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## REFLECTION OF A PLANE DETONATION WAVE

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/Figures referred to in the text are appended. Numbers in parentheses refer to the bibliography./

The law of adiabatic expansion $pv^3$ = const (1,2) is approximately correct for products of detonation of condensed explosives with high densities (>1 g/ cc).

Studying the reflection of the front of a strong detonation wave from an absolutely stable wall, it is possible to arrive at formulas (3), which give the pressure and density in the first moment,

$$p_2 = p_h \frac{5\gamma + 1 + \sqrt{17\gamma^2 + 2\gamma + 1}}{4\gamma}, \qquad (1)$$

$$v_2 = v_h \frac{9\gamma^2 - 1 + (\gamma - 1)\sqrt{17\gamma^2 + 2\gamma + 1}}{9\gamma^2 + 2\gamma + 1 + (\gamma + 1)\sqrt{17\gamma^2 + 2\gamma + 1}}, \qquad (2)$$

$$D_2 = -\frac{v_2}{v_0}\left(\frac{p_2}{p_h} - 1\right) D, \qquad (3)$$

where $\gamma$ is the polytropic index, in out case equal to 3;



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$p_h = \frac{\rho_0 D^2}{\gamma + 1}$ is the pressure on the front of the detonation wave; $\rho_0 = \frac{1}{v_0}$ is the density BB, $v_h$ is the specific volume on the front of the detonation wave; $p_2$ and $v_2$ are the pressure and specific volume on the front of the reflected percussion wave; D is the speed of the front of the detonation wave; and $D_2$ is the speed of the front of the reflected wave.

These formulas are obtained from the standard theory of percussion waves on the assumption $E = \frac{pv}{\gamma - 1} = \frac{pv}{2}$ with $\gamma = 3$ (see table, I). This assumption must not be looked upon as exact, since with successive extension it would lead to a speed of detonation $D = \sqrt{2(\gamma^2 - 1)Q} = 4\sqrt{Q}$ not depending upon the density, while the equation $pv^3 = \text{const}$ was deduced from experimental data on the dependence of the speed of detonation upon the density BB. It is possible to solve the same problem, assigning $pv^3 = \text{const}$ not only to the isentrope, but also to the Gyugonio adiabatic curve of a percussion wave and using the exact formulae of the theory of percussion waves,

$$D = u_1 \pm \sqrt{v_1^2 \frac{p_2 - p_1}{v_1 - v_2}} \quad \text{and}$$

$$u = u_2 \pm \sqrt{(p_2 - p_1)(v_1 - v_2)}$$ (see table, II).

Finally, it is possible to examine approximately the changes of the state and speed of a percussion wave, using the correct formulas for a combination of acoustic waves $du = \pm c \frac{d\rho}{\rho} = \pm \frac{2}{\gamma - 1} dc = \pm dc$ (with $\gamma = 3$) and their integral $|u_1 - u_2| = |c_1 - c_2|$ (see table, III).

All three give very similar results for the state in the initial moment.

| | I | II | III |
|---|---|---|---|
| $p_2/p_1$ | 2387 | 2347 | 2370 |
| $v_2/v_1$ | 0760 | 0753 | 0750 |
| $c_2/c_1$ | 1347 | 1329 | 1333 |

Such agreement is the result of the small ratio of the speed to the speed of sound $u_1/c_1 = 1/3$ in the current which is not running to the wall, which leads to a closeness of the percussion wave to the acoustic and, in particular, to a small change of entropy (4). It is curious that this takes place with a significant change of the pressure of almost 2.5 times. (It can be shown that with any polytropic index, including $\gamma = 1$, the entropy changes very little in the reflection of the detonation wave.)

This circumstance with $\gamma = 3$ makes it very simple to solve the problem of the reflection of a detonation wave, using the acoustic bond u and c.



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Indeed, [illegible] showed (5), [illegible] polytropic index [illegible], the general solution of the equation of the uniform unsettled movement of a gas has the form:

$$x = (u + c)\, t + F_1 (u + c), \quad (4)$$

$$x = (u - c)\, t + F_2 (u - c), \quad (5)$$

where u is the local speed of the current of gas; c is the local speed of sound; $F_1$, $F_2$ are arbitrary functions.

We shall examine such a problem. Let the detonation wave begin at the left open end BB (the coordinate begins there also). We shall designate the length of the charge through a and at the right end at x = a, we shall place a wall. The detonation wave will be described by the equations (6).

$$x = (u_1 \mp c_1)\, t, \quad (6)$$

$$u_1 - c_1 = - D/2. \quad (7)$$

The movement of products of detonation which disintegrate to the left (into a vacuum; the presence of air can always be disregarded), is described by these same equations (Figure 1, upper pair of curves). At the moment of time $t = a/D$, the detonation wave reaches the wall and is reflected from it.

From the condition that $x = a$, $u = 0$, and that on the front of the reflected wave the conditions.

$$u_2 + c_2 = u_1 + c_1 \quad (8)$$

are fulfilled, we determine the value of the arbitrary functions $F_1$ and $F_2$.

We noticed that the speed of break in the reflected wave has a sign which is the opposite of that of the speed of break on the detonation wave. Since with $t = a/D$, a new solution is determined with $x = a$ and in this $u_2 = 0$, $c_2 = - D$, then

$F_1 (u + c) = a + \frac{a}{D} = 2a$, $F_2 (u - c) = a - \frac{a}{D} D = 0$; from this we have

$$u_2 = \frac{x - a}{t}; \quad (9)$$

$$c_2 = - \frac{a}{t}. \quad (10)$$

The speed of the front for a weak percussion wave (7) is $2D = u_1 \mp c_1 + u_2 \mp c_2$, which with $\gamma = 3$ and $\Delta u = \mp \Delta c$ will give

$$D_2 = c_2 + u_1. \quad (11)$$

From this,

$$D_2 = \frac{dx}{dt} = \frac{a}{t} + \frac{x}{2t} - \frac{D}{4}.$$

Integrating and remembering that with $t = a/D$, $x = a$, we obtain

$$x = - \frac{Dt}{2} - \frac{1}{2} \sqrt{aDt + 2a}, \quad (12)$$

which gives the law of the distribution of the front of the reflected wave. From this



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$$D_2 = -\frac{D}{2} - \frac{1}{4}\sqrt{\frac{aD}{t}}\,. \qquad (13)$$

We notice that the relative amplitude of the wave in this solution increases according to the measure of its diffusion, as a result of which the error of the allowances which are made also increases. In the case of an exact solution which considers the change of the entropy, the reflected wave would have to overtake the left front of the expanded products of detonation with $t \to \infty$ $(\rho \to 0)$. The solution which we have found indicates that the meeting will take place with $x = Dt/2 = -Dt/2 - 1/2\sqrt{aDt} + 2a$, from which $t = 16\, a/D$ and $x = -8a$. The pressure on the wall in this will be $\frac{64}{27}\frac{p_H}{16} = 0.0006\, p_H$, i.e., it will actually be extremely small. Thus, the inaccuracy is only with large t, when p is very small, i.e, in the field which is of no interest to us physically. The distribution of the speed of the current and the speed of sound in the reflected wave at different moments of time is illustrated in Figure 1; the density is $\rho \sim c$, the pressure is $\sim c^3$. (The upper pair of curves gives the distribution of products of detonation in scattering until the wave reaches the wall.)

We calculate the complete impluse of the pressure acting on the wall:

$$J = \int_{a/D}^{\infty} p\,dt = \frac{64}{27}\, p_H \left(\frac{a}{D}\right)^3 \int_{a/D}^{\infty} \frac{dt}{t^3} = \frac{64}{27}\frac{a\rho_0 D}{8} = \frac{8}{27}\, a\rho_0 D. \qquad (14)$$

A curve of the pressure with an explosion of an equal charge at the wall, such that the detonation wave would be distributed from the wall to the open end of the charge is illustrated in article (5). Curves of pressure on the wall in both cases are compared in Figure 2; the maximum pressure in the case of reflection (the continous curve) surpasses by eight times the pressure on the wall for the front of the wave separated from the wall (the broken curve); however, the complete impulse of pressure in both cases is the same.

Finally, examining the case of an ordinary explosion (compare(8)), i.e., instantaneous reaction of an entire explosive with the formation in the first moment of a layer of immobile explosion products of a constant density, we obtain a pressure curve of the type $p = p_\delta$; $t < t_1 = a/c_0$; $p = p_\delta (t_1/t)^3$; $t > t_1$ and, depending upon the assumption, the following numerical results.

1. Letting $E = pv/2$, we find for the pressure of the explosion p, the speed of sound in the products $c_0$, and the impulse J

$$p_H = 0.5\, p_\delta\ ;\ c_0 = D\sqrt{3/8}\ ;\ J_\delta = \sqrt{3^7/2^{11}} = 1.035\ J.$$

2. Letting $pv^3$ - const, not only along the isentrope, but also along the Gyugonio adiabatic curve,

$$p_\delta = \frac{27}{64}\, p_H = 0.42\, p_H\ ;\ c_0 = D\,\frac{9}{16}\ ;\ J_\delta = \frac{3^5}{2^8}\, J = 0.95\ J.$$

The corresponding curves p (t), not shown in Figure 1 (in order not to encumber it), are represented by a horizontal straight line between the axis of the ordinate and the falling arm of the continuous curve and practically conforms with this curve with $t > t_1$.



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[Appended figures follow]



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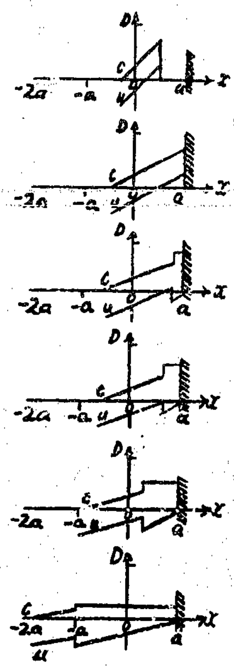


Figure 1

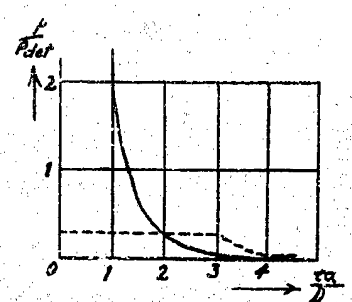


Figure 2

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