the shock wave produced at impact detonates the explosive, the plates are set in motion and interact in a complicated fashion with the projectile. Not only is this problem three-dimensional, but interface resolution must be accurate because the moving plates are thin. A related problem is to predict the loads on the underlying vehicle structure due to the reaction forces of the flying plates and the blast. To demonstrate the usefulness of MESA for reactive-armor problems, including estimating the loads on the vehicle, we have simulated the dynamics of a two-dimensional analog of typical reactive armor. The results are very encouraging because they show that the contorted deformations can be resolved reasonably well with a computational grid that consists of only about four cells across the thickness of the plate.

Currently, we are testing MESA and applying it to a variety of armor/anti-armor problems (see Table). Following this initial phase, we hope to transfer the code to other interested members of the armor and anti-armor community that might need to use it. ■