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SPH SIMULATIONS OF HYPERVELOCITY IMPACTS

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ABSTRACT

The smoothed particle hydrodynamics (SPH) method has been used to simulate several cases of hypervelocity impact in an exploratory study to determine the suitability of the method for such problems. The calculations compare favorably with experimental results and with other numerical simulations. We discuss the requirements that must be satisfied for SPH to produce accurate simulations of such problems.

I. INTRODUCTION

The SPH method is a three-dimensional free-Lagrange computational fluid dynamics algorithm that, in its most basic form, is truly grid-free. As a result, no computational effort is expended on mesh maintenance. SPH treats fluid elements as extended clouds of material whose centers of mass move according to the conservation laws of fluid dynamics. Methods similar to today's SPH were first described in 1977.^{1,2} Since then, a large number of papers describing developments of both the methodology and applications have been published. Recent introductory reviews of the SPH method present a selection of test problems that have analytic solutions or experimental data that can be compared to the numerical solutions.^{3,4}

The present study was undertaken to assess the suitability of SPH for the simulation of hypervelocity impacts. Previous studies^{3,4} suggest that SPH, used with proper care, can provide accurate solutions to flows with Mach number greater than about 0.1. In particular, SPH has several features that make it attractive for hypervelocity impact simulations. It handles voids without special programming or any computational work, it allows the use of arbitrary equations of state, and it

allows large fluid distortions and shear. Strength of materials may be included,⁵ although it has been neglected in the present study.

SPH was used to calculate several examples of hypervelocity impacts of projectiles on thin plates. Several different materials were used, and the three-dimensional capability of the method is demonstrated. A comparison between the SPH results and those from both other calculations and an experiment are presented.

II. GOVERNING EQUATIONS AND NUMERICAL METHOD

We assume that the flows we want to simulate are adequately described by the Euler equations. The Lagrangian momentum equation is

$$\rho \frac{d\vec{v}}{dt} = \rho \vec{g} - \nabla(P + q), \quad (1)$$

where ρ is the fluid density, $\vec{v}$ is the fluid velocity, $\vec{g}$ is the gravitational acceleration, P is the pressure, and q is an artificial viscous pressure. We choose to express energy conservation in terms of the specific internal energy I :

$$\rho \frac{dI}{dt} = -(P + q) \nabla \cdot \vec{v}. \quad (2)$$

The fluid is represented by N spherically symmetric particles each having a specified mass M_j that has been smoothed out in space with a density distribution given by an interpolating kernel $W(\vec{r} - \vec{r}_j, h)$, where $\vec{r}$ is an arbitrary point in space, $\vec{r}_j$ is the position vector of particle number j , and h is the smoothing length. The Euler equations are converted into a set of ordinary differential equations by multiplying them by W , integrating over all space, and approximating the integrals by integral interpolants for information at non-ordered points. The numerical algorithm reduces to an N -body problem with a special short-range force law that causes certain functionals of the particle data to approximate the solutions of the Euler equations. Mass, linear momentum, angular momentum, and energy are exactly conserved. The basic methodology is described by Monaghan.⁶ The particular implementation used in this study is described by Cloutman.^{3,4}

Mass conservation is insured by keeping the M_j 's fixed. Particle positions are evaluated from

$$\frac{d\vec{r}_j}{dt} = \vec{v}_j, \quad (4)$$

and Eq. (1) becomes

$$\frac{d\vec{v}_i}{dt} = -\vec{g}_i - \sum_k M_k \left\{ \frac{P_i}{\rho_i^2} + \frac{P_k}{\rho_k^2} + \frac{2}{(\rho_k + \rho_i)} [\beta \mu_{ik}^2 - \alpha \mu_{ik}(c_i + c_k)/2] \right\} \nabla_i W(|\vec{r}_i - \vec{r}_k|, h), \quad (5)$$

where $\alpha \approx 1$, $\beta \approx 2$, c_k is the sound speed in particle k , and

$$\mu_{ik} = \begin{cases} h(\vec{v}_i - \vec{v}_k) \cdot (\vec{r}_i - \vec{r}_k) / [(\vec{r}_i - \vec{r}_k)^2 + \eta^2] & \text{if } (\vec{v}_i - \vec{v}_k) \cdot (\vec{r}_i - \vec{r}_k) < 0 \\ 0 & \text{otherwise,} \end{cases} \quad (6)$$

where $\eta^2 \approx 0.01h^2$. The acceleration is the sum of three parts: gravity or other body forces, pressure gradients, and an artificial viscosity function. This form conserves both linear and angular momentum.

For the inviscid, nonconducting case, the smoothed internal-energy function I at each particle's location is calculated from an energy equation derived from Eq. (2):

$$\frac{dI_i}{dt} = \frac{1}{2} \sum_k M_k \left\{ \frac{P_k}{\rho_k^2} + \frac{P_i}{\rho_i^2} + \frac{2}{(\rho_i + \rho_k)} [\beta \mu_{ik}^2 - \alpha \mu_{ik}(c_i + c_k)/2] \right\} (\vec{v}_i - \vec{v}_k) \cdot \nabla_i W(|\vec{r}_i - \vec{r}_k|, h). \quad (7)$$

The SPH method allows the use of an arbitrary equation of state. In the present study, we use the parameters for the Tillotson equation of state given by Cunningham.⁷ Any other analytic or tabular equation of state could be used to provide pressure and temperature as functions of internal energy and density.

III. NUMERICAL RESULTS

Several cases of high speed impact of a projectile onto a disk were calculated with SPH. These were chosen to demonstrate various capabilities of the method, and to allow some comparisons with other programs and an experiment. All SPH calculations were done with the W_4 kernel with $h = 0.2$ cm unless otherwise noted. All initial temperatures are 300 K.

With SPH, care must be used in setting the initial conditions in problems containing steep gradients or discontinuities. The present calculations were initiated by picking random particle positions

within the target disk and the projectile. This produced localized random density fluctuations, and hence pressure fluctuations, that caused unrealistic dynamics. We avoided this problem by preconditioning the particle clouds by running 100 cycles of hydrodynamics, during which we reset the particle velocities to zero every 25 cycles, beginning with the first cycle. We then set the projectile velocities to the desired value, and the impact calculations proceeded without difficulty.

The first case is the hypervelocity impact of an iron ball into an iron disk (Fig. 1). This case is the same as shown in Fig. 19 of Ref. 3, but recalculated with a smaller time step to verify the accuracy of the time marching. It uses the Tillotson equation of state for iron.^{7,8} The target is a disk with a radius of 2.1 cm and a thickness of 0.6 cm. The target has a mass of 65.34 g divided equally among 1984 particles. The projectile has a mass of 2.37 g divided equally among 192 particles, and it impacts normal to the target with a speed of 6.0 km/s. This impact is too weak to vaporize the iron. This problem also was calculated with an explicit two-dimensional finite difference program, and that solution is shown in Fig. 2. The solid lines in the figure are boundaries between iron and air at a pressure of 8.6 mbar. The two calculations are in only fair agreement, which is not unexpected considering the different equations of state, different numerical methods, and relatively coarse resolution in both calculations. In both cases, the projectile punches a hole approximately 2.0 cm in diameter in the disk. The hole is not completely obvious in Fig. 1 because the plot shows a projection of all particles onto a plane, whereas the finite difference program plots a slice in the (r, z) plane through the axisymmetric solution. Although not clearly seen in the side views, a shock wave moves radially outward in the disk, away from the hole. SPH sends out a lump of iron approximately 2.0 cm to the right in 10 μ s, whereas the finite difference program predicts a distance closer to 3.5 cm. This lump contains the original projectile with a thin layer of target material on the leading edge. The most prominent disagreement between SPH and the finite difference solution is that a lip, or backsplash, should form on the left side of the target around the edge of the hole. It is weakly seen (if at all) in the SPH solution, but it is clearly present in the finite difference solution.

There are some negative pressures of unphysically large magnitude in the solution shown in Fig. 1, so the calculation was repeated with a crude model to represent fracture or cavitation in

the condensed phases: if the pressure for any particle was less than -10 kbar, the pressure was set to zero. The results are shown in Fig. 3. Now there is a prominent backsplash, and the hole diameter and propagation distance of the projectile and debris clouds agree much better with the finite difference solution. Comparison of these three solutions illustrates how easy it is to generate plausible but incorrect solutions. It is very important to run validation problems for which there is experimental data, a theoretical solution, or an independent numerical solution.

The next case is an iron projectile impacting a disk of limestone at 6.0 km/s. Except for the equation of state and the density of the target material, the setup is the same as for the previous problem. The results shown in Fig. 4 do not include the fracture model. The ejecta cloud is much different than that shown in Fig. 1, showing the large effect of changing the equation of state of the target from one material to another. The iron projectile is flattened, but otherwise intact, whereas the shocked limestone appears as a rapidly expanding vapor cloud. There may be a small backsplash.

Figure 5 shows three views at $7 \mu\text{s}$ of the same problem as in Fig. 4, except the initial velocity of the projectile has a speed of 2.0 km/s in the z -direction in addition to a speed of 6.0 km/s in the x -direction. This is a truly three-dimensional problem that cannot be handled by a two-dimensional program. The impact angle is sufficiently steep that the results are quite similar to the head-on case, including the nearly circular hole in the target. The projectile is intact but flattened, as before.

Figures 6 and 7 show the same problems as Figs. 4 and 5, but with the crude fracture model. The projectile has lost its cohesion, but the solutions are otherwise similar. Again, this example emphasizes the need for adequate validation studies.

Figure 8 shows the impact of a lead sphere onto a lead disk at 6.6 km/s. This impact is sufficiently energetic to vaporize some of the lead. The vapor from the projectile is in the middle of the ejecta cloud. This problem was also run with twice as many particles in both the projectile and target, and the particle plots show the same penetration, hole size, and backsplash as seen in Fig. 8.

In the final case, we increased the projectile mass to 20 g so comparison could be made to some earlier studies. The radius of the target was increased to 2.8 cm, and h was reduced to 0.159 cm.

The target contains 7777 particles of mass 23.7575 mg each, and the projectile contains 384 particles of mass 52.0833 mg each. The projectile speed is 6.6 km/s. This solution is shown in Fig. 9. The more massive projectile produces a larger ejecta cloud but with the same shape as before. This case has been calculated by Kidman and Benz⁹ using 10,400 particles. They report good agreement with experiment, including the lip on the left side of the target. They also demonstrated that the shape of the projectile is important, and they presented an off-axis impact. Holian and Holian¹⁰ and Holian and Burkett¹¹ show comparisons between Eulerian finite difference calculations and experimental data. They demonstrate the sensitivity of the numerical solutions to the equation of state. In particular, the Tillotson equation of state for lead is shown to produce a debris cloud that is too spherical because it produces too much pressure for lead vapor at a density of a few g/cm³. This effect is seen in the present calculations. Indeed, the Tillotson equation of state has also been criticized for being thermodynamically inconsistent under some conditions.^{11,12} The various programs used in all three studies produce qualitatively reasonable solutions, including the experimentally observed back splash.

IV. CONCLUSIONS

We conclude that SPH should be able to produce accuracy on the order of 10% or better in three-dimensional hypervelocity-impact simulations with calculations using on the order of a few thousand particles provided proper attention is given to using adequate constitutive relations. The ease with which voids are handled is an important feature of the method. The main disadvantage is that SPH solutions tend to be noisy and can have difficulty in matching the accuracy of finite difference methods unless an adequate number of particles is used. SPH is especially useful for exploratory studies where modest accuracy is acceptable. However, SPH may be the method of choice for problems that are difficult to solve by other methods. For example, colliding planetary bodies are difficult for finite difference methods, but this problem is treated naturally by SPH.^{8,12,13}

Although we have demonstrated that SPH is capable of simulating high speed impacts, there are several improvements that would improve the accuracy and efficiency beyond what we have obtained

with the program described in Refs. 3 and 4. First, we need an improved three-phase equation of state, such as the GRAY equation of state.¹⁴ Second, a variable h , such as that suggested by Hernquist and Katz¹⁵, is needed to allow simultaneous accurate simulations of solid and vapor phases such as we encountered in the lead impacts. Third, we need to incorporate a strength model such as that of Libersky and Petschek.⁵ At the very least we need to allow liquids and solids to fracture in tension. Fourth, a better initial particle position setup is needed to eliminate the preconditioning runs (for example, a lattice with a small random perturbation).¹⁶ Finally, the accuracy of SPH scales approximately as $(\ln N)^3/N$,¹⁷ which is slightly better than a second-order finite difference method, which scales as $N^{-2/3}$. The operation count per time step of a typical finite difference method scales as N , and algorithms for making SPH scale as $N \log N$ or better must be used if calculations using more than a few thousand particles are to be practical and competitive with finite differences. This can be done with link lists or tree algorithms.^{15,16} The technique of Rhoades¹⁸ also looks promising.

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Fig. 1. Side view of a disk of iron impacted by an iron sphere. The frames are particle cloud plots at $t = 0.0, 3.0, 7.0$, and $10.0 \mu\text{s}$.

Fig. 2. Side view of a disk of iron impacted by an iron cylinder. The solution uses a two-dimensional explicit finite difference method. The frames are at $t = 0.0, 3.0, 7.0,$ and $10.0 \mu s$.

Fig. 3. The same calculation as shown in Fig. 1, except for the inclusion of the fracture model.

Fig. 4. Side view of a disk of limestone impacted by an iron sphere. The frames are at $t = 0.0, 3.0, 7.0$, and $10.0 \mu s$.

Fig. 5. Three views at $7.0 \mu\text{s}$ of a disk of limestone undergoing an off-axis impact by an iron sphere. The initial projectile velocity was $(6.0, 0.0, 2.0) \text{ km/s}$.

Fig. 6. The same calculation as shown in Fig. 4, except for the inclusion of the fracture model.

Fig. 7. The same calculation as shown in Fig. 5, except for the inclusion of the fracture model.

Fig. 8. Side view of a disk of lead undergoing an on-axis impact by a lead sphere. The frames are at $t = 0.0, 3.0, 7.0$, and $10.0 \mu s$.

Fig. 9. Side view of a disk of lead undergoing an on-axis impact by a 20 g lead sphere. The frames are at $t = 0.0, 3.0, 7.0, 10.0$, and $15.0 \mu s$.

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