

HYPERVELOCITY IMPACT SIMULATIONS OF WHIPPLE SHIELDS

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ABSTRACT

The problem associated with protecting space vehicles from space debris impact is described. Numerical simulation is espoused as a useful complement to experimentation: as a means to help understand and describe the hypervelocity impact phenomena. The capabilities of a PC-based hydrocode, **Zeus**, are described, for application to the problem of hypervelocity impact. Finally, results of **Zeus** simulations, as applied to the problem of bumper shield impact, are presented and compared with experimental results.

INTRODUCTION

The effects of hypervelocity impact have been a topic of interest for as long as satellites have orbited the earth. The continued need to protect orbiting vehicles from impact by low mass, high velocity, particulate debris serves as the driving force for much of the ongoing study.

Space debris originates primarily from two sources. First, there is cometary meteoroid material, consisting mostly of loosely packed ice with a density of approximately 0.5 g/cm^3 .¹ Though not dense, such debris may impact with velocities of tens of kilometers per second. The second prevalent source of space debris consists of orbital debris fragments originating from man-made devices such as satellites and rockets. Such debris, typically aluminum, may range in size from sub-centimeter to satellite size. Smaller fragments are, by far, the most prevalent in number and, in this regard, pose the greatest threat of impact to orbiting bodies.

The desire to protect space vehicles from such debris spurred the invention of the bumper shield by Whipple.² The Whipple shield is a sacrificial plate, whose purpose it is to cause disintegration of the impacting fragment, and in so doing, to distribute the energy of hypervelocity impact over an area large enough to be absorbed by the space vehicle structure, without perforation. Whipple shields continue to serve as a primary means of protection and, as such, a great deal of effort continues to be directed to their study. A sample of studies, presented at the recent AIAA Space Programs and Technologies Conference (24-27 March, 1992/Huntsville, Alabama), may be examined to reveal the focus of current efforts in bumper shield technology. At this conference, experimental bumper shield work focused on novel materials^{3,4,5,6}, measurement techniques⁷ and parametric variations of

experimental parameters like impact velocity⁸ and bumper thickness⁹. Analytical efforts covered the spectrum of empirical^{10,11}, semi-empirical¹², probabilistic^{13,14}, system vulnerability modeling^{15,16} and numerical simulation¹⁷.

NUMERICAL MODELING TOOLS

The paucity of numerical simulation work on the subject speaks to the inherent difficulty in simulating bumper shield effects with computational tools. The extremely harsh pressure and failure environments of hypervelocity impact dictate the need for specialized computational tools, in order to effectively address the problem. The more commonly familiar structural analysis codes, which are geared for computing a global structural response to a distributed or point load, are simply not suitable for handling hypervelocity deformation, where inertia and stress induced failure are primary governing principles. Specially formulated hydrocodes (a.k.a. wave propagation codes) are designed to model high strain, large strain rate deformations and are thus better suited to address the hypervelocity impact problem.

However, the hypervelocity bumper shield problem, specifically, puts added burdens upon hydrocodes. In particular, the bumper shield problem differs from many other high strain rate problems in that physical material separation occurs violently, in tension, and it is the post-failure behavior of the materials which is of the the greatest interest to the bumper shield researcher.

Eulerian hydrocodes, which function by tracking the flow of materials through a mesh that is fixed in space, often perform poorly at resolving the low density, expanding, debris cloud which results from a bumper impact. The natural tendency of Eulerian material transport algorithms to numerically diffuse material through the grid, in an unrealistic manner, especially when material volume fractions are small, can inhibit effective modeling of debris clouds. More accurate (second order) Eulerian techniques have been introduced in recent years which greatly improve the ability of these codes to track material transport like that found in debris clouds. However, only through the use of computationally expensive, very finely resolved, grids have Eulerian codes begun to approach qualitative agreement on the bumper shield problem.^{18,19}

In addition to the challenges faced by many Eulerian codes in modeling diffusive transport, the algorithms employed by Eulerian codes, which are used to converge the equations of state, when multiple materials coexist within a single computational cell, may also experience difficulties, when the mass fraction of single material constituent becomes very small. Unfortunately, the debris cloud problem is one which virtually guarantees the existence of small mass fractions within so-called "mixed" cells. In some codes like HULL²⁰, difficulties in equation of state convergence are addressed by essentially sweeping away materials with small volume fractions (and replacing them with air) when equation of state convergence becomes a problem. This technique has been rather appropriately, though unofficially, dubbed Alchemy.

Though Alchemy has the beneficial effect of promoting rapid equation of state convergence, it may, in the case of a debris cloud problem, have the net result of dissipating a debris cloud to the point of non-existence.

Lagrangian hydrocodes, which function by having the numerical grid fixed, not to the laboratory, but to the deforming material, may also experience difficulties in modeling a bumper shield debris cloud. Without advanced techniques like rezoning or erosion, a Lagrangian code is unable to handle even the simpler problem of perforation. Even with rezoning capabilities, the physical material separation, which characterizes bumper impacts, can not be modeled. Lagrangian mesh erosion techniques, on the other hand, can provide a tool which offers the potential of describing, more accurately, the formation and expansion of a hypervelocity debris cloud.

The **Zeus** code is a PC-based, 2-D, explicit integration, Lagrangian hydrocode which has been employed in the present study, to model the effects of hypervelocity impact of aluminum spheres upon thin aluminum Whipple shields. Designed to simulate impact over a wide range of velocities²¹, **Zeus** has also had success at simulating hypervelocity events^{22,23}. The code makes use of the PC's extended memory so that it may, on a computer having 8MB of extended memory, simulate a problem with 28000 nodes and 56000 elements. Interactive pre- and post-processing modules are a standard part of the **Zeus** package.

Zeus employs constant strain triangular elements, in either axisymmetric or plane strain modes of computation. The Mie-Grüneisen is the standard equation of state provided, though a user definable material option exists, which allows the user to program any desired material model, using the FORTRAN computer language.

A sophisticated contact/erosion processor is employed by **Zeus**, which allows the computational meshes of many objects to interact simultaneously, by way of contact. Additionally, the contact/erosion processor permits the erosion of computational elements. Lagrangian mesh "erosion" serves two purposes in the calculation. First, it is a numerical technique designed to permit Lagrangian simulations to proceed when excessive mesh distortion would otherwise make the simulation uneconomical and eventually inaccurate. Secondly, erosion may be used to simulate physical material separation in problems where such phenomena occur.

When some suitable set of erosion criteria are satisfied by a Lagrangian computational cell, that particular cell is removed from the intact grid by the erosion processor. The new mesh topology of the remaining grid must be recomputed. The material in the eroded cell is ideally converted into a free-flying mass point, which is then capable of interacting with remaining Lagrangian grids, by way of the contact processor, and in more sophisticated treatments, with other free flying mass points.

The criterion on which to base mesh erosion is generally related

to some measure of material deformation. **Zeus** employs several erosion criteria. One such metric is equivalent plastic strain, which is a measure of distortional deformation. Another is the volumetric strain, given by

$$\epsilon_v = \frac{V - V_o}{V_o}$$

where V is the cell volume and V_o is the cell's original volume. The volumetric strain provides a measure of dilatational deformation, and is the primary operative erosion criterion when simulating the formation of a bumper shield debris cloud. These numerical erosion criteria are roughly based upon the mechanical properties governing physical material separation. Generally, a fairly wide range of values may be successfully employed for these criteria. Solution convergence and/or stability problems may arise however, if these parameters are set either excessively small or large.

On one hand, if material erosion is premature, fundamental flow patterns in the intact, deforming, Lagrangian mesh may not have had the chance to adequately establish themselves. This condition does not usually affect the numerical stability of the simulation; however the accuracy may suffer severely, with the likely result being an unrealistic simulation of deformation.

The other extreme occurs when the material erosion criteria are set to excessively large values, or disabled altogether. In this case, the imposed topology of the connected, Lagrangian grid becomes an obstacle to any large strain fields seeking to establish themselves. A section of the Lagrangian grid, in the region of large strain, will likely produce elements with large aspect ratios, in an attempt to conform to the developing strain field, while simultaneously obeying the constraints of the connected mesh topology. These high aspect-ratio elements become increasingly "stiff", in that their ability to deform fluidly becomes severely curtailed. As a result, their motive degrees of freedom become effectively reduced. Furthermore, the fixed mesh topology "encourages" other cells, in the vicinity of these high aspect-ratio elements, to also acquire the unrealistic aspects and associated stiffnesses. When this hyperdistortional condition occurs, the Lagrangian mesh is said to have "locked up", because the condition, once established, is unlikely to rectify itself. Locked-up grids will certainly produce inaccurate results, but also run the risk of becoming numerically unstable. Fortunately, the judicious use of Lagrangian mesh erosion can usually preclude the onset of grid lockup. It is in this sense that Lagrangian mesh erosion is also a "numerical" technique, in addition to its use as a "physical" technique for simulating the material separation phenomenon.

Prior to the time that erosion of a computational cell might occur, **Zeus** permits the activation of material property degradation, in the form of shear/tensile failure. Such degradation of properties is intended to address the possibility of material fracture and

rubblization. When such conditions occur, the materials effectively become fluid-like, in that only compressive forces may be resisted; shear and tensile resistance become negligible.

SIMULATIONS

For this paper, a series of experiments by Piekutowski⁹ are computationally examined with the **Zeus** code. In his experiments, Piekutowski examines the effect of aluminum bumper thickness upon the debris cloud formed by the nominal 6.7 km/s impact of a 1.275-g, 9.53-mm diameter, aluminum sphere. The ratios of target thickness to projectile diameter (t/D) ranged from 0.026 to 0.424. Over this range of bumper thicknesses, Piekutowski notes⁹

an orderly change in debris cloud morphology... For cases where the bumper was overmatched, i.e., the projectile did not breakup completely, a large single fragment of projectile remained at the center of the debris cloud. When the projectile was overmatched, numerous large bumper fragments were distributed throughout the bubble of bumper debris.

In support of his thesis, Piekutowski presents an excellent collection of radiographic records of bumper perforation events. Of particular interest in the current study, in addition to the computed debris cloud geometries, are the residual debris cloud velocity, the radial expansion velocity of the projectile portion of the debris cloud, and the debris particle size, for which Piekutowski provides experimental data points.

Both the projectile and the bumper were modeled with a maximum tensile pressure of 10 kbar. The volumetric strain, ϵ_v , over which this tensile pressure may exert itself, was 0.21, beyond which, material separation was permitted to occur. For those computational cells which did not fail as a result of volumetric expansion, an equivalent plastic strain erosion criterion of 150% strain was also retained. However, degradation in the flow stress began at an equivalent plastic strain of 60%, and continued up to the erosion strain. All of the simulations to be discussed employed a modest number of elements, ranging from 2328 to 4064 elements.

Though thirteen experiments are reported by Piekutowski, a subset of those were chosen for simulation. Two simulations were performed in the lower ranges of t/D (bumper thickness to projectile diameter ratios), namely 0.026 and 0.049 and two at higher t/D values: 0.163 and 0.234. The progressions of these simulations are shown in Figs. 1 through 4. The computational results are tabulated in Table 1, along with their experimental counterparts. For each case studied, the normalized residual velocity (V_r/V_o) and radial expansion velocity of the projectile debris cloud (V_r/V_o) are given. Furthermore, the equivalent diameter, d_r , of the largest residual debris fragment is noted (d_r is the cube root of the product of the three fragment dimensions, $(HLT)^{1/3}$). The actual impact velocity for each case is specifically noted and the computational (CPU) time required to bring the simulations to 18 microseconds is given as well. The CPU times increased substantially

for the thicker bumpers, because of the increased cost associated with computing the interaction between free flying masses, the task of which reduces to an N-body problem (with $N(N-1)/2$ pairs of interacting free-flying nodes).

TABLE 1. SUMMARY OF COMPUTATIONAL RESULTS

t/D	V ₀ km/s	Experiment			Computation			
		V _r /V ₀	V _r /V ₀ *	d _r mm	V _r /V ₀	V _r /V ₀	d _r mm	CPU** hr
0.026	6.70	0.986	0.058	5.49	0.979	0.034 [†]	8.78	2.48
0.049	6.62	0.977	0.104	2.95	0.970	0.104	8.20	3.44
0.163	6.71	0.928	0.284	1.09	0.915	0.292	1.88	9.00
0.234	6.64	0.894	0.259	0.64	0.891	0.316	1.59	9.56

*As measured from graph of Piekutowski⁹
 **Running on a 25 MHz 80486 PC.
 †Varied widely with location; ranged from 0.016 to 0.055.

The behavior of these debris clouds follows that described by Piekutowski in several important ways. For the thin bumper problem, a fragment shell is spalled off from the rear of the impacting sphere. Also, both experiment and simulation indicate that a large single fragment remains intact (Fig. 1). For thicker bumpers (Figs. 3 and 4), the projectile debris cloud becomes more evenly dispersed, since more of the projectile is fragmented as a result of the longer-duration, initial tensile rarefaction.

Fig. 2 also shows a direct comparison between a **Zeus** simulation for t/D of 0.049 and a Piekutowski radiograph. A qualitative similarity exists in the projectile debris cloud shape and position. The simulation however, does indicate a leading target debris cloud which is more dispersed in space, when compared with the radiograph. Additionally, the leading edge of the computed projectile debris appears less like a homogenous cloud, as indicated by the experiment, but instead, more akin to a large fragment. This discrepancy in the debris particle size may be confirmed by comparing the computed equivalent particle diameter with the experimental data, in Table 1. The reasons for this discrepancy are twofold: first, there is not enough resolution in the computational grid to adequately resolve smaller fragment sizes; secondly, the material failure models available to a code like **Zeus** are likely insufficient to capture the fine details of the fragmentation process. It is probably for this latter reason that the largest computed central fragments are larger than those measured by Piekutowski.

For larger bumper thicknesses (Figs. 3 and 4), the front of the debris cloud becomes more rounded in shape. The debris is expanding radially with a larger velocity. Also, more of the mass is concentrated along the leading edge of the debris cloud. These simulations did not seem to suffer from the dispersion noted for thinner bumpers.

SUMMARY

The feasibility of using a Lagrangian wave propagation code as an analysis tool in Whipple shield design studies was investigated. Specifically, the morphology of debris cloud formation was studied with the PC based, **Zeus** hydrocode. The numerical simulations indicate a qualitative similarity to the images portrayed in radiographs of experiments by Piekutowski⁹. Because of inadequate resolution and simplistic failure models, however, debris is less homogenous and debris particle size is predicted to be larger than the experiments suggest. Nonetheless, the debris cloud residual velocity, as well as the radial expansion velocity of the fragmenting projectile compared favorably with the cited study.

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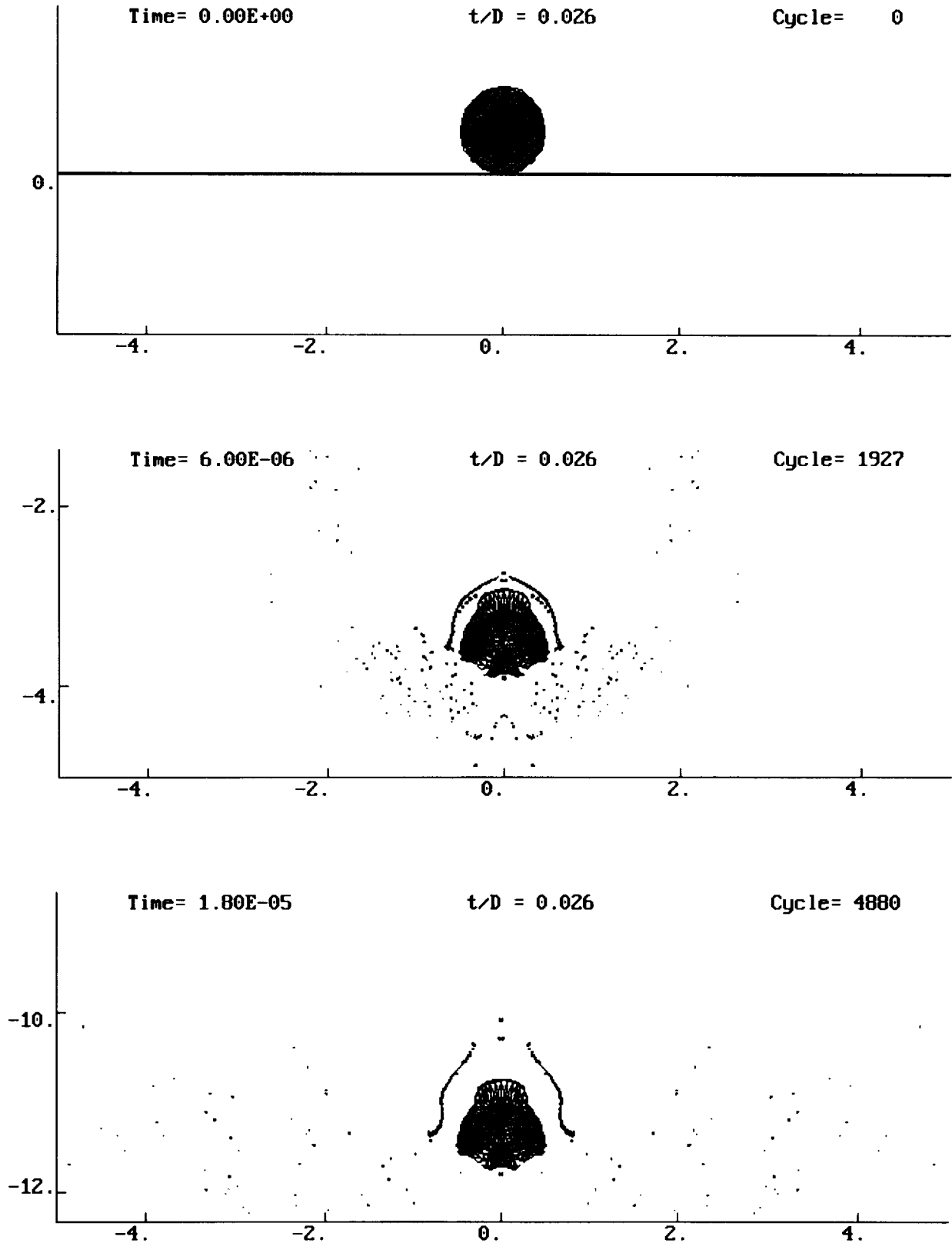


Fig. 1. Simulation of 1.275-g, 9.53-mm diameter aluminum sphere, impacting at 6.70 km/s upon aluminum bumper, $t/D = 0.026$.

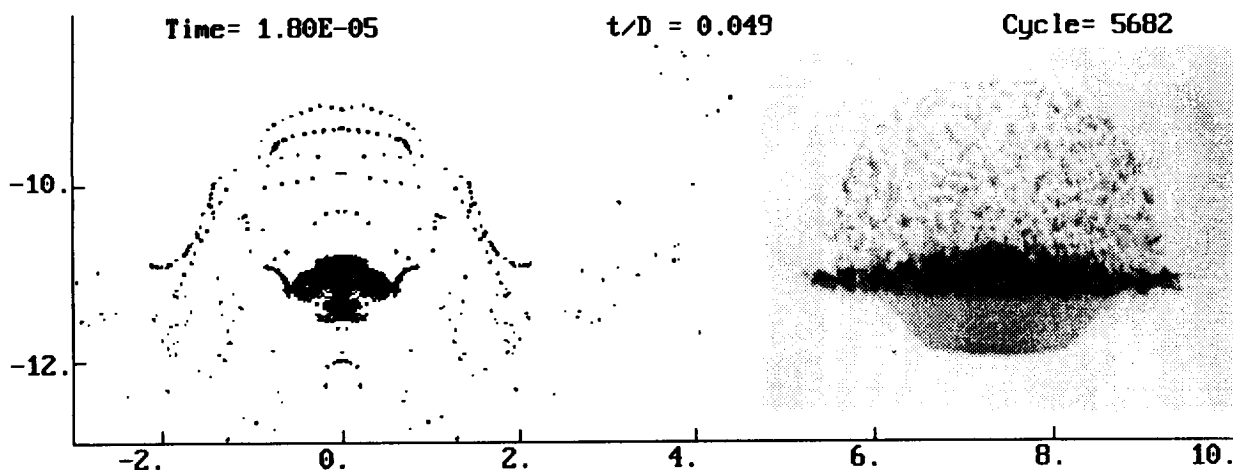
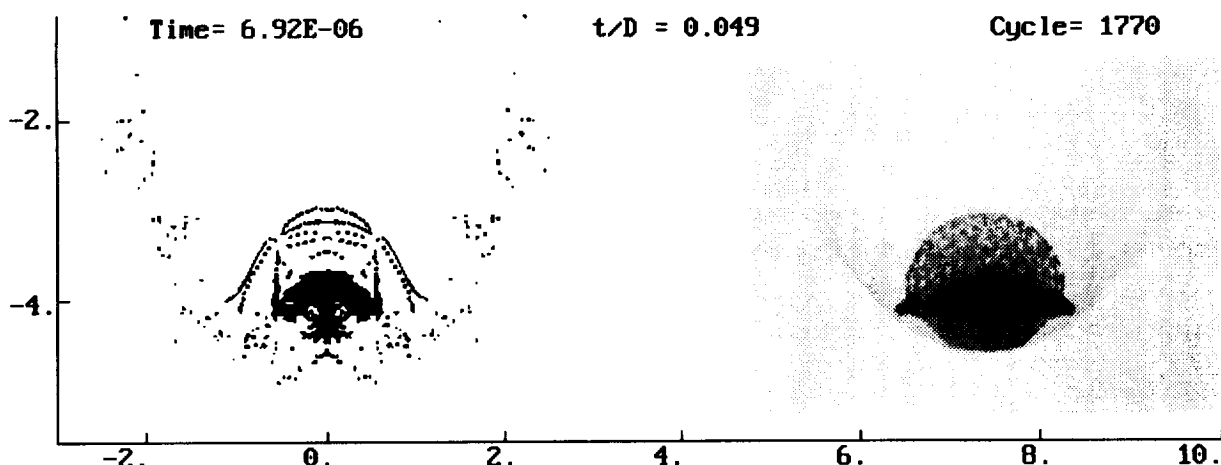
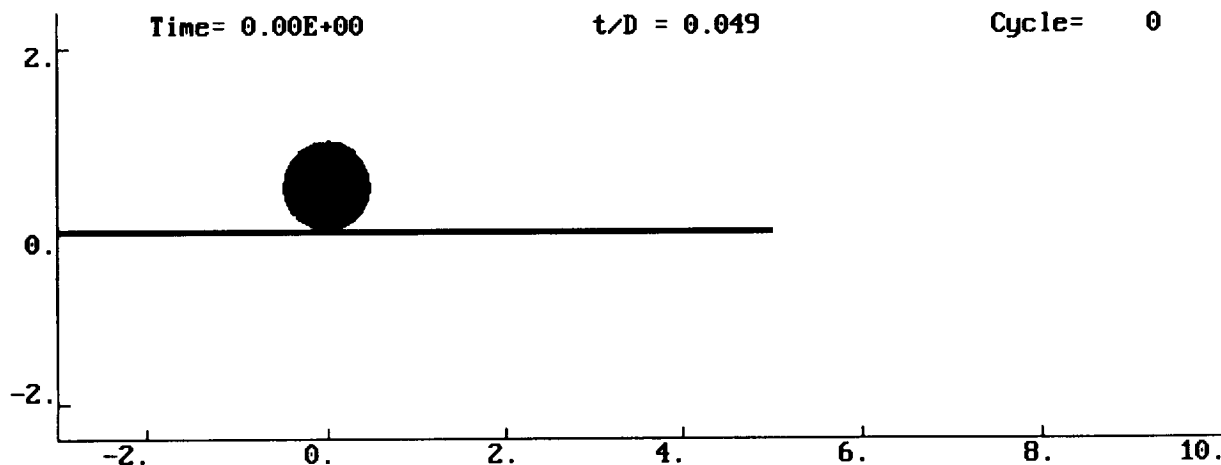


Fig. 2. Simulation and experiment of aluminum sphere impacting aluminum bumper, $t/D = 0.049$ (Photos courtesy of A.J. Piekutowski).

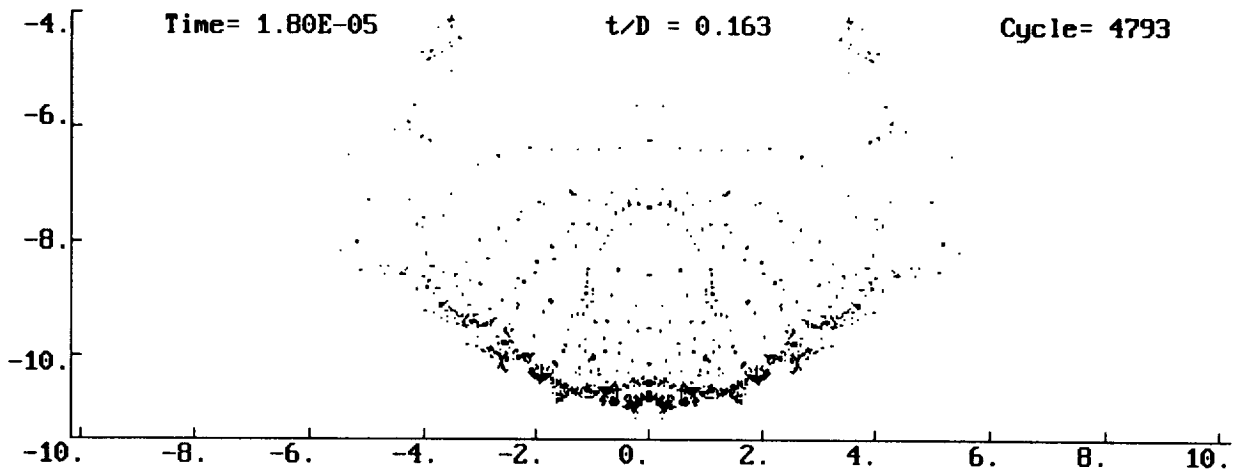
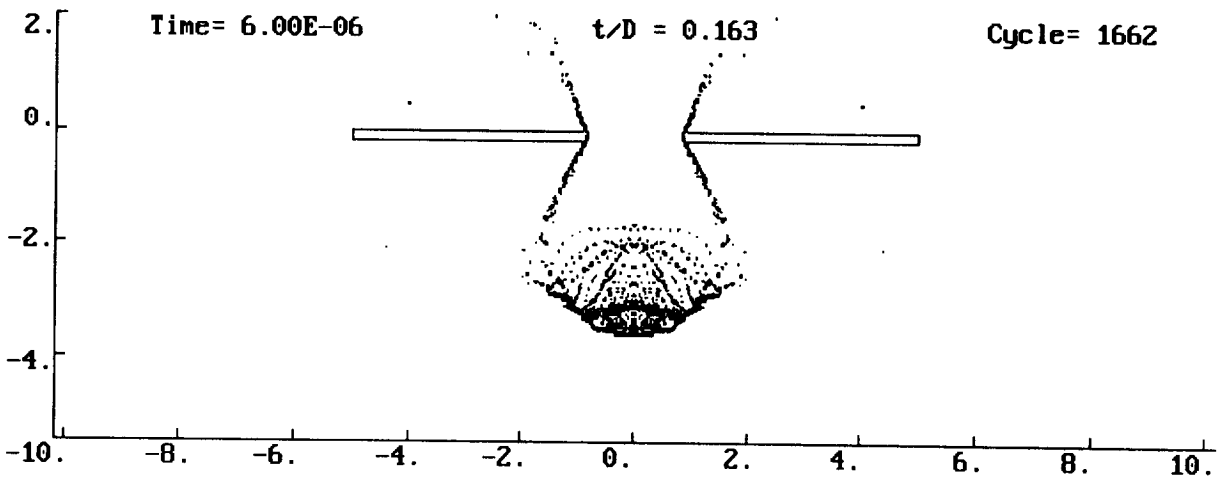
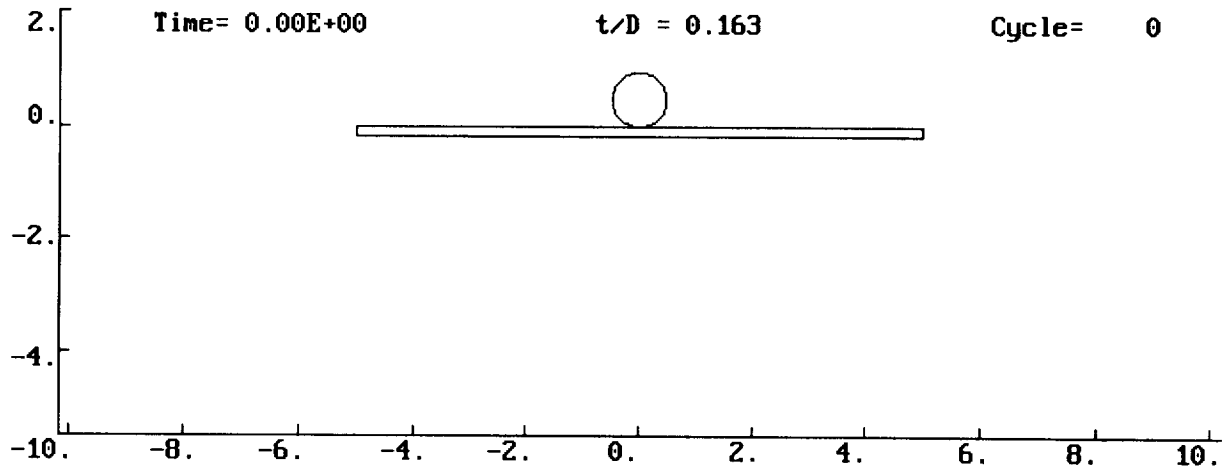


Fig. 3. Simulation of 1.275-g, 9.53-mm diameter aluminum sphere, impacting at 6.71 km/s upon aluminum bumper, $t/D = 0.163$.

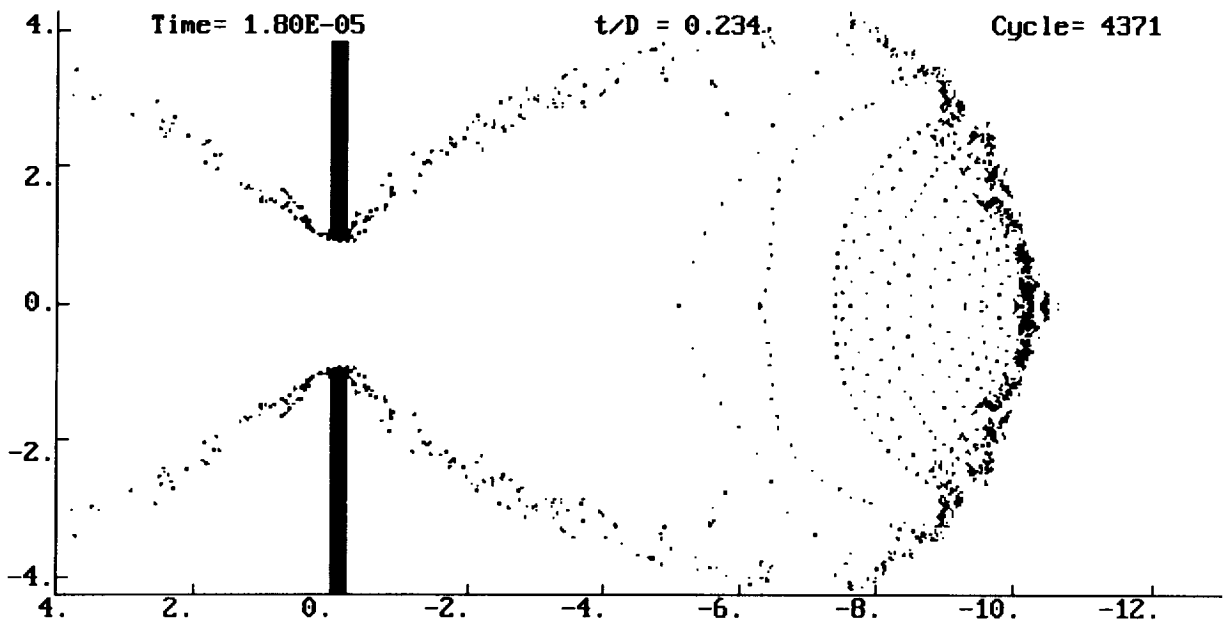
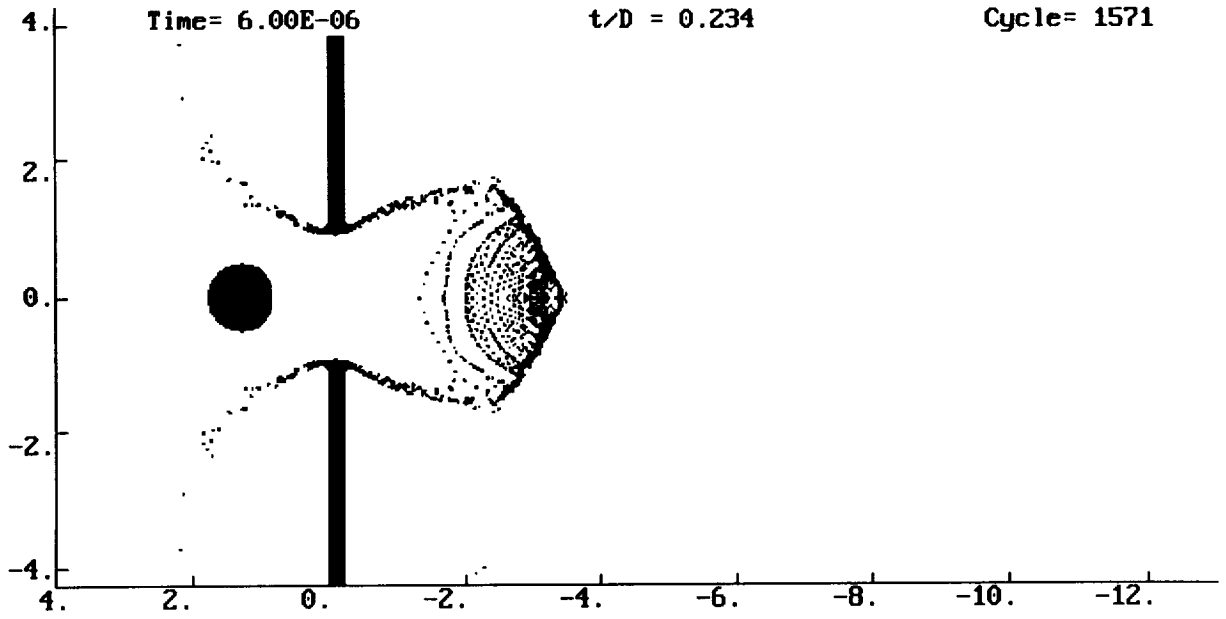


Fig. 4. Simulation of 1.275-g, 9.53-mm diameter aluminum sphere, impacting at 6.64 km/s upon aluminum bumper, $t/D = 0.234$.

