TITLE: Reflected-Shock Initiation of Explosives

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REFLECTED-SHOCK INITIATION OF EXPLOSIVES

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In a study of initiation caused by reflected shock from a high-impedance boundary, attempts to establish sufficient conditions for initiation are described. Shock polar analysis is used to discover the ranges of various flow regimes. General shock structures and pressure estimates of states behind the reflected wave. Using this knowledge, wave structure growth rates from hydrocode simulations are estimated and standard shock initiation criteria are used; experiments are described in which the initiation from a reflected shock wave structure appears likely. Two experiments are described in which a reflected shock wave from a high surface initiated PBX 9502. The experimental evidence is in good agreement with the simulations and results of the analysis.

INTRODUCTION

Shock initiation of explosives has been studied extensively and has resulted in useful models that describe the run to detonation, even though the usual shock pressure. The experiments leading to these models were designed to eliminate boundary effects. The work presented here studies the influence of high impedance boundaries on shock initiation of explosives. When boundaries are included in the problem, wave analysis is required to determine the effect of wave reflections from the boundary. Our approach to this problem was to examine the shock structure of the nonreactive reflected wave problem using shock polar analysis and hydrocode simulations. We then looked for the shock structures that appear likely to initiate the explosive, considering the known explosive properties.

To obtain the shock structure, we studied the simple geometrical configuration of the reflection of a nonreactive, plane shock traveling in the explosive impacting a flat high-impedance metal plate like lamina. In this case, classical shock polar theory applies. This simple analysis determines the pressure behind the reflected wave as a function of the interaction angle and incident shock pressure. If the wave reflection is regular, the incident wave and the reflected wave are matched to the wall. If it is irregular, a more complicated shock structure must exist between the incident and reflected shock and the wall in order to satisfy boundary conditions. Shock polar analysis is only a local analysis, and it has limitations because the flow configurations are assumed in order to do the analysis. Our hydrocode calculations of the wave reflection problem were made to validate the shock polar analysis and to obtain growth rate information of the irregular reflection.

To find a case in which a reflected shock is likely to initiate an explosive, we expect the following conditions must be met: 1) the incident shock must not decelerate the explosive; 2) the ambient pressure must be maintained over the distance approximately equal to the single shock time to detonation distance corresponding to the amplified pressure; and 3) the pressure must be maintained over a width of explosive approximately the same as the diameter radius of the explosive. These conditions are the same used on any shock to estimate whether initiation would occur, the only difference is that we are applying them to a local shock structure that occurs from a boundary interaction.

All the experimental work reported here studies the initiation of PBX 9502 by reflected waves from high impedance boundaries. To PX 9502, we found that regular reflection was most likely to result in initiation (though not very insensitive) is that the irregular reflection results in an amplified pressure wave running into explosive that was not preshocked. This wave structure, often referred to as a Mach stem or Mach reflection, is not the classical triple point solution, but reflect a curved stem structure. We will discuss the analysis that suggests shock initiation with an irregular reflection or Mach reflection is possible, two experiments in which such initiation was detected for PX 9502, and possible situations that may depin or enhance the effect.

CHARACTERIZATION OF REFLECTIVE WAVE BEHAVIOR

LOCAL ANALYSIS

The previous work and analysis included e. a plane shock incident on a flat high-impedance plate. We applied the
classical shock wave theory, shown in the contact reflection in explosive, with appropriate equations of state near Table 1.

When a shock wave encounters an interface, two basic kinds of shock reflection occur. Regular reflection is the case in which the incident wave and the reflected wave intersect at an angle (Fig. 1). Irregular reflection includes all other possible solutions, of which there are many. The most common is regular reflection: Classical Mach reflection, in which

FIGURE 1. REGULAR AND MACH REFLECTION FLOW DIAGRAM

TABLE 1. REFLECTION EQUATION OF STATE PARAMETERS

<table>
<thead>
<tr>
<th>Material</th>
<th>Density</th>
<th>Shock Mach</th>
<th>Contact Mach</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHNM</td>
<td>1.294</td>
<td>M = 3.07</td>
<td>M = 1.0</td>
</tr>
<tr>
<td>He</td>
<td>1.35</td>
<td>M = 3.07</td>
<td>M = 1.0</td>
</tr>
</tbody>
</table>

In the local shock wave analysis, the flow in the region delineated by the shocks is assumed to be one-dimensional. Shock jump conditions: assumptions of mass, momentum, and energy subject to the equations of state are satisfied across each shock. The incident shock moves the flow toward the wall and the reflected wave moves the flow away from the wall. As the walls, the boundary conditions are such that the flow behind the shock structure must be parallel to the flow in the wall and pressure is continuous across the boundary. An irregular reflection appears when a regular reflection cannot meet this compatibility condition.

The shock point in the pressure flow angle plane is a convenient means of comparing the possible solutions. The flow velocity \( V_n \) is fixed and the angle \( \theta \) between this velocity vector and the shock is varied. Jump conditions are used to calculate the normal component of the velocity \( V_n \) behind the shock, and because the tangential component is unaltered, the flow angle can also be found. Flow angle \( \theta \) and the pressure, the two variables of interest, are plotted in Fig. A. The point labeled \( F \) indicates the state achievable behind the incident shock. The point labeled \( K \) indicates the state achievable behind the reflected shock at the state behind the incident shock. The point labeled \( P \) indicates the states achievable behind the shock transmitted in the ambient. In regular reflection case \( \theta = 0 \), the flow behind the shock structure satisfies the boundary conditions at the intersection of the \( F \) and \( K \) point, where the flow across the wall is parallel and no pressure gradient exists across the wall.
In Mach reflection see the text. The T and R polars do not intersect. If T and R had intersected at more than one point, a "classical" Mach reflection would be a possible solution. In this case, however, the incident shock will merge as the wall is approached. If the flow is quasi-steady, this analysis can be continued. This assumption is equivalent to assuming that the stream pressure is not greater than the incident Mach number at the wall. This assumption also means that the flow behind the Mach stem at the wall will be approximated by the intersection of the T and R polars. Furthermore, the stream on the curved Mach stem at pressure, displaced from the wall by the incident shock. Hence, the pressure at the intersections of T with the T and R polars. Because of this assumption, the pressure at the intersections of the Mach stem and growth rate and angle. However, the shock in the T polar indicates a possible solution. The incident shock wave will have reached an amplified pressure level before a new shock front. The intersection of the two shocks are determined by the wall pressure or the shock wave front. The solution to the reflection problem can be plotted on the pressure interaction angle plane. In this case, the wall pressure determines the reflected wave front as a function of the interaction angle for fixed incident shock pressure. The solution for a 45° incident shock is shown in Figure 4.

**Figure 4:** Shock polar for regular reflection in PHX 900.

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**Figure 5:** Wall pressure interaction angle plot for 45° incident shock. The open points indicate regular reflection. The solid points indicate irregular reflection.

In either regular or Mach reflection, the pressure is elevated to a level that will initiate an oscillation. In Mach reflection, the elevated pressure propagates into the stream and causes it to decelerate, reducing the Mach number at the wall. In regular reflection, however, the shock is not vital and the pressure remains relatively constant. The shock polar analysis is convenient for giving simple results and estimates of pressures, however, the analysis does not lead to any growth rate minimum, nor does it examine the stability of the flow. To answer these questions, we examined the flow using the MESA hydrocode code.

**HYDROCODE ANALYSIS**

With MESA we obtain accurate reflected wave solution pressures, and other important parameters. The results are shown in Figure 4.
precompressed explosive has been studied. This initiation scenario may be much more important in more sensitive explosives like PBX 9404. These have much smaller failure thicknesses than the insensitive explosives, and much lower maximum shock pressures, so an overall smaller area, critical mass. In any event, we did not examine the Mach reflection regime where pre-shock was not an issue.

In Mach reflection, with sufficiently elevated pressure behind it, the shock propagates into unshocked explosive and presents a likely initiation case because the explosive has not been precompressed. Another aspect of Mach reflection enhances the likelihood of a situation in which initiation can occur. The flow behind a normal portion of the current shock wave system is adiabatic. This implies that energy release from the shocked explosive has a chance of recombining the shock wave and of building to a detonation wave.

The remaining requirement is that the Mach stem must be sufficiently large. Classical shock polar analysis provides one such growth intersection in this current stem case. However, the hydrocode calculations indicated a growth angle of 4 to 5. This would imply that initiation would occur after a run of 4 to 5 mm along the surface of the maximum plate, depending on the shock pressure and angle. Using this analysis, we determined the experiments to detect the transition from shock to detonation when a 10 kps plane shock in PBX 9404 is reflected from a flat maximum plate with an incidence angle of 20° and 30°.

**EXPERIMENTAL RESULTS**

The PBX 9404 test pieces were six-sided prisms (see the top and bottom surfaces defined two horizontal planes, 48° apart. Two sides defined planes that were perpendicular to the top and bottom plane. One of the other two surfaces was not defined as the angular surface. The other surface in which the shock was angled at 40° on the bottom plane and was defined as the observation surface. The other surface in which the shock was angled 40° or 30° with respect to the bottom plane and was covered with a 10 mm thick maximum plate together the reflection boundary. A plane shock wave was driven onto the bottom of the prism with the plane wave attenuation system shown in Fig.

The phase velocity of the wave along the maximum surface, the width of the Mach stem, and the incident wave velocity, pressure, and position must be observed to obtain a complete experimental record of the experiment. The shock arrival time along the maximum surface was measured with a series of time of arrival pins that were placed at known distances along the maximum line. Each pin represented the time at which the shock propagated to some angle through the maximum plane, north to the free surface. We examined the phase velocity of the wave at the explosive metal interface from these data to determine the time to be used. We obtained the width, shape, and velocity of the Mach stem as well as the incident wave velocity by a multiple observation technique. The measured of surface A and B and at the 10 mm of surface A were obtained at different angles of incidence and by different wave lengths shown in Fig. 8.

In Fig. 7 the shock arrival times on the metal surface for the 40° experiment shown by his show that the incident phase velocity associated with the propagation of the most Mach reflection is about 1/30 kps. About 15 mm from the source, a transition to 1/40 kps occurs. Similar results for the 30° incidence angle, also shown in Fig. 8, indicate that the wave accelerates from 1/25 kps to 1/45 kps after passing the surface for 30°.

Figure 6: PBX 9404 Test Piece With Uranium Plates Attached

Figure 7: The Plane Shock Driver System Used to Drive a Plane Shock Into the Test Plate (9x9x9cm)

Dimensions: Art in MBF 1045
sensitive film in the region away from the impact surface. These were then used to obtain the location of the incident shock and thus to estimate the incident pressure. The Mach stem developed at the impact face was observed as the camera shutter was released. The Mach stem width was then measured, and the location of the impact within the window was determined. A model was then used to estimate the shock wave from the incident pressure. The two shock waves were then be reinforced if one is willing to accept a calculated value for this angle. The Mach stem width data, as quoted as a function of position along the incident plane in Fig. 4. A sudden change in wave width is associated with the transition to detonation. This is in good agreement with the previously described pin data. The last shock wave is a detonation wave 7 μm wide in the 40° case and 17 μm wide in the 90° case.

DISCUSSION

The experiments described in PHX 9501, a Mach reflection can have the same degree of reflection for two different incident angles. However, the data on this shock wave indicate that a 2 mm radius impact shock PHX 9601 would detonate at 7.39 1/4 for the 40° case and 17.0 1/4 for the 90° case. The transition to detonation is very well predicted by these values. Minimum width of the detonation shock has been estimated is about 4 μm, and this is close to the incident radius of 1.76 mm for PHX 9501. Pressure behind the detonation was, estimated at 190 1/4 for both 40° and 90° incident angle. A shock wave was observed at these angles is about 1.8 mm and 17.0 mm respectively. The experiments assumed the shock pressure much lower than this. However, the shock behind the shock shock has not seen any measurable change in this shock front wave model to be able to model these data equitably. Calculations done by Idd Koeller show that this is indeed true and has extraneous effects that the minimum width in these cases are due to the shock distortion structure.

Further work continues on this topic in the areas of other explosive materials, divergent shock waves and the effect of convergent shock waves on shock wave interaction. We are using PHX 9501 to assess the implications of the shock wave attenuation on the shock front wave interaction. The data indicates that for PHX 9501 the angle at which Mach shock is observed important and that PHX 9501 primarily be used in the absence of information.

FIGURE 4. DETERMINATION WAVE RECORDED FOR SHOT No. 1620 - INCIDENT SHOCK WAVE ESTIMATE IN ENHANCEMENT

FIGURE 5. PIN DATA FOR SHOT No. 2640 - INCIDENT WAVE ESTIMATE IN ENHANCEMENT

The incident wave was observed clearly show the development at reflected Mach stems with profiles at 10° and 45° the transition was observed when the shock reached a tension between 2 and 4 mm in the 40° case and between 4 and 6 mm in the 90° case. After the transition, a detonation wave was clearly observed with a growth angle of about 5° in the 90° incident angle case and about 10° in the 40° case. We expect that this angle is strongly influenced by various mounting and prefocus configuration processes. These two to detonation, measured from the incident plane, are 4.5° of what one would expect to see. The uppermost existing line to detonation data to the incident shock pressure.
Divergence can occur in two different ways: the incident shock can diverge to the initial boundary, or it can move away from the incident shock. In both of these cases, computer simulations show that the transition of the Mach waves is abrupt. Experiments are currently being designed to examine these effects. We have only been able to analyze convergent geometry to date and will enhance the transition of Mach waves.

![Figure 10: Beam Camera Record for Shot No. C0014. Incident Shock Was 10 kbar at 50° Incidence. For Each Set, Time Is Increasing in the Vertical Direction. The Overexposure on the Beam in the Last Four Sets Is Due to the Bright Flash Resulting from the Detonation, as Compared with the Exposure of the Incident Shock.](image)

**Figure 10.** Beam Camera Record for Shot No. C0014. Incident Shock Was 10 kbar at 50° Incidence. For Each Set, Time Is Increasing in the Vertical Direction. The Overexposure on the Beam in the Last Four Sets Is Due to the Bright Flash Resulting from the Detonation, as Compared with the Exposure of the Incident Shock.

In summary, we have experimentally observed the transition of a Mach reflection in a detonation in PBX 9502. This mechanism can radically reduce the run-to-detonation in explosive charges with high-impedance boundaries. Classical analysis can bound the incident shock wave, and angles of Mach reflection are relevant. The resulting shock configurations and knowledge of explosive behavior can be used to help decide whether mutation is likely. However, growth angle and stem size information is not found by means of the classical analysis. Computer simulations are useful for obtaining growth angle estimates, and laser light models can be used to examine the mutation process. Even so, there are still many problems associated with the angle of the finite state and sensitive materials information for the explosive and the nature of the mutations that will need to be taken into account. Simulation of the finite state is necessary. Therefore, further experiments and analysis will be necessary to completely describe the mutation transition to shock reflection from high-impedance boundaries.

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