NUMERICAL MODELING OF ROCKET WARHEAD DETONATION AND FRAGMENTATION

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ABSTRACT

Numerical models provide a safer and more cost-effective method to evaluate the performance of military warheads and weapons systems. These simulations are increasingly employed for military research and development. The scientific community must be confident in the accuracy of these computations, and thus analysts need to continually validate numerical models. This paper presents results from a numerical study of the detonation and fragmentation of a rocket warhead commonly found throughout the world. The simulation utilizes a coupled nonlinear finite element structural and fluid dynamics codes to model the detonation of the high explosive, the case break up, and the mass, velocity, and trajectory of the resulting fragments. The analytic research program focuses on differing impact angles and velocities, and an assessment is provided of the ability to numerically represent the behavior of the rocket using simplifying assumptions.

INTRODUCTION

Rockets are frequently employed throughout the world in areas of military conflict and armed internal resistance. While they come in various shapes, sizes, and material composition, they all pose serious lethal threats to both civilians and military personnel. Thus, military research engineers and scientists need to accurately assess the lethality of these weapon systems to design countermeasures to protect human life. While experimental testing is often employed for such purposes, numerical simulations provide a cost-effective alternative. Modern finite element programs are able to accurately characterize shock propagation and material response; however, inaccurate material models can generate erroneous solutions without proper validation, and analysts can select inappropriate assumptions that yield misguided conclusions.

Accordingly, researchers should know the adequacy of both the selected numerical approach and the assumptions employed. This paper addresses the influence of two common assumptions implicit in modeling any rocket or warhead system. The first is the inclusion of rocket velocity prior to detonation. Fragmentation data for both stationary and moving rocket models are presented. This comparison will examine the relative influence of weapon velocity on the fragmentation and the need to include weapon velocity in numerical models. The second assumption examined in this paper is the inclusion of rocket impact angle at the time of detonation. Results from rocket models oriented at 0 degrees, 50 degree and 90 degrees are presented to examine the differing fragmentation patterns and to determine the necessity of modeling differing impact angles. The discussion and results presented in this paper will provide military researchers with valuable insight into the most effective and expeditious methods to model rockets and warheads.
Numerical Models

Over the last several years we have developed a numerical methodology that couples state-of-the-art Computational Fluid Dynamics (CFD) and Computational Structural Dynamics (CSD) methodologies [1,2]. FEFLO98 is the CFD code used while SAICSD handles the CSD portion. FEFLO98 solves the time-dependent, compressible Euler and Reynolds-Averaged Navier-Stokes equations on an unstructured mesh of tetrahedral elements. SAICSD solves explicitly the large deformation, large strain formulation equations on an unstructured grid composed of bricks and hexahedral elements.

Mesh generation for both CSD and CFD is performed using FRGEN3D [3], an unstructured grid generator based on the advancing front method. The CFD mesh is composed of triangular (surface) and tetrahedral (volume) elements. The CSD mesh includes beams, triangular or quad shells and bricks for the solid.

The flow solver employed is FEFLO, a 3-D adaptive, unstructured, edge-based hydro-solver that solves the Arbitrary Lagrangean-Eulerian (ALE) formulation of the Euler and Reynolds-averaged turbulent, Navier-Stokes equations. The code includes a large variety of state-of-the art numerical shock-capturing schemes, from FCT, exact or approximate Riemann, to ENO to HLLC, and from second-order to eight-order accuracy, a choice that is continuously updated as new schemes are developed. The spatial mesh adaptation is based on local H-refinement, where the refinement/deletion criterion is a modified H2-seminorm [4] based on a user-specified criteria. FEFLO supports various equations of state including real air, water, SESAME and JWL with afterburning. Particles are treated as a solid phase, exchanging mass, momentum and energy with the fluid.

The structural dynamics solver used was SAICSD [5,6]. This code solves the continuous mechanics equilibrium equation. The weak formulation (virtual work principle) is written in the spatial configuration (actual configuration) and it is discretized in time using an explicit second-order central difference scheme. In space, the virtual work equation is solved by using stable finite element types. The most used elements are: a full integrated large-deformation Q1/P0 solid element (hexahedra with an 8 nodes interpolation scheme for the cinematic variables and constant pressure) which does not present hourglass modes and it does not lock for incompressible cases. Several 3-node and 4-node large-deformation shell elements (Hughes-Liu shell, Belytschko shells, MITC shells, ASGS stabilized shells) which are formulated using standard objective stress update schemes (Jaumann-Zaremba, co-rotational embedded axis, etc.), are fully integrated to avoid hourglass spurious modes. Finally, some objective truss and beam elements (i.e. Belytschko and Hughes-Liu beams) have also been implemented. Many different material models have been included into the code. The most used are: a plasticity model which relies on a hyper-elastic characterization of the elastic material response for the solid elements, and a standard hypo-elastic plasticity model for the shell, beam and truss elements. The most often used failure criterion is based on the maximum effective plastic strain and the stress tensor inside the element. The fracture may be simulated by element erosion and/or node disconnection.

RESULTS

Weapon Details

The specific rocket dimensions and velocities are excluded for security purposes. Additionally, the size, mass, and velocity of the resulting fragmentation patterns are also excluded. The resulting fragmentation is discussed in terms of dimensionless variables. The rocket mass is
defined as $m$, and all fragment velocities for both models (stationary and moving) are specified relative to $v$ for comparison purposes. The rocket contains the fragmenting warhead filled with explosive, as well as the attached, thick-case solid rocket motor. A thick steel plate separated the explosive warhead from the motor.

**Numerical simulations**

Five simulations were conducted. The base configuration included the weapon placed (stationary) at an angle of 50° off the horizon, with the tip several centimeters off the ground. The base explosive is defined as HE-A. The second simulation replaced HE-A with a more energetic explosive, termed HE-B. The third simulation modeled the base configuration, but moving the weapon at a velocity $v$. Simulation four had the base case weapon and explosive placed horizontally (parallel to the ground), while the last simulation placed that weapon vertical to the ground.

The explosive was nose detonated. A sequence of contour plots shown in Fig 1 depicts the detonation wave propagation within the explosive, the case fragmentation, the solid motor case deformation and the expanding blast wave and fragment cloud. The simulation was conducted for the base configuration, though all other simulations are controlled by the identical physical mechanisms. Column A shows pressure contours on a cut plane of symmetry and on the ground plane. Column B shows the velocity contours on the plane cut and on the ground. Column C adds the CSD surface on top of the velocity contours, while column D shows the CSD velocity contours.

Upon detonation initiation at the nose, the detonation (point initiated) expands within the HE. Figures 1 at 40µs show the expanding detonation front within the explosive, and the expanding case (reaching maximum case velocity of 0.6$v$ km/sec). The case cracked soon afterwards, and at 100µs (Fig 2) observe the detonation products escape through the opening cracks, impact on the floor, and fragment expansion at a maximum velocity of about 0.88$v$ km/sec. At this time we observe the initial deformation of the steel plate separating the explosive from the rocket motor. This plate failed soon afterwards, and at 140µs (Fig 3) we observe the detonation products expansion through the motor case. Further detonation products and fragment expansion, as well as the thick-cased solid motor expansion, are observed in Figs 4 and 5, at 200µs, and 300µs, respectively.

Detonation products expansion through the breaking case is a complex phenomenon. Examination of the pressure and velocity evolution in columns A, B and C shows that as the case expands and breaks, the pressure within the volume enclosed by the expanding fragments is significantly higher than outside (Figs 2a through 4a), and is still noted even at a relatively very late time (Fig 5a). The solution at 200µs shows that the pressure inside the expanding fragment cloud that has expanded about 25 times the initial volume, is about 40 times higher than outside, while the velocity through the openings cracks accelerates from local subsonic to supersonic. This complex phenomenon clearly demonstrates the importance of properly modeling the coupled case breakup-fragmentation and detonation products expansion, which becomes all the more critical for non-ideal explosives.

Detonation wave evolution and interaction with nearby structures are discussed below. It is possible to construct many scenarios. We chose to examine fragment and blast loading on a circular wall at a given stand-off distance. We are focused only on the initial blast loading, i.e., maximum pressure and impulse, before reverberating waves within the enclose come into play.
Figures 1 through 5. Detonation initiation and propagation, case fragmentation and blast wave evolution at 40µs, 100µs, 140µs, 200µs and 300µs, respectively. Each showing pressure contours on a planar cut and the floor, velocity (cut and floor) without and with the CSD imposed, and CSD fragment velocity.
Figures 6 through 10 show the velocity evolution on the plane of symmetry for the five simulations, at 1.0ms, 3.0ms and 5.0ms, respectively. All velocity contours on the same column (same time) are plotted using the same scale. Hence, the white zone, such as inside the expanding flow shown in Fig 7a for HE-B, indicates a velocity higher than the maximum value. The three simulations for the rocket at 50°, include HE-A (Fig 6), HE-B (Fig 7), and the moving HE-A (Fig 8) show essentially the same pattern of blast wave expansion, with a higher expanding core velocity for the more energetic HE-B, and a slightly more directional velocity for the moving rocket, as the rocket flight velocity is significantly lower than detonation velocity. The horizontally placed weapon shows the directed jetting through the slowly-expanding motor case, while the vertical detonation shows a perfectly symmetric solution.

Next we examined the blast loading on the circumference of this enclosure, by dividing the 180° segment to four equal surfaces of 45° each, termed surfaces 9, 10, 11 and 12. Hence, surface 9 expands from 0° to 45°, where 0° deg is the tail direction (on a plane view), while surface 12 covers the zone from 135° to 180° (nose direction). The pressure and impulse values were obtained by averaging, at any time step, the values observed on all points within that surface. While this average processing diminish rise and decay time, peak and minima values, it is an excellent indication for what a structure placed within this zone will observe. Figure 11 shows a comparison on each surface for the five configuration modeled, while figure 12 shows, for each configuration, a comparison on the different surfaces. We note that:

a. Pressure and impulse values at the two central surfaces (10 and 11) for HE-B are highest, as expected for the more energetic explosive;

b. As HE-A and HE-B have the same initial conditions, the solutions on all surfaces relate similarly, i.e., identical trends, shifted up for the more energetic HE-B. For these two explosives the highest impulse values were obtained for the side surfaces, between 45° and 135°, while both produced the highest peak pressures on surface 12;

c. Moving the rocket resulted in shifting of energy from the tail (surface 9) to the nose (surface 12), where it produced the highest impulse;

d. The vertical-placed rocket loading showed no preferential direction;

e. The horizontal-placed rocket produced results identical to those expected from an arena test: maximum pressure and impulse values at the 90 to 135 quadrant (surface 11);

Another way of viewing the pressure and impulse values exerted on a given surface is shown in Figs 13 and 14. These results show the maximum over-pressure and impulse values obtained on the surface at any time during the simulation. Figure 13a for HE-A shows the peak pressure in the second and third quadrants near the ground. The more energetic explosive B increases the value of the maximum overpressure observed on all quadrants, as well as increasing the height on the surfaces on which these higher values are observed. Still, the maximum values are observed on the second and third quadrants. The rocket movement during detonation (Fig 13c) shifted the maximum pressure observed to the third and fourth quadrants (when compared to the base HE-A, Fig 13a). Placing the rocket horizontally would focus most high pressure at a narrower zone near the center, with higher peak pressures, while placing it vertically will disperse the load uniformly.
Figures 6 through 10. Velocity evolution on the plane-of-symmetry of a circular enclosure for: a. HE-A at 50°; b. HE-B at 50°; c. HE-A at 50° moving at 100m/sec; d. HE-A horizontal; and e. HE-A vertical position.
Figure 11. Averaged pressure and impulse values on surfaces 9 (0° to 45°), 10 (45° to 90°), 11 (90° to 135°), and 12 (135° to 180°). 0° is the tail direction, 180° is the nose direction.

Figure 12. Comparison of pressure and impulse values on the four surfaces for each of the five configurations studied.
The maximum impulse values observed at each point show identical trends to those indicated by the maximum pressure, and are shown in Figs 14 for completeness. To better understand the results observed we examined the maximum pressure observed on surfaces at ground level (Fig 15). Please note that $0^\circ$ denotes the tail direction (i.e., tail is on left, as opposed to the contours plots where the tail was on the right). The base configuration produced a maximum pressure at about $60^\circ$. The enhanced
explosive, HE-B produced parallel trends, with significantly higher peak pressure. Moving the rocket resulted in lower maximum levels, while pushing the peak to the third quadrant, at about 100°. The horizontally-placed rocket produced a very high peak at about the center, while the vertically-placed rocket produced an almost perfectly symmetric peak loading.

The results shown so far clearly demonstrate the peak loading dependence on rocket placement. The question risen was, when integrating the load on all walls at this range, would directionally effects wash out. Figure 16 shows the averaged pressure on all faces as a function of time, and the averaged impulse, or force, on the walls. The base HE-A case, stationary or moving, produced highly different pressure patterns (Figs 12-15), but almost identical force evolution on the walls. The more energetic HE-B produced similarly-trended but higher force. The interesting results are for the vertical and the horizontal rockets. Though significantly different in terms of average pressure evolution, the total force produced was almost identical. This is contrary to expectations as the walls were placed fairly close to the rocket, and indicates that for both cases, the energy contained within the walls height is fairly similar and lower than for the 50° angled weapon, either stationary or moving.

CONCLUSIONS

The study investigated the blast and fragment distribution produced by a rocket on adjacent surfaces. The study examined a base configuration, a stationary rocket at 50° inclination, partially filled with HE-A. The variation included a more energetic fill, HE-B, moving the rocket at a typical impact speed, and investigating angular dependence by placing the rocket at extreme angular positions: horizontal and vertical. The study demonstrated that when used for vehicular or personnel survivability, airblast pressure and impulse values greatly varied with angular position from the rocket, as well as rocket impact velocity and angle.

REFERENCES


