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Analysis on shock attenuation in gap test configuration for characterizing energetic materials

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A pyrotechnic system consisting of donor/acceptor pair separated by a gap relies on shock attenuation characteristics of the gap material and shock sensitivity of the donor and the acceptor charges. Despite of its common use, a numerical study of such a pyrotechnic train configuration is seldom reported because proper modeling of the full process requires precise capturing of the shock wave attenuation in the gap prior to triggering a full detonation of a high explosive and accurate description of the high strain rate dynamics of the explosively loaded inert confinements. We apply a hybrid particle level-set based multimaterial hydrocode with reactive flow models for pentolite donor and heavily aluminized cyclotrimethylene-trinitramine as the acceptor charge. The complex shock interaction, a critical gap thickness, an acoustic impedance, and go/no-go characteristics of the pyrotechnic system are quantitatively investigated. © 2016 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution 3.0 Unported License. [http://dx.doi.org/10.1063/1.4945777]

I. INTRODUCTION

Pyrotechnic mechanical devices often utilize gap test configuration between a donor and an acceptor for a reliable gas generation aiming at various “push-pull” actuations found in many industrial and military applications. Operability of such pyrotechnic systems depends on mechanical properties of the gap and shock sensitivity of donor-acceptor charges. A gap test is a standardized test to quantify the shock sensitivity of an acceptor that needs to be characterized. A critical gap thickness of a gap whose shock characteristics are known a priori is measured when the acceptor charge is detonated at its initiating pressure.

The gap test has advantage over other commonly used method for measuring shock sensitivity such as drop-weight impact test.1 The critical gap thickness, under highly controlled circumstances, is quite reproducible with the error less than a fraction of a millimeter.2 The test consists of four components: a donor charge, a gap, an acceptor charge, and a witness block. The four components train is first detonated at its donor usually by an electrical means. The shock wave generated by detonation is attenuated through the gap. The transmitted shock wave then may or may not trigger an acceptor depending on the level of attenuation. If the acceptor is detonated, a hole is created at the witness block. Here, the gap thickness is adjusted, and the test is repeated until a critical thickness (go/no-go) is obtained for the test sample being the acceptor charge. A critical gap thickness for which the acceptor has 50% probability of being detonated marks the shock sensitivity of the acceptor.3–5

In this research, we attempt to define a multi-material hydrodynamic simulation for a Large Scale Gap Test (LSGT) comprises a donor (Pentolite), a gap (PMMA), and an acceptor (heavily aluminized RDX). The aluminum-rich RDX is composed of 50% RDX (cyclotrimethylene-trinitramine, C3H6N6O6), 35% aluminum powder, and 15% HTPB (hydroxyl-terminated polybutadiene) binder. Its initial density after pressing is 1.78 g/cm3.The numerical simulation provides the complex shock interaction structure, the critical gap thickness, the acoustic impedance, and the corresponding detonation characteristics of high explosives in contact with a PMMA gap. A full scale LSGT experiment is also conducted for validation of the numerical predictions provided in this study.

II. APPROACH

In order to simulate the energetic material response at high temperature and pressure conditions, one requires reactive flow models, rupture model, multi-material interface tracking model, and hydrodynamic model for accurate capturing of various waves inherent to a globally hyperbolic system. For both energetic material and inert gap material, a compressible form of the governing equations is used, and the stress tensor for inert solids is composed of deviatoric stress and hydrostatic pressure.6 The Mie-Gruneisen equation of state (EOS) defines pressure of gap material, while the JWL (Jones-Wilkins-Lee) EOS is used for high explosives. The rate of chemical reaction is based on the ignition and growth steps previously built for the aluminized RDX.7 The interface between two different materials is tracked through a hybrid particle level set method, and the material properties near the interface are determined through the ghost fluid method. Here, only a brief explanation of the method is outlined. For more detailed discussions, one may refer to Ref. 8.

A. Governing equations

The compressible Navier-Stokes equations in a cylindrical coordinate system reflect the conservations of mass, momentum, and energy
\[
\frac{\partial \mathbf{U}}{\partial t} + \frac{\partial \mathbf{E}}{\partial r} + \frac{\partial \mathbf{F}}{\partial z} = \mathbf{S}(\mathbf{U}),
\]
(1)

\[
\mathbf{U} = \begin{bmatrix} \rho \\ \rho u_r \\ \rho u_z \\ \rho E \end{bmatrix}, \quad \mathbf{E} = \begin{bmatrix} \rho u_r \\ \rho u_r^2 + p \\ \rho u_ru_z \\ u_r(pE + p) \end{bmatrix}, \quad \mathbf{F} = \begin{bmatrix} \rho u_r \\ \rho u_r^2 + p \\ \rho u_z^2 + p \\ u_z(pE + p) \end{bmatrix},
\]
(2)

\[
\mathbf{S} = \begin{bmatrix} -\frac{\rho u_r}{r} \varphi & s_{rr} - s_{\theta\theta} - \rho u_z^2 r \varphi + \eta \left( \frac{\partial s_{rr}}{\partial r} + \frac{\partial s_{\theta\theta}}{\partial \theta} \right) \\ s_{rr} - s_{\theta\theta} - \rho u_z^2 r \varphi + \eta \left( \frac{\partial s_{rr}}{\partial r} + \frac{\partial s_{\theta\theta}}{\partial \theta} \right) & -s_{rr} + s_{zz} - \rho u_z^2 r \varphi + \eta \left( \frac{\partial s_{rr} + s_{zz}}{\partial r} + \frac{\partial (u_r s_{rr} + u_z s_{zz})}{\partial \theta} \right) \\
\frac{u_r s_{rr} + u_z s_{zz} - u_r(pE + p)}{r} \varphi + \eta \left( \frac{\partial (u_r s_{rr} + u_z s_{zz})}{\partial r} + \frac{\partial (u_r s_{rr} + u_z s_{zz})}{\partial \theta} \right) \end{bmatrix},
\]
(3)

where \( \varphi = 0, 1 \) for rectangular and cylindrical coordinates, respectively, and \( \eta = 0, 1 \) for fluids (liquids and gases) and solids, respectively. The governing equation is solved by a third-order Runge-Kutta and ENO (essentially non-oscillatory) method with respect to the temporal and spatial discretizations, respectively. Here, the stress effect in the unreacted solid state can be ignored in comparison with the dominant hydrostatic pressure of the reacted gas state of high explosive. However, to capture the drastic change in deformation of the inerts, the Cauchy stress tensor is formulated into deviatoric stress tensor and hydrostatic pressure as follows:

\[
\sigma_q = s_{ij} - p \delta_{ij},
\]
(4)

The rate of deviatoric stress change follows the first order differential equation:

\[
\dot{s}_{ij} = \dot{s}_{ij, \text{cor}} = \Omega_k \delta_{kj} - s_{ij} \Omega_k + 2G(D_{ij} - D_{ij}'),
\]
(5)

\[
\dot{s}_{ij, \text{cor}} = -H : D_{ij}' = -2G \mathbf{A} \mathbf{N}_{ij, \text{cor}},
\]
(6)

where each operator is defined as

\[
p_{\text{PMMA(solid)}} = \Gamma_0 E + \left\{ \begin{array}{ll}
\rho_0 C_0^2 \mu \left[ 1 + \left( 1 - \frac{\Gamma_0}{2} \right) \mu \right] & \text{if } \mu > 0 \\
C_0^2 \rho_0 \mu & \text{if } \mu < 0
\end{array} \right.
\]
(12)

\[
\sigma_Y = (A + B(\mu))^9 \left( 1 + C \ln \left( \frac{\mu}{\alpha} \right) \right) \left( 1 - \frac{T - T_0}{T_m - T_0} \right).
\]
(13)

Since PMMA is a brittle material under the present test, no strength model is used as such a constant yield stress is utilized. In this research, we set the yield stress of PMMA to...
be constant unless its temperature is less than a melting temperature. If its temperature is higher than the melting temperature, then the yield stress is reduced to zero.

C. Chemical reaction of the high explosive materials

The reactive flow model is described by the rate law that consists of both ignition and growth terms suggested by Kim et al.,

\[
\frac{d\lambda}{dt} = I(1 - \lambda)\mu^a + G(1 - \lambda)\rho^b, \quad \mu = \frac{\rho}{\rho_0} - 1. \tag{14}
\]

Here, \( \rho \) is pressure, \( t \) is time, \( \rho_0 \) and \( \rho \) are the initial and current densities, respectively. \( \lambda \) is the burned mass fraction, and constants \( I, a, G, \) and \( b \) are the unknown parameters. \( \lambda \) is a reaction progress variable (\( \lambda = 0 \) unreacted state and \( \lambda = 1 \) reacted state) and the compression term, \( \mu \), is defined as \( (\mu = \rho/\rho_0 - 1) \). Four unknown parameters of major significance in view of detonation are determined by a series of unconfined rate stick experiments performed previously.\(^{13}\)

D. Hybrid particle level set method

To obtain sharp interface between two different materials, hybrid particle level set method\(^{14}\) is applied. The motion of the level set follows the equation\(^{15,16}\)

\[
\frac{\partial \phi}{\partial t} + u_n \frac{\partial \phi}{\partial r} + u_r \frac{\partial \phi}{\partial z} = 0. \tag{15}
\]

Here, the interface of each substance is a zero level set \( \phi = 0 \). \( \phi < 0 \) indicates inner and \( \phi > 0 \) indicates outside of the material. This equation is integrated with a 4th order scheme in space and 3rd order Runge-Kutta method in time.\(^{17}\)

While calculating the interface level set function, a drastic change in the material property may give rise to distortion of the interface. To remedy this weakness, a periodic re-initialization is adapted by solving the following equation until steady state is reached:

\[
\phi_l + S(\phi)(|\nabla \phi| - 1) = 0. \tag{16}
\]

Here, \( S \) is

\[
S = \frac{\phi}{\sqrt{\phi^2 + (1 - |\nabla \phi|)^2 d^2}}, \tag{17}
\]

with \( d \) being the grid size.

Basic information like unit normal vector or curvature can be obtained easily using the following relations:

Unit normal vector : \( \vec{n} = \frac{\nabla \phi}{|\nabla \phi|} \), \( \tag{18} \)

Curvature : \( \kappa = \nabla \cdot \vec{n} = \nabla \cdot \left( \frac{\nabla \phi}{|\nabla \phi|} \right) \). \( \tag{19} \)

The dissipation characteristics of ENO scheme and re-initializations of level set lead to interface round off errors and violation of mass conservation. In order to correct these issues for precise interface tracking, a hybrid particle level set method is applied.\(^{15,16}\) Here, two types of massless particles, positive and negative particles, are placed in the region of \( \phi > 0 \) and \( \phi < 0 \), respectively. These particles are allowed to advect following the equation:

\[
\frac{d\tilde{x}_p}{dt} = \vec{u}(\tilde{x}_p), \tag{20}
\]

where \( \tilde{x}_p \) is the position of the particles and \( \vec{u}(\tilde{x}_p) \) is their velocity vector. The characteristic information of the flow is preserved due to deletion of the dissipation from the evolution equation.

Each particle has zero mass but has a volume. The radii of those particles are determined from the size of the grid as such, the maximum and minimum values are

\[
\begin{align*}
    r_{\text{min}} &= 0.1\text{min}(\Delta r, \Delta z), \tag{21} \\
    r_{\text{max}} &= 0.5\text{min}(\Delta r, \Delta z). \tag{22}
\end{align*}
\]

Initially, the particles are randomly placed and then directed to the correct direction. Then the final radii for particles follow:

\[
\begin{cases}
    r_{\text{max}} & \text{if } s_p(\tilde{x}_p) > r_{\text{max}} \\
    s_p(\tilde{x}_p) & \text{if } r_{\text{min}} \leq s_p(\tilde{x}_p) \leq r_{\text{max}} \\
    r_{\text{min}} & \text{if } s_p(\tilde{x}_p) < r_{\text{min}},
\end{cases}
\tag{23}
\]

where \( s_p \) is the sign of the particle and sets to \(+1\) if \( \phi(\tilde{x}_p) > 0 \) and \(-1\) if \( \phi(\tilde{x}_p) < 0 \), respectively. Here, if an error by the particles to move in the wrong direction with respect to the interface is detected, error correction through the local level set reconstruction is performed.

E. Ghost fluid method

The material properties change drastically across the interface between any two different materials. This is mainly due to the discontinuous entropy distribution at the interface that results in numerical truncation errors, which can be quite significant if not properly treated. In the present method, the ghost cells are populated in the opposite of the real material of interest using the extrapolation while having the continuous entropy distribution. Here, the real discontinuous entropy distribution is merged with the entropy distribution of ghost cells and generates proper boundary conditions. The physical conditions are used in the ghost band where pressure and velocity are the same as the interface conditions. Then the entropy in the ghost band is assigned the value of the real material. All other remaining variables are determined through the entropy relation and the proper EOS.\(^{18-20}\)

F. Interface conditions

At the interface, velocity components in the normal direction and stress fields must remain continuous following the conservation law as such that:

\[
\begin{align*}
    s_{\text{solid}}^{\text{m}} &= -p_{\text{fluid}}^{\text{m}}, \\
    s_{\text{solid}}^{\text{n}} &= p_{\text{fluid}}^{\text{n}}, \\
    v_{\text{solid}}^{\text{n}} &= v_{\text{fluid}}^{\text{n}}.
\end{align*}
\tag{24}
\]
III. MODELING CONSTANTS

The material properties and Mie-Gruneisen EOS constants are summarized in Table I. The chemical reaction and pressure growth of the energetic materials are calculated from the reactive flow model with JWL EOS as listed in Table II. The JWL EOS parameters of product gas of pentolite are calculated with a thermo-chemical equilibrium code.

IV. RESULTS AND VALIDATIONS

A. Shock attenuation in donor-gap configuration

We tested a combination of pentolite donor and PMMA gap to verify the shock generation and attenuation characteristics. The time evolution plot of the pressure profile along the centerline is shown in Fig. 1. Here, during the development of detonation wave, the von Neumann spike reaches approximately 31 GPa. The tendency of attenuation in the pressure is in good agreement with the LSGT data. The comparison of attenuating pressure is shown in Table III which demonstrates that the prediction of shock sensitivity is quite precise.

B. Interaction in gap-acceptor configuration

Handling of subtle motion between the gap (PMMA) and the acceptor (heavily aluminized RDX) is tested. One-dimensional Riemann problem, in which initial condition is given in Table IV, is solved and compared with the exact solution. The result with a mesh size of 0.5 mm at 6 μs is shown in Fig. 2. The interface between PMMA and RDX at x = 0.05 m moves to x = 0.065 m while retaining a sharp

TABLE I. Material properties for PMMA.

<table>
<thead>
<tr>
<th>Mechanical constant</th>
<th>Mie-Gruneisen EOS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial density (kg/m³)</td>
<td>1182</td>
<td>1780</td>
</tr>
<tr>
<td>Young’s modulus (GPa)</td>
<td>0.42</td>
<td>1.410</td>
</tr>
<tr>
<td>Shear modulus (GPa)</td>
<td>2.32</td>
<td>0.85</td>
</tr>
<tr>
<td>Thermal constant</td>
<td>Strength model</td>
<td></td>
</tr>
<tr>
<td>Specific heat capacity (J/kg·K)</td>
<td>1466</td>
<td></td>
</tr>
<tr>
<td>Room temperature (K)</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td>Melt temperature (K)</td>
<td>330.3</td>
<td></td>
</tr>
</tbody>
</table>

TABLE II. Modeling constants for Pentolite and heavily aluminized RDX.

<table>
<thead>
<tr>
<th>Model parameter</th>
<th>Pentolite</th>
<th>Aluminized RDX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactant</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ρ₀ (kg/m³)</td>
<td>1560</td>
<td>1780</td>
</tr>
<tr>
<td>A (GPa)</td>
<td>12.82</td>
<td>...</td>
</tr>
<tr>
<td>B (GPa)</td>
<td>0</td>
<td>...</td>
</tr>
<tr>
<td>C (GPa)</td>
<td>119.30</td>
<td>...</td>
</tr>
<tr>
<td>C₀ (mm/μs)</td>
<td>...</td>
<td>2.60</td>
</tr>
<tr>
<td>S</td>
<td>...</td>
<td>1.86</td>
</tr>
<tr>
<td>Γ</td>
<td>...</td>
<td>0.99</td>
</tr>
<tr>
<td>Product</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A (GPa)</td>
<td>507.91</td>
<td>2633.31</td>
</tr>
<tr>
<td>B (GPa)</td>
<td>6.52</td>
<td>8.59</td>
</tr>
<tr>
<td>C (GPa)</td>
<td>1.27</td>
<td>1.09</td>
</tr>
<tr>
<td>R₁</td>
<td>4.62</td>
<td>6.68</td>
</tr>
<tr>
<td>R₂</td>
<td>1.02</td>
<td>1.11</td>
</tr>
<tr>
<td>w (J/g K)</td>
<td>0.33</td>
<td>0.09</td>
</tr>
<tr>
<td>Chemical kinetics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I (s⁻¹)</td>
<td>1.4 × 10⁸</td>
<td>3.2 × 10⁸</td>
</tr>
<tr>
<td>A</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>G (s⁻¹ Mbar⁻¹)</td>
<td>3.3 × 10⁵</td>
<td>3.5 × 10⁷</td>
</tr>
<tr>
<td>b</td>
<td>1.3</td>
<td>0.7</td>
</tr>
<tr>
<td>p₀ (GPa)</td>
<td>1.2</td>
<td>5.9</td>
</tr>
</tbody>
</table>

TABLE III. Initial parameters for a Gap-Acceptor problem.

<table>
<thead>
<tr>
<th>Working mediums</th>
<th>PMMA</th>
<th>Al-RDX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>1182</td>
<td>2300</td>
</tr>
<tr>
<td>Pressure (GPa)</td>
<td>0</td>
<td>25</td>
</tr>
<tr>
<td>Velocity (mm/μs)</td>
<td>0</td>
<td>2.1</td>
</tr>
<tr>
<td>Initial yield stress (GPa)</td>
<td>0.42</td>
<td>None</td>
</tr>
<tr>
<td>Shear modulus (GPa)</td>
<td>2.32</td>
<td>None</td>
</tr>
<tr>
<td>Strength model</td>
<td>Constant yield stress</td>
<td>None</td>
</tr>
</tbody>
</table>
discontinuity, thanks to the hybrid particle level set method used. Although minor undershoots are observed around the contact line (especially in the case of density), two shocks propagating through the acceptor and the gap are captured quite precisely.

C. Shock attenuation inside PMMA gap

Shock attenuation through a PMMA gap is reproduced following the experimental LSGT data.\textsuperscript{23,24} The gap diameter of 5.08 cm is considered. The particle velocity following a shock wave is tracked along the central axis and plotted for each mesh size used in the simulation in Fig. 3. The present method is shown to capture the shock attenuation pattern in the PMMA quite well for all grid resolutions considered. The mesh size of 0.1 mm\textsuperscript{2} is suggested for all future gap test simulation.

D. LSGT of pentolite-PMMA-aluminized RDX

The large-scale gap tests were conducted. The length of gap substance was varied to observe the critical gap thickness until acceptor is detonated in 50\% of the trials. The donor charge is Pentolite whose initial density is 1.56 g/cm\textsuperscript{3}, and the acceptor is heavily aluminized RDX of its initial density 1.78 g/cm\textsuperscript{3}. The gap is provided by stacking PMMA discs to adjust its thickness height. All materials were shaped into a 50.8 mm diameter circle. The height of donor is 50.8 mm and that of acceptor is 139.7 mm. The gap length was varied. The gap test specimen and configuration are shown in Fig. 4.

Three trials are conducted at gap thicknesses varied by 0.254 mm interval. Go/No-go criterion is obtained until the witness plate breakage. From the experiment, the critical thickness was found to be 25.75 mm as any thicker value resulted in undamaged witness plate. Table V lists the LSGT experimental result.

<table>
<thead>
<tr>
<th>PMMA gap thickness (mm)</th>
<th>Go/No go</th>
</tr>
</thead>
<tbody>
<tr>
<td>24.480</td>
<td>Go</td>
</tr>
<tr>
<td>24.734</td>
<td>Go</td>
</tr>
<tr>
<td>24.988</td>
<td>Go</td>
</tr>
<tr>
<td>25.242</td>
<td>Go</td>
</tr>
<tr>
<td>25.496</td>
<td>Go</td>
</tr>
<tr>
<td>25.750</td>
<td>Go/No go</td>
</tr>
<tr>
<td>26.004</td>
<td>No go</td>
</tr>
<tr>
<td>26.258</td>
<td>No go</td>
</tr>
<tr>
<td>26.512</td>
<td>No go</td>
</tr>
<tr>
<td>26.766</td>
<td>No go</td>
</tr>
<tr>
<td>27.020</td>
<td>No go</td>
</tr>
</tbody>
</table>
The schematic of the gap test simulation is shown at the right hand side in Fig. 4. The gap sizes are varied from 15 mm to 30 mm with 1 mm interval. Pentolite cylinder block with a height of 50.8 mm and Al-RDX cylinder block of height 139.7 mm are modeled in a computational domain of 190.5 (+ gap height) mm. As for the initial condition for detonating a donor charge, 1 km/s impact is applied at the bottom. All other outer boundaries are unconfined.

The gap size is varied from 15 mm to 30 mm. The full simulation of the gap test for 25 and 26 mm is shown in Fig. 5. For clear illustrations, reaction progress variable ($\lambda$) and pressure are used for explosive charges (donor and acceptor) while density is used for PMMA. Pentolite is shown below the PMMA gap, and aluminized RDX is above. The subsequent initiation of acceptor then determines the sensitivity of the acceptor in the LSGT.

There are LSGT experimental data presented by Wall and Franson$^{21}$ and Bourne et al.,$^{22}$ where they measured the shock attenuation through PMMA. In Refs. 23 and 24, the peak particle velocities against gap thickness have been appraised. Our LSGT experiment has provided the critical gap thickness of an aluminized RDX acceptor, in a form that is rather brief but simplified for use in the computational research. The hydrodynamic simulation on the peak pressure

![Reactions and pressure plots](image-url)

(a) Go Case at 25 mm PMMA thickness

(b) Nogo Case at 26 mm PMMA thickness

FIG. 5. Shown reaction progress and pressure for donor (bottom)/acceptor (top), density for PMMA (middle). (a) 25 mm gap and (b) 26 mm gap at times $t = 7$, 8, 10, 12, 13, and 15 $\mu$s.
histories and particle velocity curves shown in Figs. 1 and 3 are in good agreement with the experimental data, including both the detonation pressure of energetic materials and its attenuation within the non-reactive materials.

Figure 5 shows how the donor detonation wave is attenuated through the gap depending on PMMA thickness. The go/no-go of acceptor is determined. A full set of reactive compressible equations of two energetic materials are solved while comprehensive stress field calculation is used to accurately track the evolution of PMMA undergoing its shape change. The go case in (a) shows the initiation of acceptor with initiating pressure shown in several GPa ranges, where as in (b) the no-go case is shown with diminishing pressure following pressure attenuation leaving the gap. The importance of the equation of state for materials involved in LSGT is of particular interest. The precise capturing of the gap thickness for go/no go is also due to resolving the impedance mismatch between reactive medium and inert, namely, PMMA. At 26 mm, the detonation failure might have occurred because such a critical gap thickness ($t_c$) must lie somewhere below this thickness, namely, 25 mm.

The shape change of PMMA during the test is quite interesting. As the pressure is less attenuated in 25 mm case as such most of the donor pressure is transmitted to the acceptor, causing a higher compression of the gap during successive acceptor initiation. The density of the deformed gap in Fig. 6(a) remains higher than no go case shown in Fig. 7(b). Under the condition that the gap length is

FIG. 6. Shape evolution of PMMA during shock attenuation: (a) initial PMMA thickness of 25 mm and (b) initial PMMA thickness of 26 mm at times 8, 14, 20, and 26 μs.

FIG. 7. Time trace of consecutive pressure profiles of LSGT simulation with 25 mm and 26 mm gap thickness.
relatively short, transmitted shock pressure becomes increasingly high near the central axis of the acceptor due to highly reactive detonation front in the center. The resulting curvature of PMMA is therefore concave up or down as shown in Figs. 6(a) and 7(b).

The time trace of consecutive pressure profiles along the centerline of LSGT simulation with 25 mm PMMA gap which is a Go and 26 mm No-go are shown in Fig. 7. The initial shock pressure at the Pentolite donor is about 31 GPa. The shock is attenuated through the gap. When donor shock triggers the acceptor charge, the initiating pressure \( p_i \) of the acceptor was approximately at 5.9 GPa.

E. Impedance calculation for validation

For the impedance analysis, the considered LSGT test near the contact between gap and high explosive is assumed one-dimensional. The acoustic impedance calculation becomes quite effective in providing a secondary view on the go/no-go prediction from LSGT test in addition to a standardized pressure calculation.

Figure 8 shows reflection and transmission of a plane wave incident on contact surface between the two different matters with distinct impedance.

The ratios of the pressure amplitudes and intensities of the reflected and transmitted waves depend on the characteristic acoustic impedance and the speed of sound in the two media. The incident and reflected waves travel in the first medium of characteristic acoustic impedance \( r_1 = \rho_1 c_1 \), where \( \rho_1 \) and \( c_1 \) are the equilibrium density and the speed of sound in the first medium, respectively. The transmitted wave travels in the second medium whose characteristic acoustic impedance is \( r_2 = \rho_2 c_2 \). If pressure amplitude of the incident wave is \( p_i \), those of the reflected and transmitted are \( p_r \) and \( p_t \), respectively. Therefore, one can define pressure transmission and reflection coefficients using the following equations:25

\[
T = \frac{p_t}{p_i}, \quad (25)
\]
\[
R = \frac{p_r}{p_i}. \quad (26)
\]

The boundary conditions need to be satisfied at all times on the contact surface as such the pressure and particle velocity on both sides of the surface must equal to each other

\[
p_i + p_r = p_t, \quad (27)
\]
\[
u_i + u_r = u_t. \quad (28)
\]

Division of (27) by (28) yields

\[
\frac{p_i + p_r}{u_i + u_r} = \frac{p_t}{u_t}. \quad (29)
\]

Since the continuity of acoustic pressure across the surface demands \( p/u = r \), (29) becomes

\[
\frac{r_1}{\rho_1 c_1} + \frac{r_2}{\rho_2 c_2} = \frac{r_2}{\rho_2 c_2}, \quad (30)
\]

which leads directly to the transmission and reflection coefficients26

\[
T = \frac{\rho_2 c_2 + \rho_1 c_1}{\rho_1 c_1} = \frac{r_2 + r_1}{r_2 + \rho_1 c_1}, \quad (31)
\]
\[
R = \frac{\rho_2 c_2 - \rho_1 c_1}{\rho_1 c_1} = \frac{r_2 - r_1}{r_2 + \rho_1 c_1}. \quad (32)
\]

Here, T-R equals 1. Thus if \( \rho_1 c_1 = \rho_2 c_2 \), acoustic wave will not be reflected at the contact surface.

FIG. 8. Jump in the acoustic impedances.

FIG. 9. Pressure and acoustic impedance of LSGT configuration (donor, gap, and acceptor).
Pressure and acoustic impedance profiles at the contact interfaces of LSGT are plotted in Fig. 9. The incident pressure is approximately 31.27 GPa right before the impact on the first contact. Subsequently, the incident wave is split into two, namely, 15.67 GPa transmitted and 13.85 GPa reflected waves. Here, the negative sign represents the direction of the wave propagation.

As the wave is propagated, the intensity of impedance varies from high to low and back to high again, going through two contact interfaces. Based on Eq. (32), reflection coefficient is positive when \( r_1 < r_2 \), but negative when \( r_1 > r_2 \). Consequently, at the interface, the acoustic pressure of the reflected wave is either in phase or 180° out of phase with the incident wave. When the acoustic impedance of the third medium is greater than that of PMMA, a positive pressure in the incident wave is reflected as a positive pressure. On the other hand, if \( r_1 > r_2 \), a pressure is reflected backwards. When \( r_1 = r_2 \), reflection coefficient equals 0, and such all is transmitted. Transmission coefficient being the ratio between incident pressure and transmitted pressure is calculated to be 0.52 while reflection coefficient is a bit less, \(-0.48\). The summation of these coefficients equals one as discussed.

V. CONCLUSION

We have presented a modeling strategy necessary for accurately reproducing the large scale gap test result for characterizing the heavily aluminized RDX. The methodology for such a numerical calibration of shock pressure attenuation within the gap is quite straightforward assuming the models are properly implemented and solved in the well-formulated hydrodynamic shock physics code. The present strategy can also accommodate any other type of non-ideal energetic materials (acceptor) subject to a precise characterization.

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