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Experimental Validation of Detonation Shock Dynamics in Condensed Explosives

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14. ABSTRACT

Experiments on HMX-based, condensed explosive PBX-9501 were carried out to validate a reduced asymptotically derived description of detonation shock dynamics (DSD). The experiments, coined 'passover experiments' have embedded disks of lead in right circular cylinders of PBX-9501. A range of dynamically changing states, with both divergent and convergent shock shapes are realized as a detonation front is created on one end of the cylinder and passes over the embedded disk of lead. The time-of-arrival of the detonation shock at the output end of the cylinder is recorded and compared against simulations using the DSD model. The experiment and DSD theory are found to be in excellent agreement and offer a high-fidelity, yet computationally efficient means for complex wave-front tracking in explosive systems.

15. SUBJECT TERMS

Detonation Shock Dynamics, wave-front tracking, equation of state

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EXPERIMENTAL VALIDATION OF DETONATION SHOCK DYNAMICS IN CONDENSED EXPLOSIVES

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Abstract. Experiments on the HMX-based, condensed explosive PBX-9501 were carried out to validate a reduced asymptotically derived description of detonation shock dynamics (DSD) where it is assumed that the normal detonation shock speed is determined by the total shock curvature. The passover experiment has an embedded lead disk in a right circular cylindrical charge of PBX-9501 and is initiated from the bottom. A range of dynamically changing states, with both divergent (convex) and converging (concave) shock shapes are realized as the detonation passes over the disk. The time of arrival of the detonation shock at the top surface of the charge is recorded and compared against the DSD simulation and a separate multi-material simulation (DNS). A new wide-ranging equation of state (EOS) and rate law is used to describe the explosive and is employed in both the theoretical (DSD) calculations and the multi-material simulations. The experiment, theory and simulation are found to be in excellent agreement.
Keywords: Detonation shock dynamics, PBX-9501, experiment, validation

INTRODUCTION

For most applications of condensed explosives, the length of the reaction zone that powers the lead detonation shock is a fraction of a millimeter or smaller. The typical ratio of the device size to the reaction zone is typically $O(1000)$ or larger. The asymptotic theory of detonation shock dynamics (DSD), is a theory that assumes that the radius of curvature of the shock is large compared to the length of the reaction zone that supports the detonation and accounts for change to the detonation shock speed due to shock curvature during quasi-steady evolution. The present short account describes a validation of the reduced theory by experiment and by direct simulation. A full account of this work and complete references are found in [1], and [2].

The simplest DSD theory derives the result that total curvature $\kappa = \kappa_1 + \kappa_2$, is a function of the normal detonation shock velocity, D_n, written as

$$\kappa = F(D_n)\,, \tag{1}$$

with the property $F(D_{CJ}) = 0$, where D_{CJ} is the Chapman-Jouguet velocity. To derive (1) from theory, one assumes that the explosive is described by an EOS and rate law of the general form $e(p,v,\lambda)$ and $r(p,v,\lambda)$, and that the Euler equations hold. One solves for the quasi-steady detonation structure in the shock-attached frame. The equations for the structure contain both the normal detonation speed D_n and the total curvature κ. Since it is assumed that the detonation structure passes through a sonic plane near the end of the reaction zone, the value of D_n is not independent of κ and their relationship is determined as a nonlinear eigenvalue. Since the normal shock, curvature relation is dependent on the explosive's equation of state and reaction rate law, experiments serve as a powerful constraint on the allowable forms for $e(p,v,\lambda)$ and $r(p,v,\lambda)$, as well as a check on the theory.

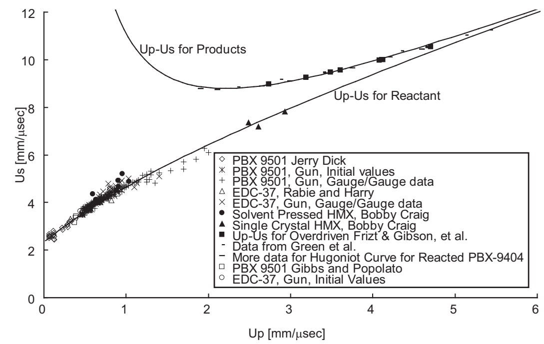

FIGURE 1. PBX 9501 $U_p - U_s$ Hugoniots with experimental data shown

DESCRIPTION OF THE EXPLOSIVE: WIDE RANGING EOS AND RATE LAW

Space does not permit recitation of the detailed forms used for the equation of state or the calibration procedure used to assign the the model parameters for the wide ranging rate law for PBX-9501; full details are given in [1]. The methods used in the calibration are also described in detail in [2]. Here we provide a brief summary. Davis developed a wide ranging equation of state for detonation products whose form was chosen to accurately describe the behavior of adiabatic γ (dimensionless sound speed) and Grüneisen gamma, Γ. Davis also developed a similar reactants equations of state fit to PBX-9404, 9501. Stewart, Yoo and Davis in the 12-th Detonation Symposium, proposed a modification of Davis' reactant equation of state and introduced a closure model to develop a mixture EOS that includes the reaction progress variable of the form $e(p,v,\lambda)$ and that uses the standard rules for a binary mixture of reactants and products, where λ is the mass fraction of the products and is the reaction progress variable. The equation of state parameters were fit to the shock Hugoniot data for both reactants and products. Fig. 1 shows a plot of the particle velocity, shock velocity (U_P, U_S) Hugoniot (top curve) calculated from the products EOS, and Hugoniot (bottom curve) calculated from the reactants EOS, compared with experiment. The experiment data shown was was compiled by R.Gustavsen, LANL. The calibration considers work done by expanding gases and the temperatures of the reactants and products.

A rate law is proposed for PBX-9501 with a

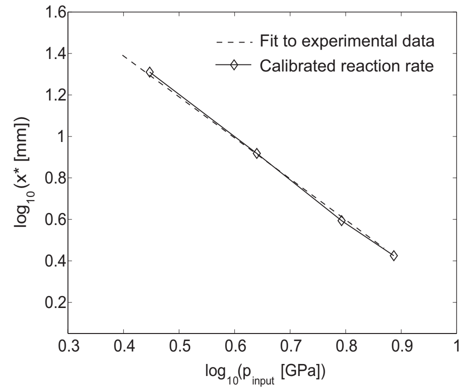

FIGURE 2. "Pop"-plot, run to detonation distance versus input shock pressure (P_{input}) for PBX 9501 from experiments and direct simulation results.

single-term, fractional depletion, pressure dependent reaction rate of the form

$$r(p,v,\lambda) = k(1-\lambda)^{\nu}\left(\frac{P}{P_{CJ}}\right)^{N}. \qquad (2)$$

Shock to detonation data ("Pop"-plot) and detonation shock speed curvature data, is used to calibrate the parameters of the rate law. Hull's experimental data suggests the D_n, κ relation is linear near the CJ point. The depletion exponent ν is picked primarily to match Hull's data, see Fig. 3. The pressure exponent N and rate constant k are adjusted to match the shock initiation data. One-dimensional, reverse impact simulations were carried out using the specified EOS and rate law to match the published experimental data for PBX-9501, and the results are shown in Fig. 2. The calibrated rate law parameters were found to be $p_{CJ} = 36.3$ GPa, $k = 110\,\mu sec^{-1}$, $N = 3.5$, $\nu = 0.93$.

Figure 3 shows the detonation velocity curvature relation calculated using this EOS/rate law pair described by asymptotic theory. This $D_n - \kappa$ relation is the shock motion rule that is used to compute the shock motion according to the reduced DSD description. Hull's D_n, κ experimental data is also shown.

THE PASSOVER EXPERIMENT

The experimental set up is shown in Fig. 4. The PBX-9501 explosive (white material) has a disk of

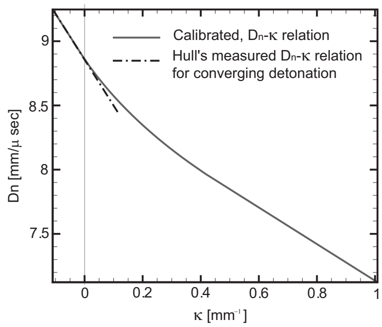

FIGURE 3. The D_n, κ relation for PBX-9501 calculated from the wide-ranging EOS and rate law model

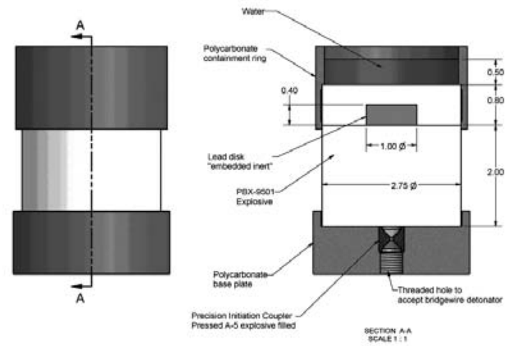

FIGURE 4. Assembly sketch for DSD validation experiment

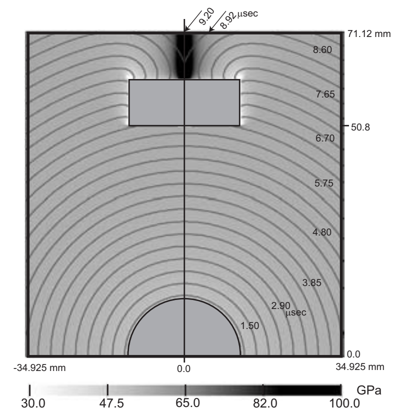

FIGURE 5. DSD simulation of the axisymmetric passover experiment. The grey-scale shows the shock pressure in GPa when a shock passes a point (x,y) in the explosive.

pure lead (grey object) embedded along the central axis. A detailed description of the experiment is found in [1]. The experiment transforms a single, quasi-steady, convex hemispherical shock into a shock with a high concavity at the central implosion axis. PBX-9501 was chosen to test previous experimental DSD-characterization from Hull's work. Pure lead was selected as the inert for its high shock-impedance and well-characterized shock Hugoniot properties.The charge is initiated at the bottom of the PBX-9501 charge. The detonation shock front propagates as a simply connected surface with convex, positive curvature hemisphere for 50-mm and then encounters the lead disk within the top piece of PBX-9501. The shock speed in the inert lead is much lower than the detonation velocity in the PBX-9501 and a diffraction event occurs as the detonation sweeps about the disk and encompasses it. Water sits atop the charge and extinguishes the reactive shock as it transmits into the water. Light from the explosive/water plane records the time-of-arrival of the detonation shock through a single 150-micron slit aperture plate as captured by a Cordin 132A camera. Four (4) passover experiments were conducted with identical hardware. Figure 5 (as computed from DSD-theory) illustrates the subsequent shock motion in the experiment.

COMPARISON OF DSD, NUMERICAL SIMULATIONS (DNS) AND EXPERIMENT

Two different types of simulations were carried out to compare with the time of arrival results obtained by the passover experiments. The first uses the reduced DSD-model defined by the D_n, κ shock motion rule, shown in Fig. 1, subject to inert angle confinement boundary conditions. The lead disk is described by a Mie-Gruneisen (U_p, U_s) EOS $e(p,v)$. Shock polar analysis for the DSD confinement derives the angles at the PBX-9501/lead interface (the interior angle between the shock and interface normals) as $\omega = 35^o(sonic)$ and $66^o(subsonic)$. The initial shock in the DSD simulation was a hemi-sphere of radius 5 mm centered at the bottom of the charge.

The multi-material numerical simulation (DNS) was carried out with the wide-ranging EOS and rate law for the explosive and the Mie-Gruneisen EOS for the lead. An outflow boundary condition is used at the lateral boundaries. The multi-material simulation code combines two high-order solvers, a high-order total variation diminishing (TVD) solver for the Euler equations and a level-set solver to move the material interface that separates explosive and lead. The DNS simulation uses an initial condition of a hemispherical hot spot of radius $R = 5\ mm$, centered at the bottom. Figure 6 shows a comparison of the DSD and DNS simulation, to show that they give consistent results (i.e. that the shocks overlap).

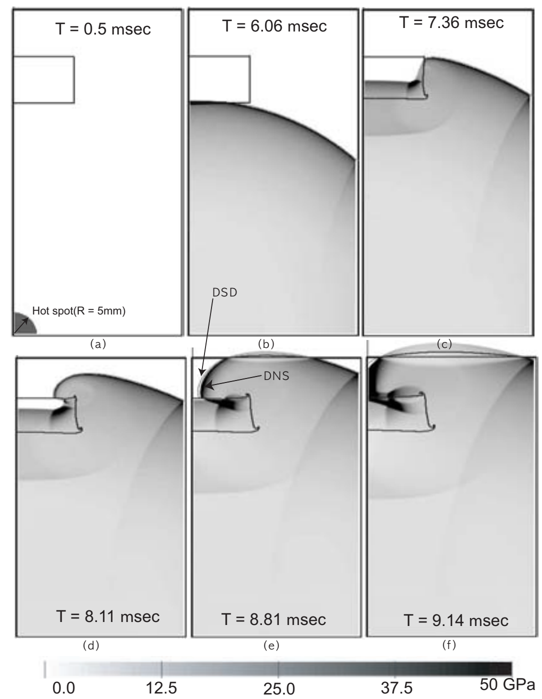

FIGURE 6. Comparison of DSD and DNS simulation

CONCLUSION

Figure 7 is a composite of TOA records for the passover experiments that includes experiments, DSD simulations, DNS simulations and the ideal Huygens construction. The Huygens construction assumes that the detonation propagates at a constant normal shock speed of $D_{cj} = 8.86\ mm/\mu sec$ and does not account for the slowing of the wave due to curvature effects. The excellent level of agreement, both qualitative and quantitative, between experiment, DSD and DNS is encouraging because it indicates that one can use the wide ranging EOS/rate law and the corresponding DSD description effectively to model real explosives and predict complex dynamic behaviors.

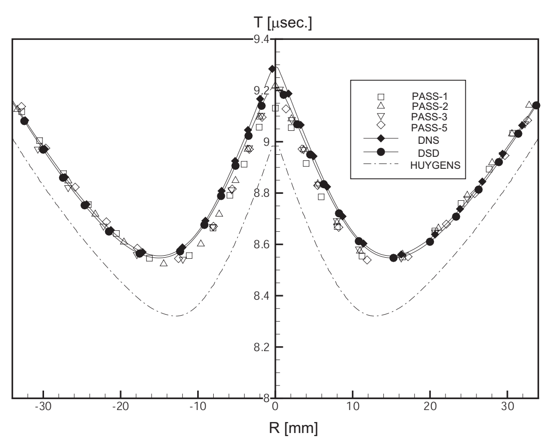

FIGURE 7. TOA comparison of experiments, DNS, and DSD simulations at the top of the charge

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