Hydrocode Analysis at APL

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An overview of hydrocode analysis at the Applied Physics Laboratory is presented. Starting with an Independent Research and Development project that simulated a high-velocity impact test of a full missile, the Laboratory developed a damage-scoring method for hydrocode simulations of missile impacts that opened the possibilities for a number of other applications. Applications of hydrocode analyses at the Laboratory included a study of directed energy explosives warheads against fighter aircraft and Standard Missile-3 impacts against target missiles. A practical methodology for lethality assessment of a missile system on a workstation using hydrocodes and probabilistic methods is being investigated. Other possible applications of hydrocodes are discussed, such as evaluation of rain erosion of missile radomes and flight test range safety.

(Keywords: High-velocity impact, Hydrocode, Lethality, Missile, Physics-based tools, Workstation.)

INTRODUCTION

APL has traditionally been involved in all aspects of science and engineering of missile systems to deliver a missile to its target. At that point—the final engagement—organizations such as the Naval Surface Warfare Center in Dahlgren, Virginia, perform the science and engineering to predict weapons' effectiveness or lethality. With the end of the Cold War and the lessons learned from the Persian Gulf War, attention has shifted to defense against tactical ballistic missiles. For example, theater missile defense systems currently in development, such as the Navy's Standard Missile-3 (SM-3) Aegis Lightweight Exoatmospheric Projectile (LEAP) interceptor and the SM-2 Block IVA, as well as the Army's Theater High-Altitude Area Defense and Patriot Advanced Capability-3, all use the kinetic energy of high-velocity impact (>1.5 km/s) rather than explosives energy for their damage mechanism.[1] Until recently, APL did not have the detailed physics-based tools such

as hydrocodes to evaluate these high-velocity missile impacts. The successful development of a three-dimensional hydrocode analysis capability at APL for these and other applications is discussed in this article.

Hydrocodes are finite-difference and finite-element computer programs that model the response of materials to very short duration loading.[2] A more accurate descriptor is shock wave physics code, but the popular term hydrocode (an abridgment of the term hydrodynamics code) has endured. It alludes to the fluid-like behavior of solid materials at striking velocities much greater than the materials' local sound speed. Analytically, equations of motion and high-pressure equations of state are the key descriptors of material behavior. While early codes modeled only hydrodynamic effects and neglected material effects, current hydrocodes include material effects such as modulus, strength, and fracture.

HISTORICAL HIGHLIGHTS AT APL

Interest in hydrocode analysis at APL began in 1992 with the acquisition of a hydrocode called CTH from the Sandia National Laboratories. No significant program funding was available to support the code's implementation, so activity in that area remained at a very low level for the next few years. One current method of evaluating missile system lethality is with a fast-running engineering code such as the Parametric Endo- and Exoatmospheric Lethality Simulation (PEELS), which is not a hydrocode. Researchers have become interested in making physics-based hydrocodes (which are computer-intensive) more practical tools for lethality assessment by increasing their execution speed and improving evaluation of their results. An opportunity to develop a hydrocode analysis capability at APL and eventually to contribute toward these goals was provided by Independent Research and Development (IR&D) funding in Fiscal Year 1996, using the SPHINX hydrocode from the Los Alamos National Laboratory.[3] The objective of the 1996 IR&D project entitled "Investigation of Lethality of Warhead Fragments" was to take the results of a test of missile warhead fragments fired out of a light gas gun against a replica of a target missile carrying a chemical (fluid-filled) submunitions payload, simulate the test with the SPHINX hydrocode, and compare the hydrocode simulation with the test results. The IR&D project was successful in that the number of damaged submunitions predicted by the SPHINX hydrocode simulation agreed with test results to within 7%. Development of a failure criterion for submunitions from a hydrocode simulation has been a priority for the lethality community. Working independently and using the results of the IR&D hydrocode simulation, we developed a method of scoring damage for submunitions that agreed with test results to within 3%. The method uses a failure criterion based on the pressure levels in the fluid fill, the location within the fluid fill, and the time of occurrence.

After the IR&D task was finished, a study of the effectiveness of directed energy explosives warheads for an air-to-air missile (AAM) and simulations of the SM-3 Aegis LEAP interceptor were conducted with hydrocodes.

HYDROCODE ANALYSES

Air-to-Air Missile Study

Our task was to explore directed energy explosives for the warhead of the AAM to determine if lethality could be increased while reducing warhead weight and length, thereby allowing more propellant to be carried. The baseline AAM warhead is cylindrically shaped. It is an isotropic, or roll-symmetric, fragmenting warhead that explodes and expels warhead fragments over 360° in azimuth. In contrast, a directed energy explosives warhead concentrates a large fraction of its warhead fragments in the target azimuth direction. We developed a strategy to perform the task using hydrocode analysis. Since we did not have hydrocode vulnerability models for internal components of fighter aircraft, we used what we did have—vulnerability models of fluid-filled steel submunitions developed for the damage-scoring methods described previously. This is the first time that such an approach has been used in this program.

The first hydrocode analysis phase was to determine the best possible performance that each warhead could deliver. This was done at a close-in miss distance of 1 m against an arbitrary fuselage-like section with internal components consisting of two tiers of submunitions, each in turn consisting of an inner and an outer ring of submunitions. The hydrocode results for the baseline warhead are shown in Fig. 1, and the damage-scoring method indicated 10 out of 60 submunitions
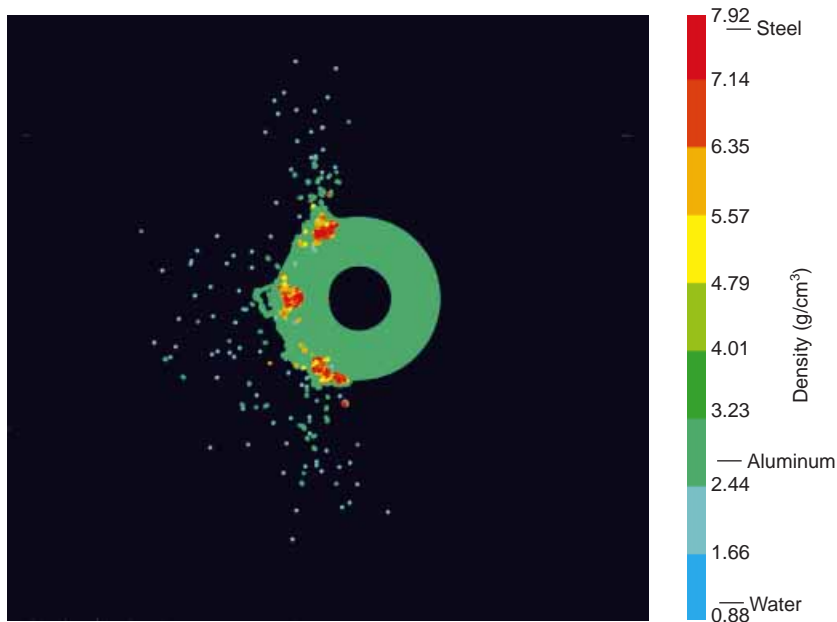

Figure 1. Hydrocode simulation of baseline air-to-air missile warhead fragments impacting a generic fuselage target. The target has 60 submunitions.

damaged. The hydrocode results for the directed energy warhead are shown in Fig. 2, and the damage-scoring method indicated 13 out of 60 submunitions damaged. Neither warhead damaged any submunitions in the inner ring. It is only valid to compare these results to each other, since the submunition vulnerability models do not represent any actual aircraft internal components.

An overview of the next phase of the analysis follows. The approach was to use the warhead construction and geometric ray-tracing to determine the fragment lay-down pattern on a generic wing target from various miss distances for both the baseline warhead and the directed energy explosives warhead. For each warhead, each hitpoint on the wing from a fragment was modeled individually to determine the amount of damage that the fragment caused. Then total numerical damage caused by each of the warheads was plotted against miss distance to compare their relative effectiveness.

The fragment lay-down patterns on a generic wing for both warheads at various arbitrary miss distances are shown in Fig. 3. An orthogonal view for the baseline warhead is shown in Fig. 4, showing the fragment hitpoints and strike angles. A typical hitpoint at time $t = 0$ is shown in Fig. 5. The target is composed of an aluminum plate, representing the aircraft skin, and three fluid-filled submunitions in back, representing internal components. The targets are placed such that the velocity vector of the incoming fragment

intersects the centroid of the fluid in the middle submunition. Three submunitions at each hitpoint are used to allow for a larger potential damage area.

Figure 6 shows the hydrocode results at the three separate hitpoints for the baseline warhead at a miss distance of 11 m, at times $t = 200$, 300, and 400 μs. Based on the scoring method, three of the fluid-filled submunitions were damaged at each hitpoint, for a total of nine damaged for each row of fragments. The hydrocode simulation of each hitpoint used 50,000 particles and ran in 1.4 central processing unit (cpu) hours on the Digital Equipment Corporation (DEC) Alphastation 500/500-MHz workstation. The wall clock time was slightly longer than the cpu time since the cpu utilization was just under 100%.

The hydrocode results at the 12 hitpoints for the directed energy warhead at a miss distance of 11 m are shown in Fig. 7, all at time $t = 300$ μs. Based on the scoring method, one of the fluid-filled submunitions was damaged at each of the hitpoints except for the last two, where two submunitions were damaged, totaling 14 damaged submunitions for each row of fragments.

From the information given in Figs. 3, 6, and 7, Fig. 8 shows the numerical damages caused by the baseline warhead and the directed energy explosives warhead on the generic wing plotted against the miss distance. The directed energy explosives warhead either causes more damage than the baseline warhead at the same miss distance or it causes the same damage at a greater miss distance. The directed energy explosives warhead that was studied was shorter and lighter than the baseline warhead. Whereas it is valid to compare these results to each other, the relationships of the targets used with real-world aircraft are unknown. Also, these curves of damage against miss distance are not the missile lethality, which is defined as the probability of causing a specified level of damage to a target to prevent a specified level of its performance. To close these gaps, the method presented here must be used with more representative vulnerability models, and guidance, target-detecting, and fuzing considerations must be incorporated.

SM-3 Targets

The SM-3 strategy to provide a Navy theater-wide defense of littoral and inland assets against tactical ballistic missiles builds upon
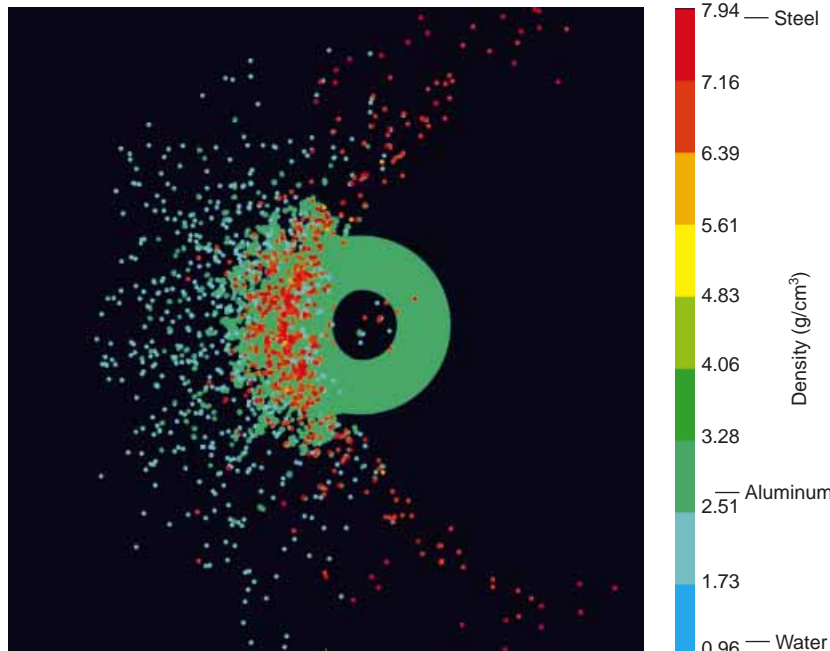

Figure 2. Hydrocode simulation of directed energy explosives warhead fragments impacting a generic fuselage target. The target has 60 submunitions.

Density (g/cm^3) scale: 7.94 — Steel, 7.16, 6.39, 5.61, 4.83, 4.06, 3.28, 2.51 — Aluminum, 1.73, 0.96 — Water

□ Directed energy explosives warhead fragment
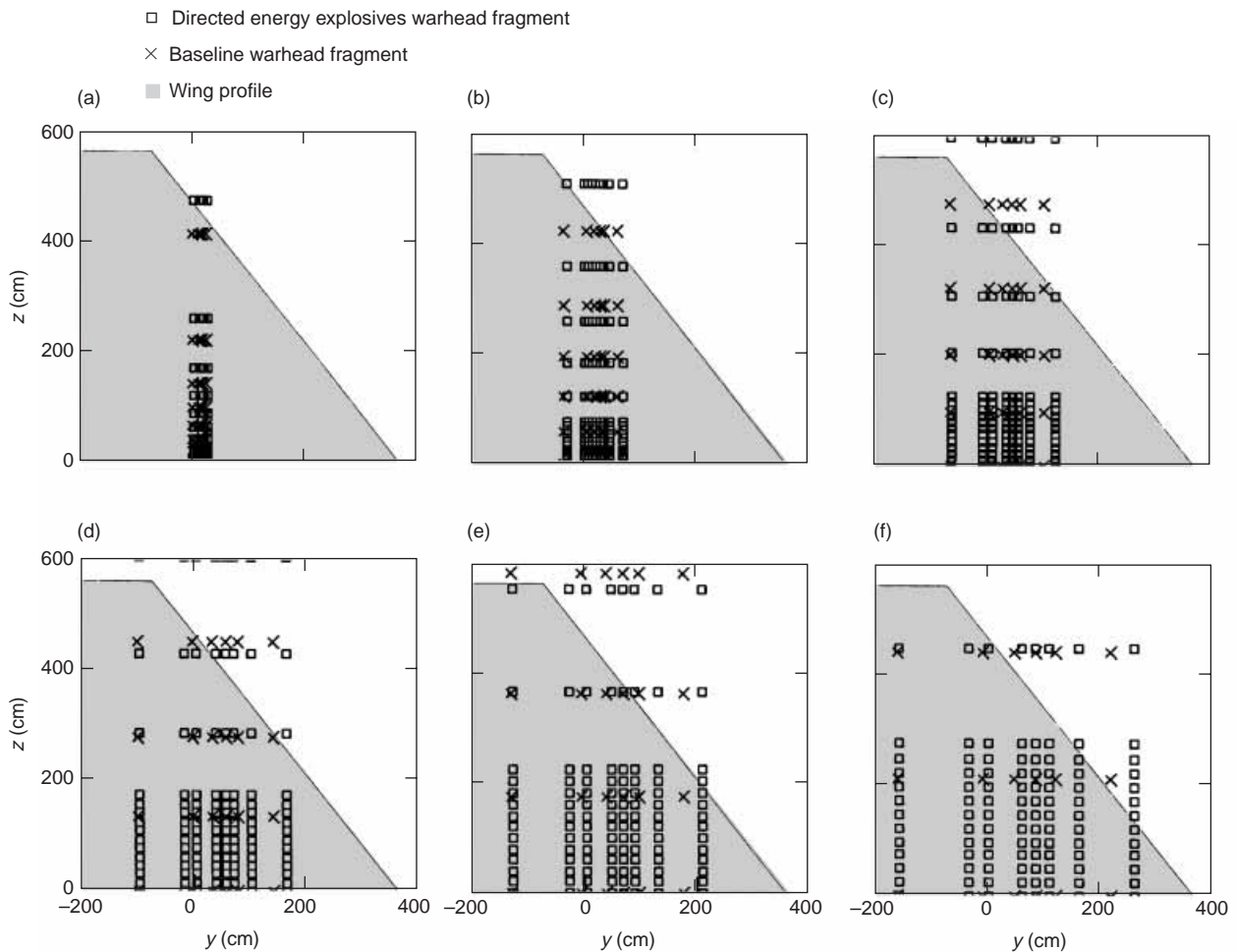× Baseline warhead fragment
▪ Wing profile

Figure 3. Lay-down patterns of warhead fragments on a generic wing target at miss distances of (a) 1 m, (b) 3 m, (c) 5 m, (d) 7 m, (e) 9 m, and (f) 11 m.

the long pedigree of the Standard Missile family and existing infrastructure such as Aegis ships and the Vertical Launching System. Using the same booster and dual-thrust rocket motor as the SM-2 Block IVA, the SM-3 adds a third-stage rocket motor and a

kinetic warhead (KW). A hydrocode simulation of a hypothetical intercept of an Aries rocket target by the KW at time $t = 0$ is shown in Fig. 9. Hydrocode analysis can help determine the effectiveness of the SM-3 KW against various targets.

Several nations, including Iran and North Korea, have offensive chemical warfare capabilities or military doctrine for attacking naval targets with chemical agents. For example, North Korea has an advanced chemical warfare capability and several hundred Scud missiles.[4] The Scud B missile can reportedly carry 555 kg of the viscous persistent nerve agent VX, which is dispersed into a dense aerosol cloud by detonating a high explosive charge.[5] The Scud B has a launch mass of 6370 kg, a length of 11.16 m, a body diameter of 0.88 m, and a range of 300 km.
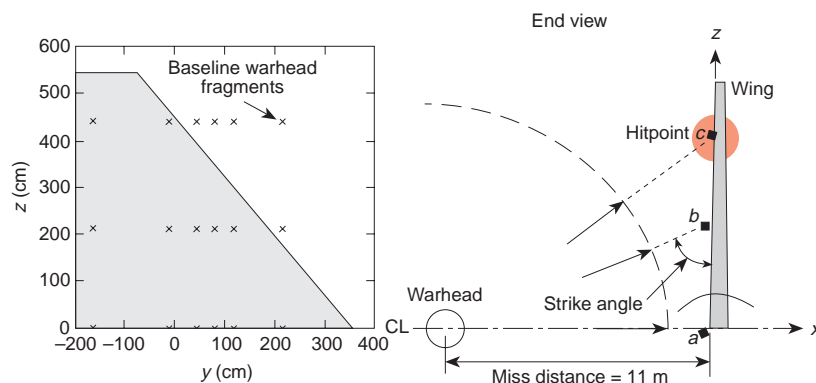

Figure 4. Impact configuration of warhead fragments on a generic wing target at a miss distance of 11 m.
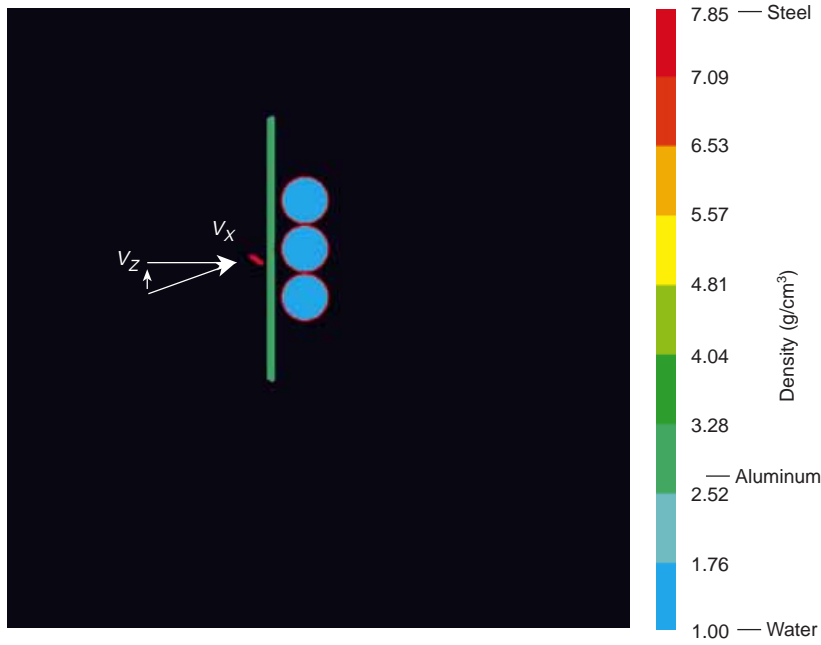
Figure 5. Typical hitpoint of a warhead fragment on a generic wing target.

A SPHINX hydrocode model of the SM-3 KW and a target missile with a bulk chemical weapon payload in a hypothetical engagement scenario was developed. The half-symmetric model used 79,000 particles and ran in about 6 cpu hours on the DEC Alphastation 500/500 workstation. The target missile is considered damaged if the shell holding the bulk chemical agent is broken open and the agent is dispersed at a point far removed from its intended target (water is used as a simulant in this analysis). The disposition of the chemical after it leaves the missile because of dispersion, transport, and diffusion in the atmosphere, and ultimately to the ground, is important, but is not considered in this analysis.

For chemical warfare, chemical submunitions are considered among the hardest payloads to defeat because there are many submunitions in a missile payload.[6] Each submunition carries its own discrete payload, and each individual submunition must be defeated. A hypothetical scenario of the SM-3 KW impacting a target missile with a chemical submunitions payload was simulated with the SPHINX hydrocode. The full model used 150,000 particles and ran in about 28 cpu hours on the DEC Alphastation 500/500 workstation. The damage-scoring methods for submunitions described previously were used to determine how many submunitions were damaged. For lethality purposes, each submunition is considered damaged if it is rendered unable to deliver its chemical agent payload to its intended target.
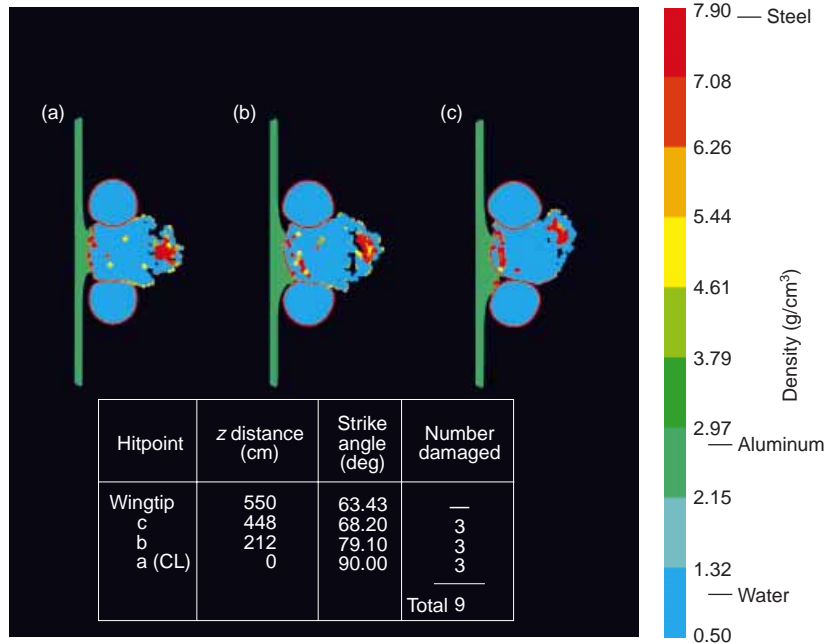

Hitpoint	z distance (cm)	Strike angle (deg)	Number damaged
Wingtip	550	63.43	—
c	448	68.20	3
b	212	79.10	3
a (CL)	0	90.00	3
			Total 9

Figure 6. Hydrocode results of baseline air-to-air missile warhead fragments impacting hitpoints on a generic wing target at (a) 200 μs, (b) 300 μs, and (c) 400 μs. Miss distance = 11 m = 1100 cm.

Missile System Lethality Assessment with Workstation-Based Hydrocodes and Probabilistic Methods

The next logical step in the evolution of a hydrocode analysis capability is to integrate all the pertinent technologies to fill a need in the lethality community, specifically, to demonstrate that a practical lethality assessment for a missile system can be performed on a workstation with physics-based hydrocodes. Historically, missile system lethality assessments have been performed with empirical codes such as PEELS because other means, such as physics-based hydrocodes, were too computer-intensive for the millions of runs required for a conventional Monte Carlo analysis. We believe that a
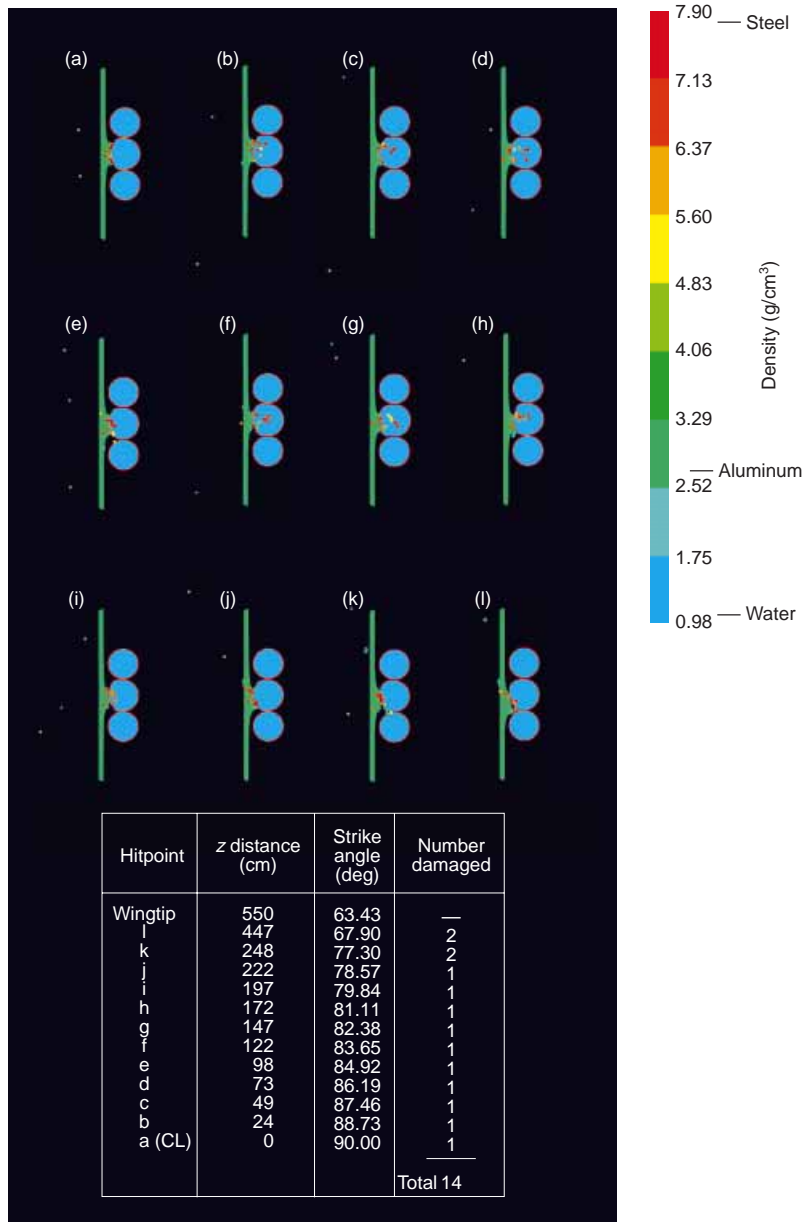
Hitpoint	z distance (cm)	Strike angle (deg)	Number damaged
Wingtip	550	63.43	—
l	447	67.90	2
k	248	77.30	2
j	222	78.57	1
i	197	79.84	1
h	172	81.11	1
g	147	82.38	1
f	122	83.65	1
e	98	84.92	1
d	73	86.19	1
c	49	87.46	1
b	24	88.73	1
a (CL)	0	90.00	1
			Total 14

Figure 7. Hydrocode results of directed energy explosives warhead fragments impacting hitpoints on a generic wing target at 300 μs. Miss distance = 11 m = 1100 cm.

the SPH method eliminates the mesh-tangling problems associated with traditional codes.

2. Hardware improvements have increased the speed of today's workstations. We have experienced an increase in speed of 5 to 10 times for three-dimensional hydrocode simulations of missile-to-missile impacts on the DEC Alphastation 500/500 workstation compared with the Silicon Graphics Incorporated Challenge L workstation.

3. The damage-scoring method using a failure criterion for submunitions described previously allows a numerical method to score the results of each hydrocode simulation and thus can be programmed into a postprocessing computer program.

4. The Fast Probability Integration (FPI) code developed by the Southwest Research Institute is a tool for probabilistic engineering analysis and design.[7] Whereas a standard Monte Carlo simulation randomly samples the input parameters, the FPI method uses various statistical methods that can significantly reduce the number of runs required by using knowledge of the statistical properties of the distributions of the parameters and the relationships of the parameters to each other. An illustration using an example statistical analysis follows.

missile system lethality assessment can be performed with physics-based hydrocodes on workstations, based on four recently developed enabling technologies:

1. The SPHINX hydrocode uses the smooth-particle hydrodynamics (SPH) method, which reduces the computational burden over traditional Eulerian or Lagrangian hydrocodes by its architecture. The SPH method is a gridless Lagrangian method that uses pseudo-particle interpolation to compute smooth hydrodynamic variables.[3] Each pseudo-particle has a mass, Lagrangian position and velocity, and internal energy, whereas other quantities are derived by interpolation or from constitutive relations. Being gridless,

In a simplified two-dimensional battlespace of strike angles and closing velocities, a strong correlation between the two parameters offers the potential to significantly reduce the number of permutations required for lethality assessment. For example, a statistical analysis of strike angles versus closing velocities was conducted for a hypothetical interceptor against a target missile. A very strong anticorrelation between closing velocity and strike angle was found from examining 18,180 intercepts (correlation coefficient = −0.97); that is, the closing velocity generally gets larger as the strike angle gets smaller (closer to head-on). The closing velocity population is binned by deciles, and the relationships between the closing velocity deciles and
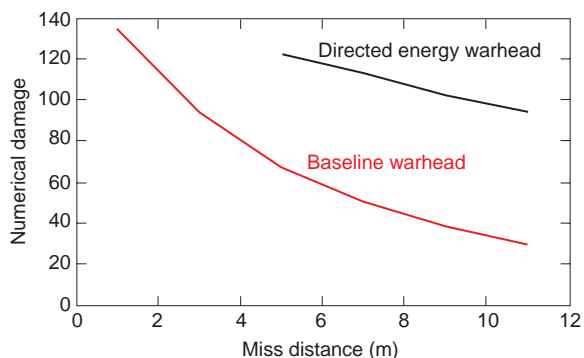
Figure 8. Comparison of numerical damage on a generic wing target against miss distance for the baseline air-to-air missile warhead and the directed energy explosives warhead.

strike angles are shown in Fig. 10, along with the percentages of the total population for each decile. The maximum, minimum, and mean strike angles for each closing velocity decile are also shown in Fig. 10. The strike angle populations within each closing velocity decile can be approximated with uniform distributions. Using probabilistic methods such as those in the FPI code, results of impacts of these two missiles over this two-dimensional battlespace can be approximated with three to six hydrocode runs. The lethality is then given as the probability of engagement times the percentage of damage as a function of various parameters, such as closing velocities and strike angles. Successful demonstration that a lethality assessment
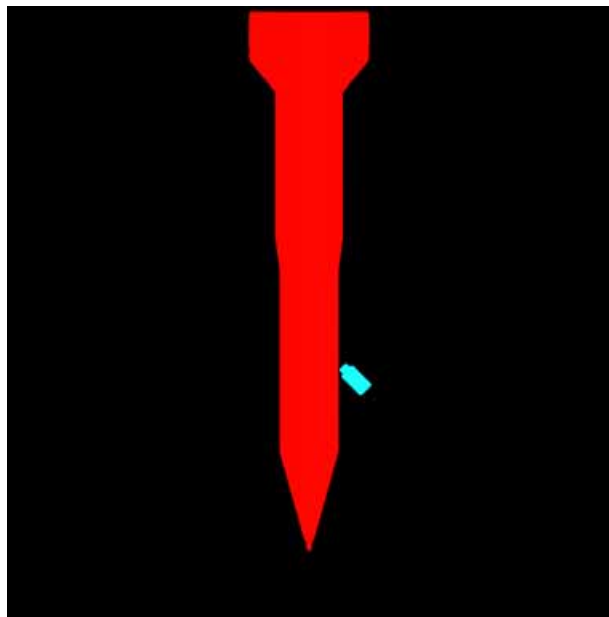
for a missile system can be performed on a workstation with physics-based hydrocodes and probabilistic methods in a reasonable amount of time would be a significant contribution to the lethality community.

OTHER APPLICATIONS

Rain Erosion of Missile Radomes

Rain erosion of missile radomes can result from supersonic flight through rain fields. Operating in this environment is obviously a requirement for an all-weather missile. Rain erosion can have many effects, such as structural weakening of the radome material (e.g., Pyroceram or slip cast fused silica), but a more important effect is an increase in boresight error. To illustrate the use of hydrocodes for rain erosion studies, comparisons to published results are presented next.

Evaluation of rain erosion on glass has been conducted by W. Adler of General Research Corporation,[8] where a spherical raindrop impacting a glass plate was modeled with the DYNA code from the Lawrence Livermore National Laboratory. The model used over 60,000 solid-brick elements and ran in "tens of hours" on a Pentium personal computer. The three-dimensional model is shown in Fig. 11a. The deformed shape of the raindrop model is shown in Fig. 11b, the stress contours on the plate are shown in Fig. 11c, and pressure contours on the raindrop are shown in Fig. 11d. Good agreement with experiment was reported by Adler. The SPHINX simulation of a similar raindrop on glass at various time steps is shown in Fig. 12, with pressure in units of dynes/cm^2 (multiply by 1.45×10^{-5} to get lb/in^2). Although the impact parameters of the SPHINX and the DYNA simulations are different, there is good agreement in the shapes of the deformed

Figure 9. Hydrocode simulation of SM-3 kinetic warhead and Aries rocket engagement at $t = 0$.
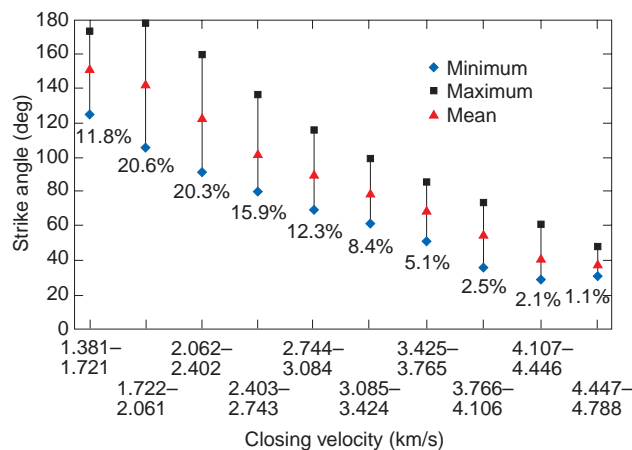

Figure 10. Correlation between closing velocity and strike angle. Percentages of the total population for each closing velocity are given.

raindrop, the shapes of the pressure contours, and the locations of the damage. In both simulations, the ratio of the diameter of the high-stressed and damaged region of the glass to the original diameter of the raindrop is about 1.6. As opposed to the DYNA simulation, the SPHINX simulation used only 900 particles and ran in only 4 cpu minutes on a Hewlett-Packard 715 workstation. Since one obviously needs to model many raindrops on a radome in a rain field, the computational time advantage afforded by the SPHINX hydrocode is apparent.

Range Safety for Missile Flight Tests

APL uses the Fragmentation Algorithms for Strategic and Theater Targets (FASTT) to conduct range safety studies, which are required to protect commercial and military ships, planes, and satellites, as well as populated areas around missile flight impact test sites, from fragments formed as a result of the impact. FASTT is an empirical model that calculates the distributions of the number, mass, size, ballistic coefficients, and change in velocity of fragments after a hypervelocity (>5 km/s) impact.[9] Originally developed for orbital debris studies, the model has been expanded to include theater missile impacts. The FASTT algorithms are essentially curve fits to observed test data, using parameters such as energy density of the impact, mass ratio and volume density of the impacting structures, and material considerations. Although FASTT has been used successfully for range safety studies in the past by APL, there is room for improvement: the
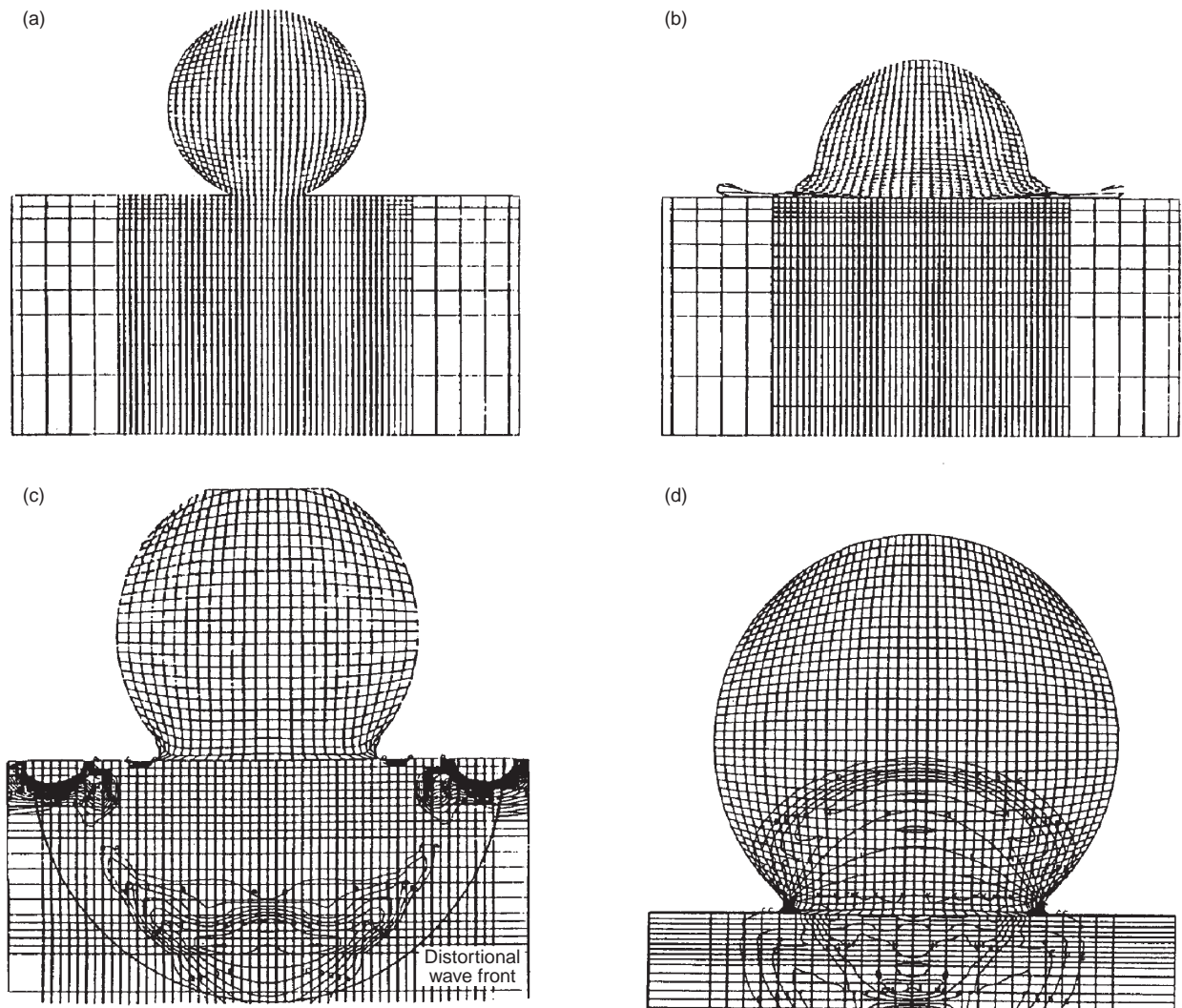

Figure 11. DYNA model of a spherical raindrop impacting a glass plate. (a) Waterdrop impacting at 305 m/s; (b) deformed shape; (c) tensile radial stress distribution; (d) pressure contours. (Adapted from W. F. Adler, "Waterdrop Impact Modeling," *WEAR*, **186–187,** 341–351, 1995, with permission from Elsevier Science.)
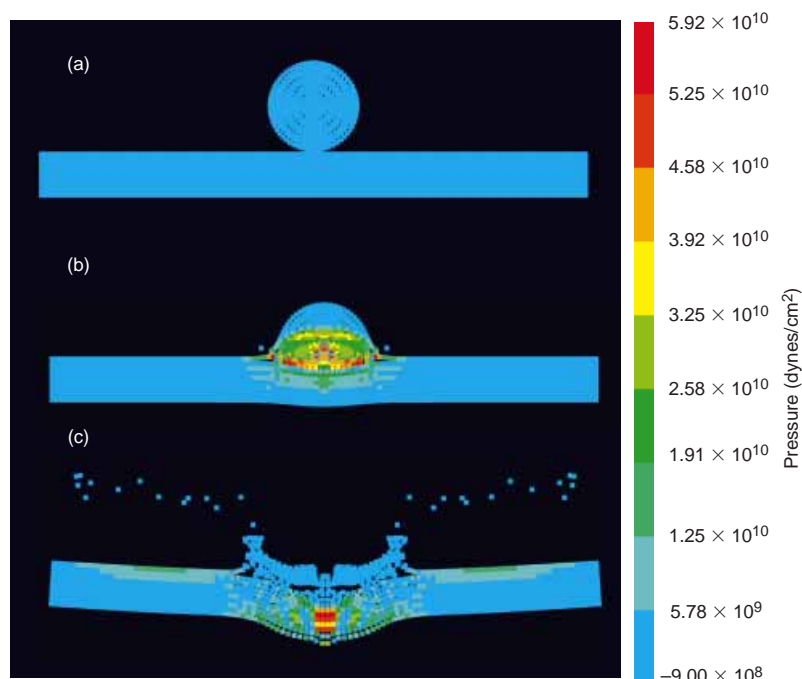
Figure 12. SPHINX model of a spherical raindrop impacting a glass plate at (a) 0 μs, (b) 2 μs, and (c) 20 μs.

CONCLUSION

Hydrocodes have been in existence since the 1970s. Until recently, their utility was limited because they had to be run on supercomputers, but now they can be executed on workstations. In my own experience over the past 2 years, the execution speed has increased by up to a factor of 10 simply as a result of improvements in workstations. It is now possible to run three or four three-dimensional missile-to-missile impact hydrocode analyses in a 24-h period on a single workstation. However, development of a hydrocode model prior to its final execution may take days to months, similar to the amount of time to develop a finite-element model. The DEC Alphastation 500/500 workstation at APL has sufficient memory (1 GB), hard-disk storage capacity (17 GB), and availability to run just about any hydrocode analysis. Whereas previously APL relied on empirical codes such as FASTT and PEELS, whose predictions in unchartered or nonbenchmarked parameter space were often questionable, hydrocodes can now provide a physics-based tool to make these predictions. In that sense, their utilization is no different from that of finite-element analysis and computational fluid dynamics codes.

available data used for curve fitting have wide scatter, some of the methodology relies on heuristic arguments, and the mass ratio of the interceptor and the target may be beyond the data bounds. To circumvent these concerns, a physics-based approach using hydrocode models and engagement parameters of the actual impacting structures is proposed.

In a hydrocode simulation of a missile intercept such as that shown in Fig. 9, the velocities of both the interceptor missile and the target missile are modeled, not just the closing velocity of the engagement. The missile intercept is simulated to a suitable final time where no further significant breakup is expected. Each particle produced by the impact (post-impact particle) has a mass and a velocity. A control volume that bounds all the particles from both vehicles is placed around the intercept point, where each face of the control volume is defined by a plane. In SPHINX, particles can be artificially projected or transported forward in time onto any orthogonal plane based on the particles' positions and velocities at any chosen time step. Masses of individual particles that stay bonded together to form a post-impact fragment can be integrated over all the member particles to obtain the fragment mass. In this way, the requisite mass, velocity, number, and distribution of post-impact fragments can be obtained. These data are then fed into 3-degree-of-freedom codes that propagate the fragments to the Earth's surface or into orbit.

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