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# **SIMULATION OF DYNAMIC MATERIAL RESPONSE WITH THE PAGOSA CODE**

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## **ABSTRACT**

The 3D Eulerian PAGOSA hydrocode is being run on the massively parallel Connection Machine (CM) to simulate the response of materials to dynamic loading, such as by high explosives or high velocity impact. The code has a variety of equation of state forms, plastic yield models, and fracture and fragmentation models. The numerical algorithms in PAGOSA and the implementation of material models are discussed briefly.

## **INTRODUCTION**

PAGOSA is a 3D Eulerian hydrocode that runs on the massively parallel Connection Machine (CM). In Eulerian codes, the computational grid is fixed in space and the fluid or material being represented flows through the grid. Such codes are useful for simulations involving rapid material deformation in large scale systems. A comprehensive overview of the numerical methods used in PAGOSA has been published by Kothe *et al.* (1993). Specific features of PAGOSA relevant to the simulation of dynamic material response will be highlighted here.

Many of the numerical methods used in PAGOSA were previously implemented in the MESA code, which runs on the Cray XMP and YMP vector supercomputers (Holian *et al.*, 1990; Cagliostro, *et al.*, 1990). MESA and PAGOSA development was supported in part by ARPA, the U. S. Army, and Marine Corps. The transition from vector machines to massively parallel processors (MPP) like the CM is driven by computing needs. The memory and speed of the MPP are needed for simulations involving full systems and to handle the finer meshes that are needed for advanced material models. MPPs are expected to show continued performance improvements.

MESA and PAGOSA have been used for simulating dynamic events resulting from explosive loading and high speed impacts. Some examples are shaped charge jet formation, armor penetration, theater missile defense, munitions safety, and the impact of space debris on spacecraft. Calculations show the sensitivity of results to changes in design dimensions or materials, provide information inaccessible to measurement, and extend the range of experimental data in time or to similar systems. With calculations, fewer complex and expensive tests are required to support systems integration studies. In addition, simulations can expose blind spots as overlooked phenomena become apparent in the code results.

While the Eulerian nature of these codes allows them to treat large distortions, the remapping to a fixed grid can introduce spurious diffusion. Numerical diffusion is reduced in MESA and PAGOSA through the use of an interface reconstruction algorithm for following material interfaces in mixed cells. In addition, high order advection methods are used to preserve gradients in the density and other quantities in the solutions. Even so, the necessity of advecting nonconserved quantities, such as damage, limits the accuracy of the material models implemented in these codes.

## MATERIAL MODELS IN MESA AND PAGOSA

The material models in MESA and PAGOSA can be divided generally into those related to the equation of state, models for high explosives, material strength, and fracture and fragmentation. The equation of state models in PAGOSA include void, ideal gas, Mie-Gruneisen, and several other analytic forms, as well as JWL and BKW for explosive reaction products. The Sesame tabular equation of state is implemented in MESA and is being implemented in PAGOSA. Besides the equation of state for the reaction products, simulations of explosives also involve explosive "burn models," ranging in complexity from a simple programmed burn to a full reactive burn model.

The constitutive models used in these codes must have enough detail to describe the macroscopic behavior of the materials while still being computationally efficient. Even with relatively simple models, the code runs are very long because of the physical scale of the systems and the number of time steps calculated. The strength models include elastic/perfectly plastic with constant yield strength or with the yield models developed by Dan Steinberg and colleagues at Livermore or by Gordon Johnson and colleagues at Alliant TechSystems. The Mechanical Threshold Stress and Zerilli-Armstrong dislocation dynamics models are available in MESA. There are currently two fracture and fragmentation models, which are described below.

## ISSUES INVOLVING MATERIAL MODELING IN EULERIAN CODES

The implementation of material models in Eulerian codes is made difficult because of the use of a single velocity field for all materials. Under some circumstances, mixed cell components can behave nonphysically if they have very different compressibilities or shear moduli. Pressure and stress relaxation methods are being developed to deal with this. The single velocity field also makes it difficult to accurately represent slip at material interfaces.

The advection process itself can affect material models because nonconserved quantities, such as stress components and internal variables like damage, must be advected. In extreme cases, numerical dispersion can cause fractured material to "heal." Anisotropic materials also present a challenge because finite material rotations must be calculated accurately and then advected.

Internal variables like fracture porosity or damage can be used to represent material failure in a continuum sense, but discrete fractures cannot be followed. Parting of material in regions with heavy damage requires a separate void opening model. This makes the prediction of fragment size distributions and fragment motions difficult.

MESA is written in FORTRAN 77 in a traditional style to be used on computers with shared memory and efficient indirect addressing. PAGOSA, however, is written in CM FORTRAN (FORTRAN 90 with extensions) for use on the SIMD CM-200 Connection Machine. Thus, implementing material models in PAGOSA must be done taking the SIMD nature of the machine into account. One objective of the original development of PAGOSA was to demonstrate that the hydrodynamic algorithms would perform well on a SIMD machine. Similar techniques to those used in the initial development are now used in implementing the material models described here to achieve good performance. PAGOSA is now also being run on the CM-5, and work is under way to take advantage of the MIMD features of that machine.

## EXAMPLES OF MODEL IMPLEMENTATION

Experience with ceramics models and two fracture and fragmentation models shows that these models can be used successfully in spite of the difficulties described above. The implemen-

tation of the Johnson-Holmquist, and Steinberg ceramic models in the MESA code has been described by Mandell and Henninger (1992) and Mandell (1993). These models have been used successfully to calculate one and two dimensional impact experiments conducted at Sandia National Laboratories. In spite of this success, some of the experiments are difficult to match. The models may still be reasonable, but the constants may not be appropriate for the particular samples used in the tests. These models and others are being studied in MESA before being implemented in PAGOSA.

One difficulty was recognized in the use of the Johnson-Holmquist ceramics model in MESA. The problem was related to the abrupt failure of the ceramic as the damage parameter reached one. Inaccuracies in advection can allow failed material to recover spuriously after advection if the damage parameter later drops below one. This model is being revised by Johnson and Holmquist to make it easier to use in Eulerian codes by allowing a smoother transition from intact to failed ceramic.

The fracture and fragmentation models have also been studied in MESA and they are now being implemented in PAGOSA. One of the models, the ductile void growth model of Johnson (1981), was modified by Kathy Holian with the addition of a "void opening" model. The fracture porosity is treated as an internal variable as it increases under sufficient tensile loading. When it reaches a first threshold value, the pressure and the stress deviators are set to zero and held there to represent loss of cohesion. When porosity increases further and reaches a second threshold, the porosity is converted from an internal variable to an explicit void component. The model is further augmented with a "void bunching" algorithm to cause nearby voids to coalesce and better represent material separation.

Another fracture model, the continuum damage model developed by Johnson and Cook (1985), was modified by John Bolstad and Dominic Cagliostro to allow for void opening. When the damage parameter reaches a threshold value, some of the damaged material in a cell is arbitrarily replaced with a void component. In spite of the *ad hoc* nature of this model, it has been used successfully to represent that breakage of metal rods subjected to impact.

## CONCLUSIONS

Eulerian codes have significant advantages for simulations, but have characteristics that make it difficult to implement advanced material models. A number of equation of state, explosive, strength, fracture, and fragmentation models have been implemented in the MESA and PAGOSA codes. Even with these relatively simple models, these codes have been used successfully in simulations of complex large scale systems.

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