View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by NASA Technical Reports Server

N92-22380

Simulating Hypervelocity Impact Effects on Structures Using the Smoothed Particle Hydrodynamics Code MAGI

Larry Libersky
Center for Explosives Technology Research
New Mexico Institute of Technology
Socorro, N.M. 87801

Firooz Allahdadi
Phillips Laboratory
Space Kinetic Impact & Debris Branch
Kirtland AFB N.M. 87117

Theodore C Carney
Advanced Sciences Inc.
6739 Academy Road N.E.
Albuquerque, N.M. 87109

INTRODUCTION

Analysis of interaction occurring between space debris and orbiting structures is of great interest to the planning and survivability of space assets. Computer simulation of the impact events using hydrodynamic codes can provide some understanding of the processes but the problems involved with this fundamental approach are formidable. First, any realistic simulation is necessarily three-dimensional, e.g., the impact and breakup of a satellite. Second, the thickness of important components such as satellite skins or bumper shields are small with respect to the dimension of the structure as a whole, presenting severe zoning problems for codes. Thirdly, the debris cloud produced by the primary impact will yield many secondary impacts which will contribute to the damage and possible breakup of the structure. Characterization of the debris cloud requires accurate fragmentation modeling as well as accurate tracking of the fragments through large regions of void. For these reasons hydrodynamic simulation of hypervelocity impact and breakup of orbiting structures is extremely difficult. We have approached the problem by choosing a relatively new computational technique that has virtues peculiar to space impacts. The method is called Smoothed Particle Hydrodynamics (SPH). In this paper we describe the SPH method and why we believe that it can be used to answer many questions concerning the survivability of space assets due to kinetic impacts. We also present several calculations to show the power of SPH towards such problems.

SPH BASICS

Smooth Particle Hydrodynamics is unique in computational fluid dynamics in that SPH uses no grid. It was the genius of the inventors, Lucy (1977) and Gingold & Monaghan (1977) to figure out how to take a derivative (get the force on a fluid element) without using a mesh. Previously a mesh was the only known way to compute a spatial derivative using finite differences. The mathematical theory of SPH will not be discussed here. The reader is referred to Gingold & Monaghan (1977,1982), Monaghan (1982,1985) and Monaghan & Gingold (1983) for detailed treatment of the subject. We present here only some basic features as discussed by Benz (1989) that are necessary to understand the method. Consider a function f, a kernel W which has a width measured by the parameter h, and the following equation:

$$< f(\mathbf{r}) > = \int W(\mathbf{r}-\mathbf{r}', h) f(\mathbf{r}') d\mathbf{r}'. \quad (1)$$

If we impose a normalization condition such that the integral of W is unity, then it follows that

$$< f(\mathbf{r}) > \xrightarrow{h \to 0} f(\mathbf{r}) . \quad (2)$$

Relation (1) therefore defines the kernel estimate $<f>$ of f. If W is the Dirac delta function then we have the equality $<f>=f$. Now suppose f is known only at N discrete points that are spatially distributed according to the number density distribution:

$$n(\mathbf{r}) = \sum_{j=1}^{N} \delta(\mathbf{r} - \mathbf{r}_j) \qquad (3)$$

If the number density at $\mathbf{r}_j$ is written as

$$< n(\mathbf{r}_j) > = \frac{\varrho(\mathbf{r}_j)}{m_j} \ , \qquad (4)$$

thus introducing the concept of particle mass (m), the following equation can be derived:

$$< f(\mathbf{r}) > = \sum_j f_j \ W(\mathbf{r} - \mathbf{r}_j, h) \frac{m_j}{\varrho_j} \qquad (5)$$

This equation defines a procedure for transforming integral equations to particle equations and is therefore called "integral evaluation by the particle method." The choice of kernel or "smoothing function" is discussed by Monaghan and Lattanzio (1985). The W most frequently used in SPH codes is a B-spline with compact support which goes to a zero at a distance $2h$ from its peak. When the conservation laws of fluid dynamics are cast into the SPH framework using the procedure described above, the following equations are obtained.

$$\varrho_i = \sum_j m_i W_{ij} \qquad (6)$$

$$\frac{d\vec{u}_i}{dt} = -\sum_j \left[\frac{P_i}{\varrho_i^2} + \frac{P_j}{\varrho_j^2} + \Pi_{ij} \right] m_j \ \vec{\nabla} W_{ij} \qquad (7)$$

$$\begin{aligned} \frac{de_i}{dt} &= \frac{P_i}{\varrho_i^2} \sum_j m_j (\vec{u_i} - \vec{u_j}) \ . \vec{\nabla} W_{ij} \\ &+ \frac{1}{2} \sum_j m_j \Pi_{ij} (\vec{u_i} - \vec{u_j}) \ . \ \vec{\nabla} W_{ij} \end{aligned} \qquad (8)$$

Equation (6) is the density computation of particle "i" using the masses of neighboring "j" particles. The acceleration of particle "i" is given by (7) and the evolution of the specific internal energy (e) is described by equation (8). These equations also involve the pressure (P) and the artificial viscous pressure Π. Terms involving material strength are omitted here but are discussed by Libersky and Petschek (1991). It should be emphasized that equations (6) thru (8) are the continuum equations of fluid dynamics cast into a discrete Lagrangian frame by kernel interpolation. Therefore, the Smoothed Particle Hydrodynamics method is a true and complete hydrodynamic calculational procedure.

IMPORTANCE TO SPACE IMPACTS

Simulating the mechanics of irreversible processes that take place between a structure and a projectile during a hypervelocity collision in space is extremely difficult. There are three main reasons for this. First, problems are three-dimensional. Second, the thickness of important components such as satellite skins, electronic components or bumper shields are small with respect to the dimension of the structure as a whole. Three-dimensional calculations using mesh-based codes do not seem feasible for such problems. Thirdly, the debris cloud produced by the primary impact produces secondary and tertiary impacts important to the overall damage and breakup. Simulation of these events requires detailed characterization of the debris cloud which in turn requires good fragmentation modeling as well as accurate tracking of the fragments through large regions of void. Eulerian codes have difficulty tracking sub-grid scale fragments through the mesh. Also, large regions of void within the structure need to be zoned in anticipation of material arriving there at some later time. SPH suffers from neither of these difficulties because there is no mesh. Following the debris cloud through large regions of void presents no difficulty to SPH. Furthermore, interfaces between materials in a problem consisting of several materials are accurately tracked. These virtues of SPH are true of any Lagrangian code, except that mesh-based Lagrangian codes cannot treat large fluid distortions. Obviously, hypervelocity impact produces highly distorted flows. It can be said that SPH contains the best features of grid-based Eulerian and Lagrangian methods without the limitations of either. The price to be paid is that SPH is slower than the other methods, (having to determine new neighbors each computational cycle) but not prohibitively so. The efficiency of SPH appears to be much better than Eulerian in 3D (Durisen, 1988) and we are paying close attention to vectorization and parallelization. The ability of SPH to accurately track debris resulting from hypervelocity impact through large regions of void in 3 dimensions and compute the impact of the debris on other parts of the structure make the method extremely attractive for space applications. In working towards that goal we have performed several two-dimensional calculations to evaluate SPH and get a feel for how impact events might damage and lead to breakup of the large-scale structure.

SYNTHESIS OF A PREDICTIVE BREAKUP MODEL

Determination of processes that contribute to the failure and ultimately to the breakup of a complex and integrated space asset under impulsive loading is of vital interest. Currently, such a predictive model does not exist. Until recently, virtually all breakup modeling of a spacecraft under intensive loading used a phenomenological approach. Although this approach provides some qualitative measure of the interactions, it lacks the physics necessary to identify those processes that control generation of the resulting debris cloud. To characterize the environment of a debris cloud accurately (in terms of debris mass, velocity and number distribution), a first principles physics based predictive model has been synthesized. This approach considers the synthesis of a total predictive model based on the response of elementary components. Internal components of a generic satellite are shown in Figure 1 and an example matrix of calculations leading to the total predictive model is shown in Figure 2. The design of these and other calculations is motivated by the various geometries of the components internal to the satellite. Two simulations of local impact events on small regions of a large scale structure are shown in Figure 3 and Figure 4. These calculations give us detailed understanding of how the debris cloud interacts with nearby structural elements producing damage.

Figure 3a is a particle plot showing initial conditions for the impact of an tantalum projectile on an aluminum (2024-T86) frame. Each arm of the frame had length 20.5 cm and thickness 0.5 cm. The projectile had 1.0 cm sides, a speed of 7 km/s and a 60 degree impact obliquity. The calculation was performed in a two-dimensional Cartesian frame of reference. A Gruneisen equation of state and an elastic-perfectly plastic constitutive model were used to describe the metals. The calculation used 12,240 particles and the smoothing length was 0.08333 cm. Results of the calculation at 1 and 20 microseconds are shown in Figures 3b and 3c respectively. A very large opening is created in the first plate impacted due to the large impact obliquity. This "hole" is approximately 7 times the initial projectile size. One end of the plate is bent inward. There is a large splash of material moving upward and away from the structure typical of high speed cratering events and a debris cloud expanding towards the other arm of the structure. This cloud has fragments of various sizes but most of the mass is concentrated in the part of the cloud that is about to impact the second structural arm.

Results of a similar calculation employing a slightly more complex aluminum structure are displayed in Figure 4 where particle plots at four different times (0, 10, 20, 30 μs) are shown. In this calculation the debris cloud, resulting from the impact upon one member of the aluminum frame, is seen impacting other structural elements. Severe damage is seen on the upper panel. In fact, a secondary debris cloud has been produced by the interaction. It is easy to see from this calculation, that in an actual satellite with many more composite parts, how a cascade of debris clouds could form to cause massive breakup of the structure. Some damage is also seen on the outside panel furthest from the impact. These calculations were performed on a 1 megaflop machine and required approximately 1 hour of cpu time per 10 μs of simulation time.

Target Name: chucksat.tp4
Aimpoint(X,Y,Z) (cm) = (0.00 0.00 45.50)
Observer Azimuth (degrees) = 91.00
Observer Elevation (degrees) = 0.00

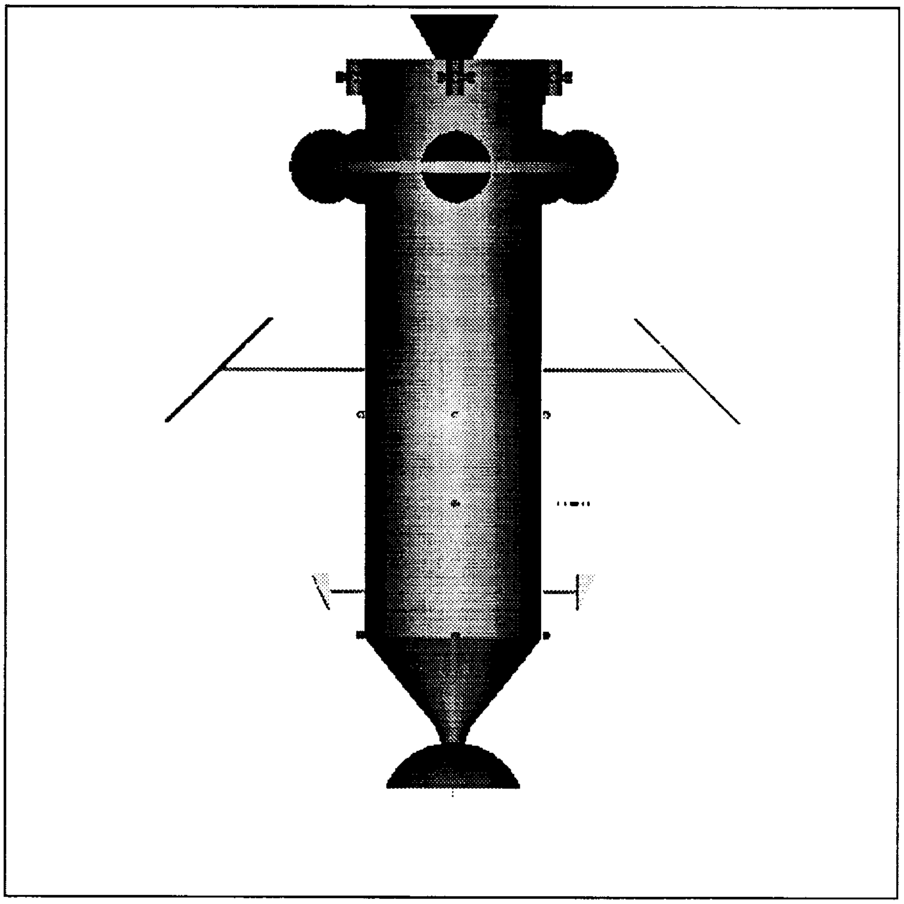


Figure 1. A Generic Satellite

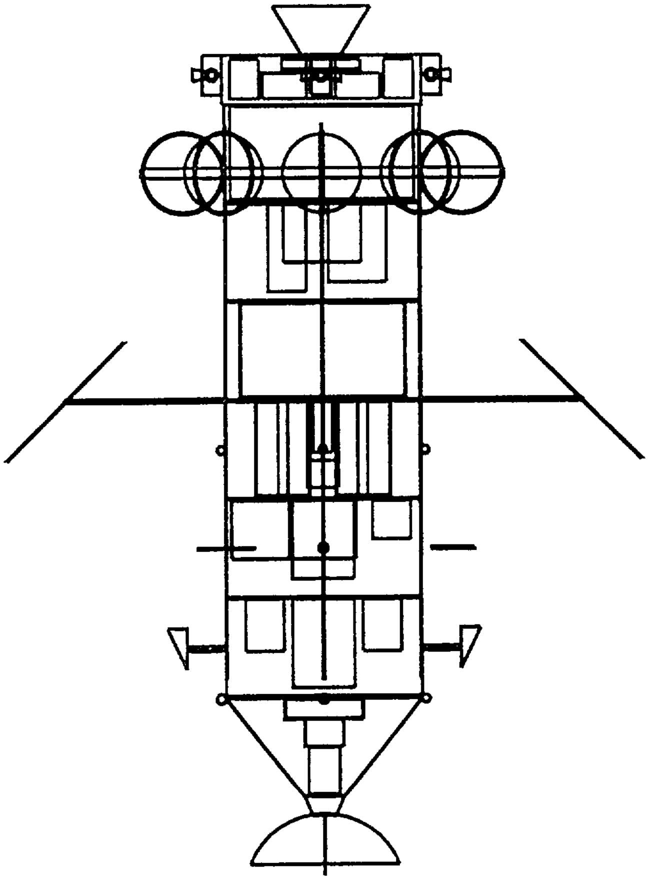


Figure 1A. Interior Components of Satellite

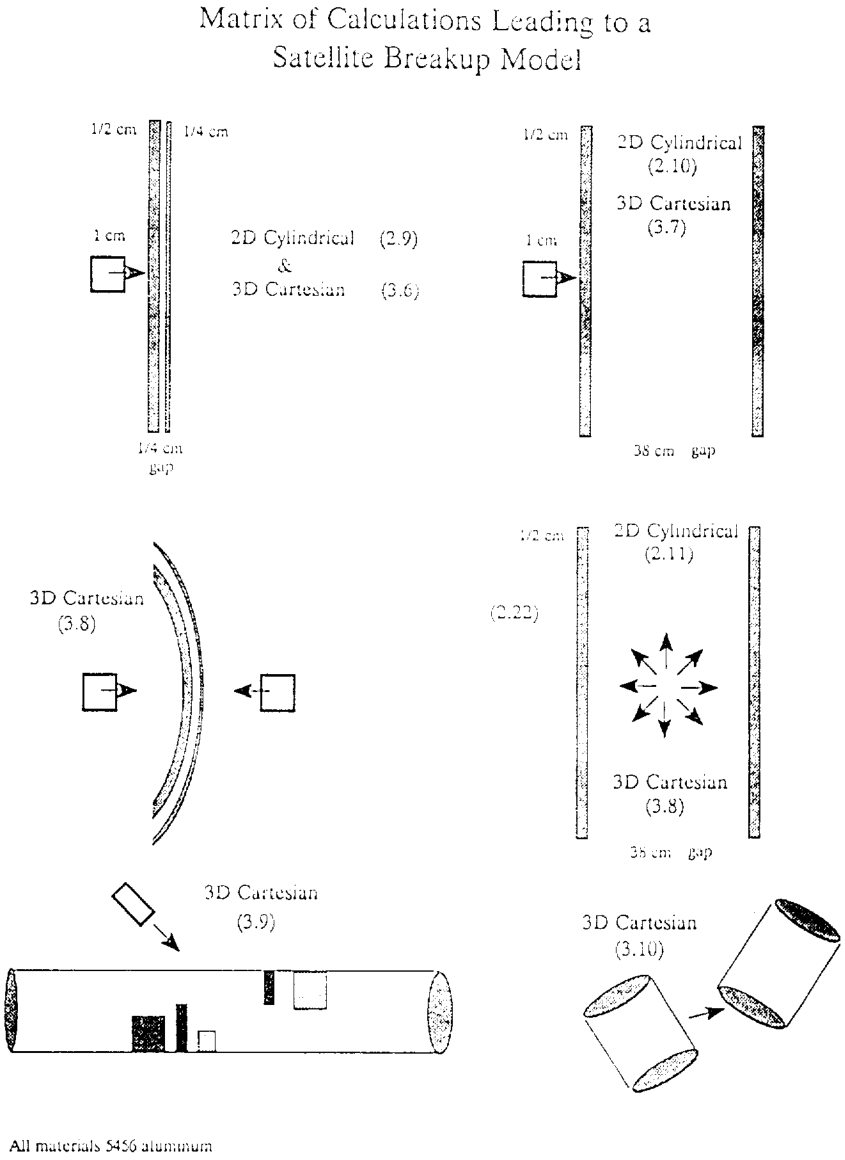
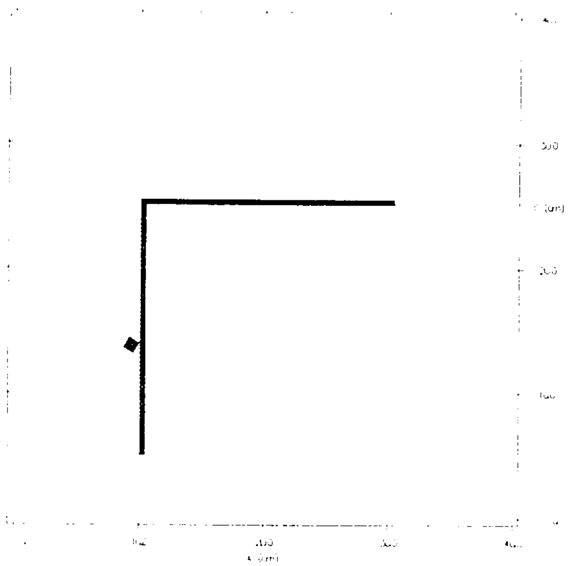
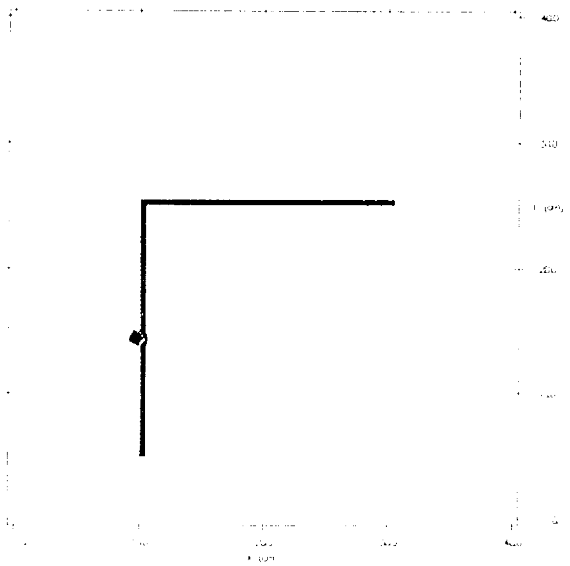


Figure 2. Matrix of Calculations

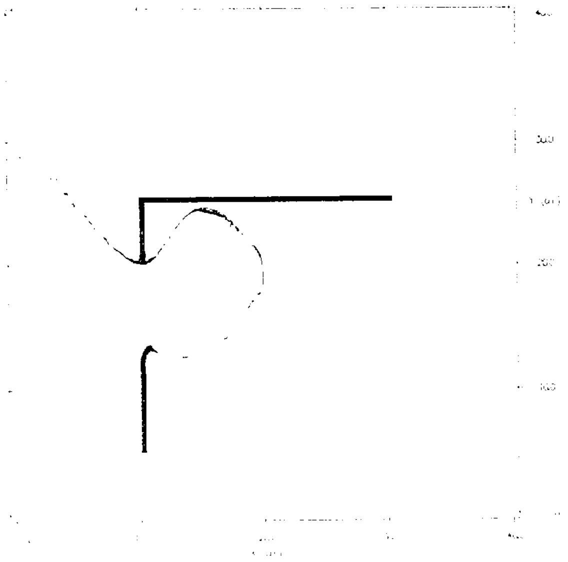


(3a) Initial configuration.



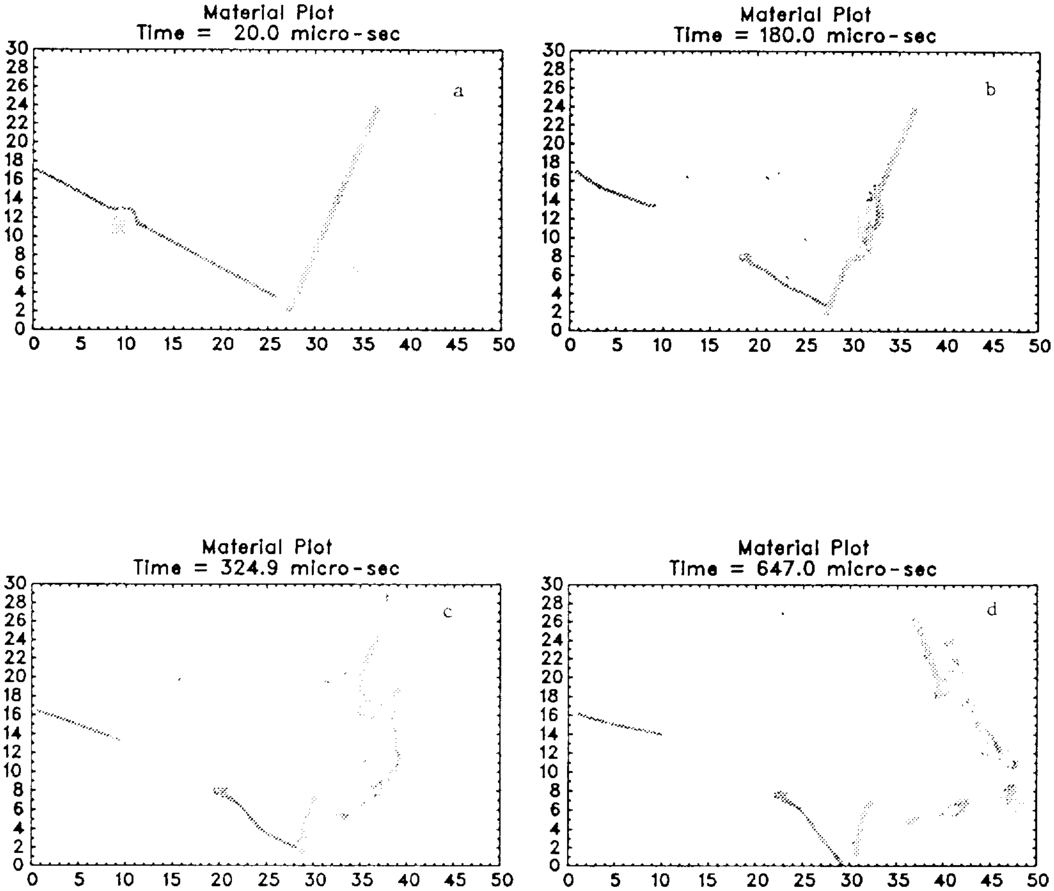
(3b) 1 microsecond after initial impact.

Figure 3. Material plot of a tantalum projectile penetrating an aluminum frame at 60° obliquity.



(3e) 20 microseconds after initial impact.

Figure 3 (cont). Material plot of a tantalum projectile penetrating an aluminum frame at 60° obliquity.



Material Plot
Time = 20.0 micro-sec

Material Plot
Time = 180.0 micro-sec

Material Plot
Time = 324.9 micro-sec

Material Plot
Time = 647.0 micro-sec

Figure 5. Smoothed Particle Hydrodynamics simulation of a liquid filled steel pellet impacting multiple spaced plates at 2 km/s and high obliquity. The first plate impacted is aluminum amd the remaining two are steel. The calculation was done in two-dimensional Cartesian coordinates using the SPH code MAGI. Frames a - d show results at 20, 180, 325, and 647 µs.

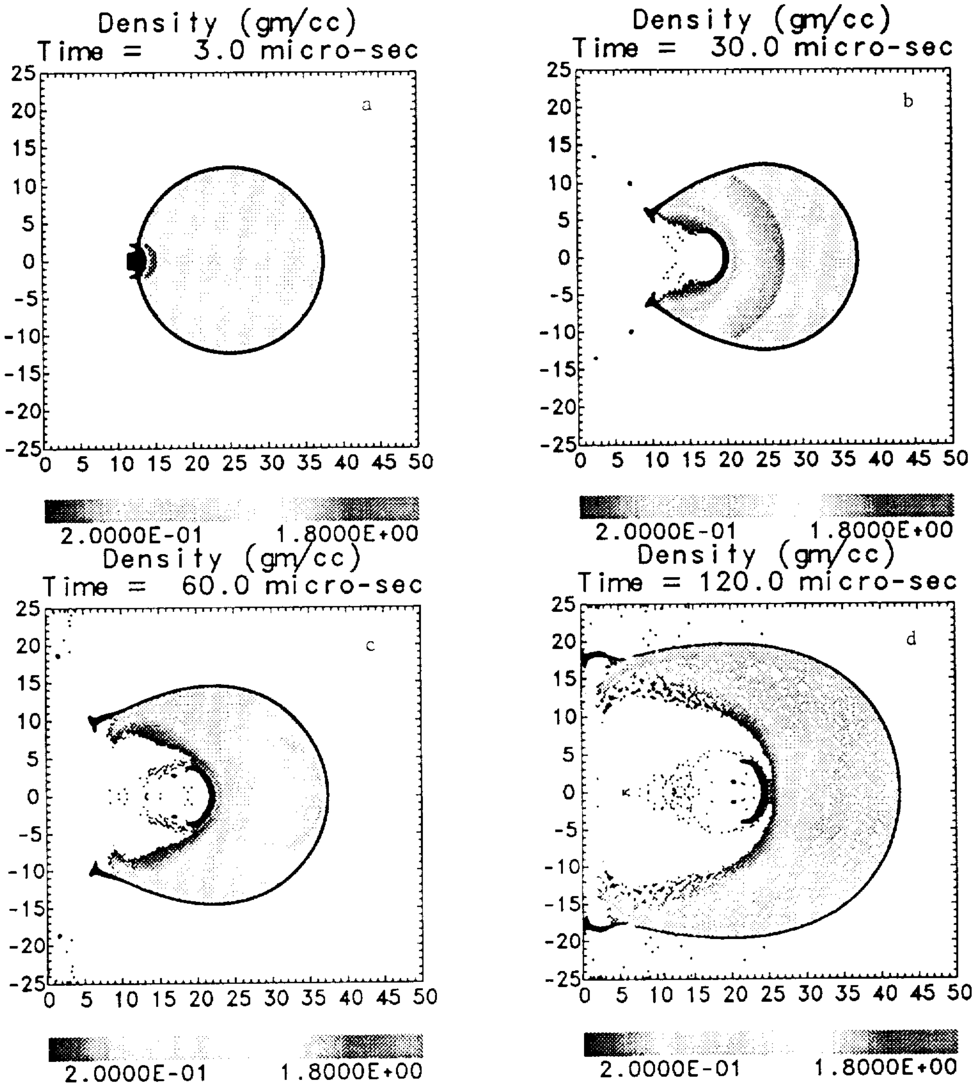


Figure 6. Smoothed Particle Hydrodynamics simulation of a liquid filled aluminum tank hit by an aluminum projectile moving at 7 km/s. The calculation was done in two-dimensional Cartesian coordinates using the SPH code MAGI. The liquid particles are gray-scaled by density and the aluminum particles are shown in black. Frames a - d show results at 3, 30, 60, and 120 μs.

Several calculations have been presented – two hypervelocity impacts on simple structures, and two other impact problems possessing interesting features. We are encouraged by the results. The code has been extended to three-dimensions and we are currently performing test problems.

REFERENCES

Benz, W., Numerical Modeling of Stellar Pulsation: Problems and Prospects, Nato Workshop, Les Arcs, France, March, 1989 (Harvard Smithsonian Center for Astrophysics, Preprint No 2844, (1989).

Durisen, R.H., R.A. Gingold, J.E. Tohline and A.P. Boss, *The Astrophysical Journal*, 305, (1986), 281-306.

Gingold, R.A. and Monaghan, J.J., *Mon Not Roy Astron Soc* 181 (1977), 375-389.

Gingold, R.A. and Monaghan, J.J., *J Comput Phys* 46 (1982), 429-453.

Libersky, L.D. and A.G.Petschek, *Lecture Notes in Physics*, Springer Verlag, in print (1991).

Lucy, L.B. *Astron. J.* 83 (1977) 1013-1024.

Monaghan, J.J., *SIAM J Sci Stat Comput.*, **3** (1982), 422.

Monaghan, J.J., *Comp Phy Rev* 3 (1985), 71-124

Monaghan, J.J and Gingold, R.A, *J Comput Phys* 52 (1983), 374-389.

Monaghan, J.J. and Lattanzio, J.C., *Astron Astrophys* 149 (1985), 135-143.

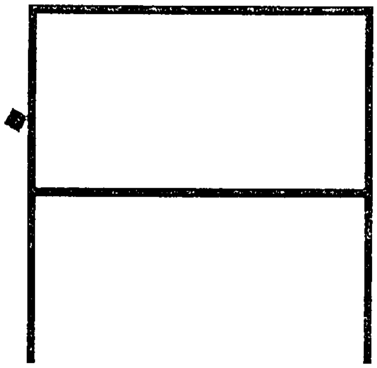
ADDITIONAL IMPACT CALCULATIONS

Two additional calculations are presented in order to show the power of SPH towards impacts. Figures 5a–5d are particle plots showing a liquid filled projectile impacting a series of spaced plates at high obliquity. The projectile casing was steel and the simulated liquid was modeled as carbon–tetrachloride. The length of the projectile was 3.75 cm and the thickness 2.50 cm. The first plate to be impacted was aluminum with thickness 0.254 cm, and the remaining two plates were steel with thicknesses 0.48 cm and 1.58 cm respectively. The projectile speed was 1.6 km/s. The problem was run in a two–dimensional rectangular Cartesian frame of reference (plane–strain) with approximately 4,000 particles. The smoothing length was 0.127 cm. An elasctic–perfectly plastic constitutive model and Gruneisen equation of state were used to describe the solids. No explicit failure model was included in the calculation. Figure 5a shows the aluminium plate being impacted (t = 20 μs). Figure 5b shows the calculational result at 180 μs. The projectile has struck the first steel plate and the lower aluminum plate which was set in motion by the impact has also hit the steel and started to buckle. At 325 μs, as shown in Figure 5c, the aluminum plate has continued to buckle and the portion of the broken steel plate at the bottom of the figure has rotated as a result of the impact torque. These are two interesting features of the strength model operating in the code. It is very encouraging to see these effects captured by the code. Other interesting features are the crack formation at the back of the thick steel plate and the enhanced upward momentum of the first steel plate due to the crater splash from the projectile on the second plate. We expect these kinds of secondary effects to be important in the actual satellite breakup from impact. An obvious key feature of simulation is the "plug" of steel plate seen in Figure 5d. This is not due to any explicit failure model in the code but results from intrinsic model fracture in SPH. In response to elastic waves in the plate, some particles find themselves outside of the smoothing length range of communication with its neighbors. This separation manifests itself as a "crack" which propagates through the metal. We cannot, at this point, claim that this effect is actually a physical one. Nevertheless, it appears that the code is trying, on its own, to accommodate failure, and the results seem physical. This calculation required 2 hours of cpu time on the CRAY 2 at the Phillips Laboratory.

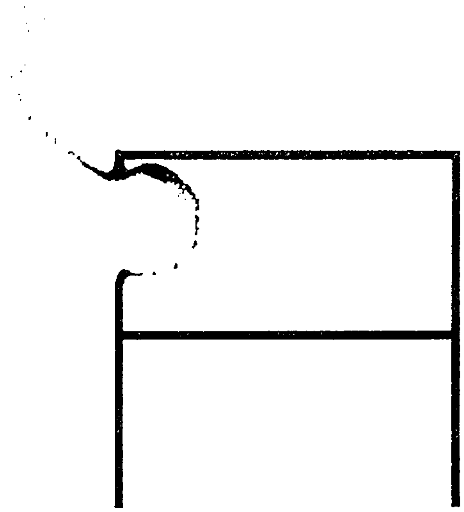
Results of a hypervelocity impact (7 km/s) simulation of an aluminum projectile into a water–filled aluminum tank are shown in Figure 6 where the particles are gray–scaled according to their density. The diameter of the tank was 25 cm initially and the wall thickness was 0.5 cm. The projectile length was 3.0 cm and the thickness was 2.0 cm. The geometry was 2D Cartesian. Approximately 20,000 particles were used in the simulation. The smoothing length was 0.2 cm. Notice the shock propagation in the water and along the tank inner surface which comes to a focus at the rear of the cylinder and then strongly reflects back. The reflected shock is evidenced by the flattening of the particle distribution just ahead of the projectile. Notice also the rapid deceleration of the aluminum projectile and its large deformation. This calculation took 7 hours on the CRAY 2. For these two specialized problems there is no experiment data to which the simulations can be compared, so we must be careful not to draw unjustified conclusions about the codes performance. However, we can get a feel for how the code responds to difficult impact problems with the goal of extending the calulations to three–dimensions with extensive comparison to experiments.

CONCLUSIONS

The Smoothed Particle Hydrodynamics (SPH) approach to computational fluid dynamics has been briefly described with emphasis on its natural ability to model hypervelocity impact on orbiting structures. Our goal is to exploit these virtues of SPH towards the development of a complete structural breakup model in order to answer important questions concerning the survivability of space assets due to kinetic impacts.

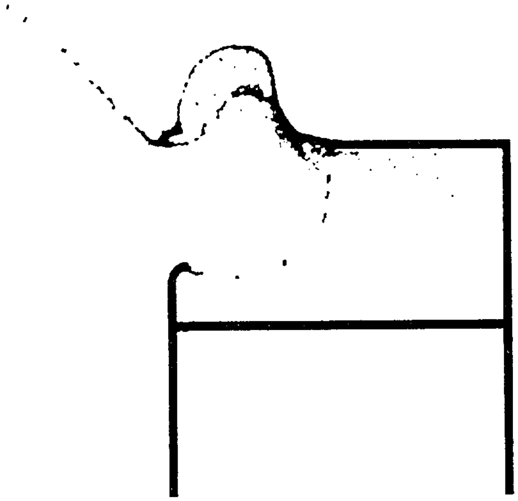


(4a) Initial configuration.

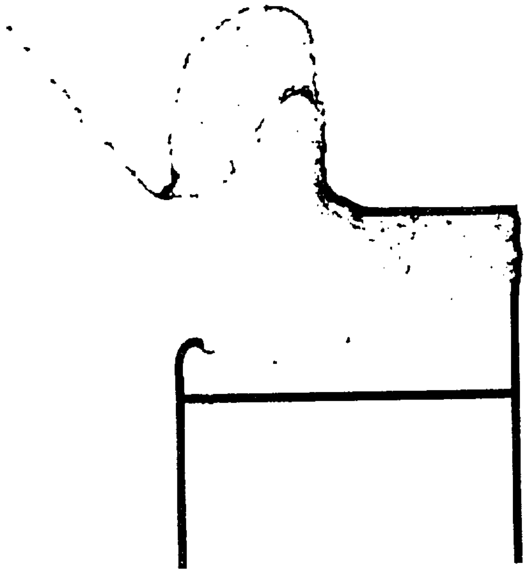


(4b) 10 microseconds after initial impact.

Figure 4. Material plot of a tantalum projectile penetrating an aluminum A-frame structure at 60° obliquity.



(4c) 20 microseconds after initial impact.



(4d) 30 microseconds after initial impact.

Figure 4 (cont). Material plot of a tantalum projectile penetrating an aluminum A-frame structure at 60° obliquity.