Defence Science Journal, Vol. 70, No. 4, July 2020, pp. 353-358, DOI : 10.14429/dsj.70.14005

Determination of Delay in Detonation of a Sandwiched Explosive Impacted by a Shaped Charge Jet

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ABSTRACT

A simple analytical model has been developed to determine delay in detonation of an explosive sandwiched between two metal plates and impacted by a shaped charge jet. The analytical model consists of a relation between detonation delay and depth of jet penetration in a target kept in contact across the explosive sandwich. This relation is derived by expressing depth of jet penetration P as a function of detonation delay T_{dx} and duration T_w of free passage of the jet through the hole in the top plate of the sandwich. One more relation between T_{dx} and T_w has been obtained from the theory of expansion of hole produced in a metal plate by jet impact. These two relations have been solved simultaneously to get values of both these parameters as a function of jet penetration. It is proposed that this analytical model can be used in two ways. First, this model can be used to calculate detonation delay by experimental measurement of jet penetration in a target. The detonation delay thus determined can be used to calculate insensitivity constant A_j of an explosive. Second, this model can be used to theoretically calculate jet penetrations obtained by different shaped charge warheads when using a sandwich of explosive with a given insensitivity. Both uses of this analytical model are illustrated using numerical examples.

Keywords: Shaped charge Jet; Virtual origin; Explosive sandwich; Detonation delay; Plate velocity; Jet shifting; Standoff distance; Jet penetration

1. INTRODUCTION

Condensed explosive gets detonated when a uniform shock wave[1-2] of critical energy ($E_c = PUT$, where P, U and T denote pressure, particle velocity and duration of shock wave, respectively) is produced in the explosive by impact of a plane metal plate. Impact of high velocity shaped charge jet, however, does not produce a uniform shock wave in the explosive. But its impact initiates detonation in the explosive if its diameter d_j and velocity V_j are such that[3-4] $d_j V_j^2 = C$, where C is characteristic constant of the explosive. The impact of a shaped charge jet on an explosive detonates it after a finite time delay, T_{dx}. This detonation delay has been shown experimentally to be given by relation[5-6].

$$T_{dx} = \frac{A_j}{\left(d_j V_{jp1}^2\right)^2} \tag{1}$$

where d_j and V_{jp1} denote the diameter and velocity of jet impacting the explosive respectively and A_j is insensitivity constant of the explosive.

In some armament stores such as explosive reactive armour (ERA), an explosive layer is sandwiched between two metal plates and initiated by jet impact. The conventional methods for measurement of detonation delay require sophisticated high-speed instrumentation which are very difficult to use for accurate measurement of delays of the order of a few microsecond duration in case of sandwiched explosives. Therefore, an alternate method for determining delay in detonation of sandwiched explosives due to jet impact has been proposed in this paper. This method takes advantage of the fact that jet penetration in a target in contact with the sandwiched explosive is a function of the detonation delay. Therefore, one can measure the jet penetration in the target, which is convenient to measure accurately, and infer the detonation delay from this jet penetration. In this paper, a mathematical model is developed to express detonation delay as a function of jet penetration in the target and example calculations of detonation delay for different jet penetrations has been carried out. This detonation delay has then been used to illustrate the method for theoretical calculation of jet penetration of a specified shaped charge warhead.

Received : 06 January 2019, Revised : 21 October 2019
Accepted : 14 February 2020, Online published : 13 July 2020

2. THEORETICAL FORMULATION

For deriving a relation between depth of jet penetration and detonation delay, one needs to analyse the interaction of the shaped charge jet with the metal plate moving rapidly across the jet after detonation of the sandwiched explosive. This analysis is carried out by using following assumptions:

(i) The shaped charge jet is a real jet with linear variation in velocity along its length.
(ii) All jet elements of different velocities are produced at a virtual origin at time, $t = 0$.

(iii) Jet of velocity, $V_j > 2\frac{mm}{\mu s}$, penetrates the target hydrodynamically.
(iv) The jet length which passes without interruption through the hole made by its impact in the sandwich penetrates the target.
(v) The plate remains plane during its motion against the jet after detonation of the explosive.
(vi) Experimentally determined relation given by Eqn. (1) holds good for detonation of a sandwiched explosive by jet impact.

2.1 Jet Interaction with Moving Plate

Suppose the jet is produced at a virtual origin at time $t = 0$ at a standoff distance S_0 from the sandwich and impacts the top plate P_1 of the sandwich with velocity V_{jp0} at time T_{jp0} obliquely at an angle θ with plate normal as shown in Fig. 1. The jet makes a hole in the top plate and reaches the exit of this plate at time T_{jp1} with velocity V_{jp1}. Thus, it penetrates this plate in time $\left(T_{jp1} - T_{jp0}\right)$. It then impacts the explosive which detonates after a time delay T_{dx}. The pressure of detonation products produces a shock wave in the top plate. When this shock wave reaches the free surface of the top plate, it reflects as a rarefaction wave in this plate. When this rarefaction wave reaches the interface of the plate and detonation products, the top plate starts moving in a direction normal to itself against the jet with a constant velocity V_p.

Let T_s denote the total travel time of shock and rarefaction waves which is also the time interval between the detonation of the explosive and the beginning of plate motion against the jet. Due to the motion of the plate in a direction along its normal, the point of impact of jet impacting obliquely on the plate begins to shift from the centre of the hole towards the wall of the hole as shown in Fig. 2.

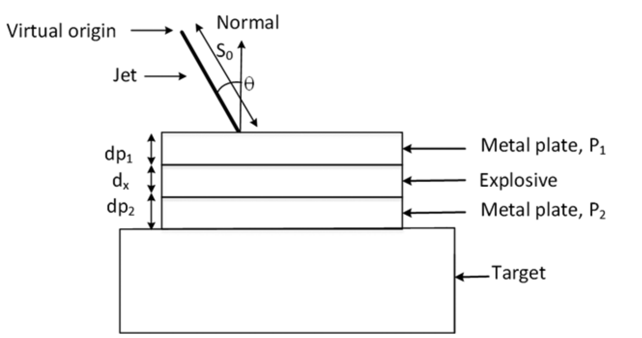

Figure 1. Setup for measurement of jet penetration in target across an explosive sandwich.

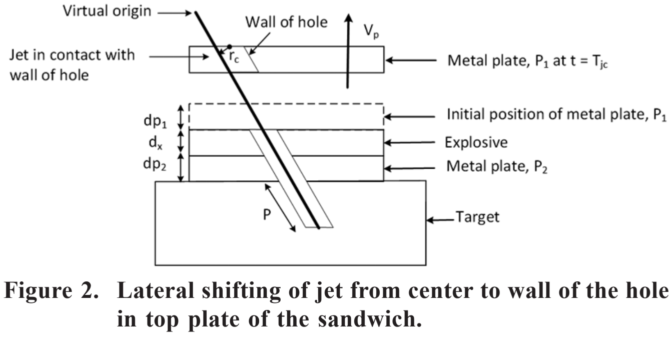

Figure 2. Lateral shifting of jet from center to wall of the hole in top plate of the sandwich.

This hole is expanding even during plate motion. The shifting of the point of impact of the jet and the expansion of the hole occur concurrently but with different rates. The rate of hole expansion decreases with time and becomes zero after formation of complete diameter of the hole, $d_h = 2r_{cm}$ where r_{cm} denotes the maximum radius of this hole. On the other hand, the point of impact of the jet shifts with a constant velocity because the plate moves with a constant velocity V_p. Due to this difference in rates of shifting of point of jet impact and expansion of the hole, the jet comes in contact with the wall of the hole of radius r_c in time T_w after start of plate motion. Thus, the jet touches the wall of the hole at time T_{jc} which is given as

$$T_{jc} = T_{jp1} + T_{dx} + T_s + T_w \tag{2}$$

where T_{jp1} is the arrival time of the jet at the exit of the top plate of the sandwich and T_{dx}, T_s and T_w are time intervals as defined above.

The wall of the hole comes in contact with the jet at time T_{jc} and disturbs its coherency continuously after this time. This disturbance reduces the penetrating power of the jet[7-8]. The jet penetration P at a point of the target is only due to that length of the jet which passes the explosive sandwich before the jet is disturbed at time T_{jc}. If tip and tail velocity of this length of jet are V_{jp2} and V_{jc} respectively, then theory of real jet penetration[9-10] gives jet penetration P as follows.

$$P = S_t\left[\left(\frac{V_{jp2}}{V_{jc}}\right)^{\frac{1}{\gamma_t}} - 1\right] \tag{3}$$

here $\gamma_t = \sqrt{\frac{\rho_t}{\rho_j}}$ and ρ_t , ρ_j are the densities of the target and the jet respectively and S_t is the standoff distance between the virtual origin of the jet and the target. This standoff distance can be written as follows.

$$S_t = S_0 + \left(d_{p1} + d_x + d_{p2}\right)sec\theta \tag{4}$$

here d_{p1}, d_x and d_{p2} denote the thicknesses of plate P_1, explosive layer and plate P_2 respectively.

In Eqn. (3), the only variable that depends on detonation delay is tail velocity V_{jc}. If jet penetration P is known, the tail velocity of jet V_{jc} can be obtained from Eqn. (3) as

$$V_{jc} = \frac{V_{jp2}}{\left(1 + \frac{P}{S_t}\right)^{\gamma_t}} \tag{5}$$

This velocity is the tail velocity of the jet which exits the top moving plate of the sandwich at time T_{jc}, when the moving plate starts disturbing the jet. Plate P_1 travels a distance V_pT_w before it starts disturbing the jet. The jet element having velocity V_{jc}, therefore, travels a distance $[S_0 + d_{p1}\sec\theta - V_pT_w\sec\theta]$ from the virtual origin before it exits plate P_1 with velocity V_{jc}. One can therefore express T_{jc} as

$$T_{jc} = \frac{S_0 + d_{p1}\sec\theta - V_pT_w\sec\theta}{V_{jc}} \tag{6}$$

Substituting Eqn. (5) in Eqn. (6), one gets,

$$T_{jc} = \left[\frac{S_0 + d_{p1}\sec\theta - (V_p T_w)\sec\theta}{V_{jp2}}\right]\left(1+\frac{P}{S_t}\right)^{\gamma_t} \tag{7}$$

In this Eqn, V_p is the velocity of the top plate given by relation[11-12]

$$V_p = \left[\frac{1.4D^2}{2(\gamma^2-1)\left(\frac{\rho_p d_{p1}}{\rho_x d_x}+\frac{1}{3}\right)}\right]^{\frac{1}{2}} \tag{8}$$

where, γ is specific heat ratio of detonation products, D is velocity of detonation of the explosive in the sandwich, ρ_p is the density of plate P_1, ρ_x is the density of the explosive and d_x is the thickness of the explosive. Substituting Eqn. (2) in Eqn. (7), one gets

$$\frac{\left[S_0 + d_{p1}\sec\theta - (V_p.T_w)\sec\theta\right]\left(1+\frac{P}{S_t}\right)^{\gamma_t}}{V_{jp2}} = T_{jp1} + T_{dx} + T_s + T_w \tag{9}$$

Rearranging above equation, one gets

$$T_{dx} = \frac{\left(1+\frac{P}{S_t}\right)^{\gamma_t}\left(S_0 + d_{p1}\sec\theta - V_p T_w \sec\theta\right)}{V_{jp2}} - \left(T_{jp1} + T_s + T_w\right) \tag{10}$$

This relation shows the dependence of jet penetration P on detonation delay, T_{dx}.

One can determine T_{dx} from this relation if penetration of jet P is experimentally measured and the values of V_p, V_{jp2}, T_{jp1}, T_s and T_w are known. The values of V_{jp2} and T_{jp1} can be determined from the velocities and arrival times of the jet at the exit of different elements of the sandwich. The value of T_s can be obtained from the shock and rarefaction wave velocities in the top plate. To complete the model of T_{dx} as a function of target penetration P, we will also need to write an Eqn to express T_w as a function of detonation delay T_{dx}.

2.2 Relations for Velocities and Arrival Times of Jet

The velocities and arrival times of the jet at the exit of different elements of the sandwich can be written using the theory of real jet penetration. The terminology of relevant exit velocities and arrival times is shown in Fig. 3.

If the jet impacts the top plate at a standoff distance S_0 with velocity V_{jp0}, at time $T_{p0,}$ then its velocity at the exit of plate P_1 is obtained by noting that the jet, in penetration of plate P_1, has penetrated a thickness of $d_{p1}\sec\theta$. Therefore, substituting $P = d_{p1}\sec\theta$ in Eqn. (5), one gets the jet velocity V_{jp1} at the exit of plate P_1 as

$$V_{jp1} = \frac{V_{jp0}}{\left(1+\frac{d_{p1}\sec\theta}{S_0}\right)^{\gamma_p}} \tag{11}$$

where $\gamma_p = \sqrt{\frac{\rho_p}{\rho_j}}$, ρ_p is the density of the plate and ρ_j is the density of the jet.

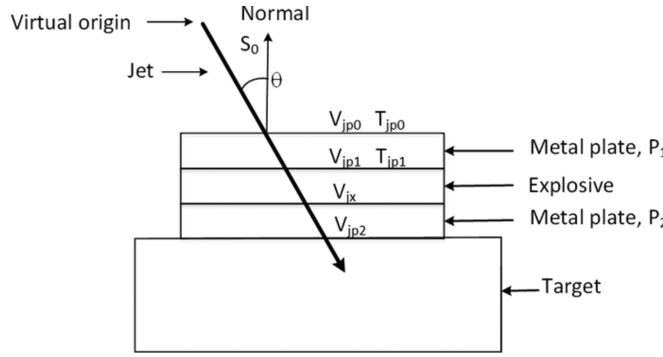

Figure 3. Terminology of velocities and arrival times of jet at the exit of sandwich plates.

Similarly, the jet velocity at the exit of explosive of thickness d_x is obtained as

$$V_{jx} = \frac{V_{jp1}}{\left(1+\frac{d_x\sec\theta}{S_0 + d_{p1}\sec\theta}\right)^{\gamma_x}} \tag{12}$$

In this relation, V_{jp1} is the tip velocity of the jet impacting the explosive, $S_0 + d_{p1}\sec\theta$ is the standoff distance between virtual origin and the explosive, $d_x\sec\theta$ is the length that the jet penetrates in the explosive, $\gamma_x = \sqrt{\frac{\rho_x}{\rho_j}}$ and ρ_x is the density of the explosive.

Similarly, the jet velocity at the exit of plate P_2 is given by Eqn. (13)

$$V_{jp2} = \frac{V_{jx}}{\left(1+\frac{d_{p2}\sec\theta}{S_0 + (d_{p1}+d_x)\sec\theta}\right)^{\gamma_p}} \tag{13}$$

In this relation, $S_0 + (d_{p1}+d_x)\sec\theta$ is the distance between virtual origin and surface of plate P_2 and $d_{p2}\sec\theta$ is the thickness penetrated in plate P_2.

Since the distance of lower surface of plate P_1 from virtual origin is $S_0 + d_{p1}\sec\theta$ and velocity of jet at the exit of plate P_1 is V_{jp1}, the time of jet arrival at exit of plate P_1 is obtained as

$$T_{jp1} = \frac{S_0 + d_{p1}\sec\theta}{V_{jp1}} \tag{14}$$

If shock and rarefaction wave in plate P_1 are assumed to have equal velocity U_s, then time T_s taken by this plate to start its motion after detonation of the explosive is obtained as

$$T_s = \frac{2d_{p1}}{U_s} \tag{15}$$

Substituting values of known parameters of a typical combination of jet, sandwich and the target in Eqns. (8) and (11-15), one gets the values of V_p, V_{jp2}, T_{jp1} and T_s for use in Eqn. (10). To complete the relation between T_{dx} and P in Eqn. (10), the only remaining variable to address is T_w. This needs to be expressed as a function of T_{dx}.

2.3 Relation between T_{dx} and T_w

To get one more relation between T_{dx} and T_w, one analyses Fig. 2 and gets

$$T_w = \frac{r_c}{V_P \sin(\theta)} \tag{16}$$

where r_c is the perpendicular distance from centre to wall of the hole in the top plate. At time $T_{jc} - T_{jp0}$ after jet impact on plate P_1, the distance r_c can be written as follows using the theory of expansion of hole produced by jet impact[13], as

$$r_c^2 = \frac{A_1}{B_1} - \left[\left(\frac{A_1}{B_1} - r_j^2 \right)^{\frac{1}{2}} - (T_{jc} - T_{jpo})(B_1)^{\frac{1}{2}} \right]^2 \tag{17}$$

where $A_1 = \frac{(r_j\ V_{jp0})^2}{2(1+\gamma_p)^2}$, $B_1 = \sigma / \rho_p$, σ is yield strength of plate, r_j is the radius of jet, $\gamma_p = \left(\frac{\rho_p}{\rho_j} \right)^{\frac{1}{2}}$, ρ_p is the density of the plate and ρ_j is the density of the jet.

Substituting r_c from Eqn. (16) and T_{jc} from Eqn. (2) in Eqn. (17), one gets

$$(V_p T_w \sin\theta)^2 = \frac{A_1}{B_1} - \left[\left(\frac{A_1}{B_1} - r_j^2 \right)^{\frac{1}{2}} - (T_{jp1} - T_{jp0} + T_s + T_w + T_{dx}) * (B_1)^{\frac{1}{2}} \right]^2 \tag{18}$$

2.4 Solution of Equations for T_{dx} and T_w

Equations (10) and (18), form a set of two equations between T_{dx} and T_w. In order to solve these equations, one substitutes T_{dx} from Eqn. (10) in Eqn. (18) and gets Eqn. (19)

$$(V_p T_w \sin\theta)^2 = \frac{A_1}{B_1} - \left[\left(\frac{A_1}{B_1} - r_j^2 \right)^{\frac{1}{2}} - \left\{ \frac{\left(\begin{array}{c} S_0 + d_{p1}\sec\theta \\ -V_p T_w \sec\theta \end{array} \right) \left(1 + \frac{P}{S_t} \right)^{\gamma_t}}{V_{jp2}} - T_{jp0} \right\} \sqrt{B_1} \right]^2 \tag{19}$$

Rearranging of Eqn. (19), one gets

$$A T_w^2 = \frac{A_1}{B_1} - [C + B T_w]^2 \tag{20}$$

where

$$A = (V_p \sin\theta)^2, \quad B = \frac{V_p \sec\theta}{V_{jp2}} \left(1 + \frac{P}{S_t} \right)^{\gamma_t} \sqrt{B_1} \text{ and}$$

$$C = \left(\frac{A_1}{B_1} - r_j^2 \right)^{\frac{1}{2}} - \frac{(S_0 + d_{p1}\sec\theta)\left(1 + \frac{P}{S_t} \right)^{\gamma_t} \sqrt{B_1}}{V_{jp2}} + T_{jp0}\sqrt{B_1} \tag{21}$$

After rearranging Eqn. (20), one gets

$$(A + B^2) T_w^2 + 2BCT_w + C^2 - \frac{A_1}{B_1} = 0 \tag{22}$$

Writing $a = A + B^2$, $b = 2BC$ and $c = C^2 - \left(\frac{A_1}{B_1} \right)$ in Eqn. (22), one gets

$$a T_w^2 + b T_w + c = 0 \tag{23}$$

Solving above quadratic equation, one gets two values of T_w for a known value of jet penetration P. Only the positive solution for T_w is of interest to us. Substituting the positive value of T_w in Eqn. (10), one gets a relation between detonation delay T_{dx} and jet penetration P. This Eqn is readily solved to get the value of T_{dx} as penetration P is known. This value of T_{dx} and the velocity V_{jp1}, obtained from Eqn. (11), can be substituted in Eqn. (1) to get the explosive insensitivity constant A_j as

$$A_j = T_{dx} (V_{jp1})^4 (d_j)^2 \tag{24}$$

After determining A_j of the explosive, one can use this value of A_j to get the delay in detonation of this explosive due to impact of any other jet.

3. RESULTS AND DISCUSSION

Suppose, a typical sandwich consists of an explosive layer of thickness d_x, detonation velocity D, density ρ_x and two metal plates, each of thickness d_p and density ρ_p as shown in Fig. 1. Typical numerical values of these parameters of jet and sandwich are given in Tables 1 and 2. This sandwich is impacted by a typical shaped charge jet of tip velocity $V_{jp0} = 9\frac{mm}{\mu s}$. The jet is produced at virtual origin at time $t = 0$ and impacts the sandwich at an angle $\theta = 60^0$ with the plate normal. The standoff distance between virtual origin and the sandwich is $S_0 = 200\,mm$. Suppose, the penetration P in the target across this sandwich for this shaped charge jet be 260 mm.

Substituting the constant parameters from Tables 1 and Table 2 in Eqns. (8) and Eqns. (11)-(13) one gets the velocities V_p, V_{jp1}, V_{jx} and V_{jp2}. The arrival time T_{jp1} and time interval T_s can be obtained from Eqns. (14) and (15), respectively. Using values of these parameters and $P = 260\,mm$, one can calculate the coefficients of Eqn. (23). Solution of this equation then gives the value of jet shifting time T_w which, when substituted in Eqn. (10), gives detonation delay time T_{dx}. The explosive insensitivity constant A_j is then obtained by solving Eqn. (24) using this value of T_{dx}. Calculated values of these parameters are given in Tables 3 and 4. The detonation delay T_{dx} for this example is calculated to be 11.68 μs and the corresponding value of explosive insensitivity A_j is 274411.323 $mm^6 / \mu s^3$.

Figure 4 shows the results of calculations of T_{dx} and T_w for a range of target penetration values for a shaped charge jet with tip velocity $V_{jp0} = 9\,mm/\mu s$ and the input parameters of Tables 1 and 2. The minimum target penetration would be achieved if the detonation delay T_{dx} is zero. Even if the explosive detonates without delay, the jet shifting time T_w has a minimum non-zero value. Therefore, there would still be some penetration in the target caused by the part of the jet that passes uninterrupted before it touches the wall of the hole in the top plate and becomes incoherent. The minimum target penetration $P_{min} = 75.59\,mm$ in this example which occurs when $T_{dx} = 0$ and the corresponding value of jet shifting time $T_w = 5.339\,\mu s$. The upper value of target penetration $P = 627.61\,mm$ in Fig. 4 corresponds to a detonation delay which is just large enough so that the shifting jet reaches the

Table 1. Jet, target and shock wave parameters.

$r_j\,(mm)$	θ	$d_{p1}\,(mm)$	$d_x\,(mm)$	$d_{p2}\,(mm)$	$S_o\,(mm)$	$V_{jp0}\left(\frac{mm}{\mu s}\right)$	$U_s\left(\frac{mm}{\mu s}\right)$
1.0	60°	3.0	8.0	3.0	200	9.0	5.2828

Table 2. Jet, target and shock wave parameters

$D\left(\frac{mm}{\mu s}\right)$	$\sigma\left(\frac{dynes}{cm^2}\right)$	$\rho_t\left(\frac{gm}{cm^3}\right)$	$\rho_j\left(\frac{gm}{cm^3}\right)$	$\rho_p\left(\frac{gm}{cm^3}\right)$	$\rho_x\left(\frac{gm}{cm^3}\right)$	γ
7.6	$5*10^9$	7.8	8.9	7.8	1.53	3.0

Table 3. Calculated values for $V_{jp0} = 9.0\,mm/\mu s$ and S_0=200 *mm*

$A_1\left(\frac{mm^4}{\mu s^2}\right)$	$B_1\left(\frac{mm^2}{\mu s^2}\right)$	γ_p	γ_x	$S_t\,(mm)$	$V_p\left(\frac{mm}{\mu s}\right)$	$T_s\,(\mu s)$
10.8	0.0641	0.936	0.415	228	1.500	1.136

Table 4. Velocities and arrival times of jet of tip velocity $V_{jp0} = 9.0\,mm/\mu s$ and S_0=200 *mm*

$V_{jp1}\left(\frac{mm}{\mu s}\right)$	$V_{jx}\left(\frac{mm}{\mu s}\right)$	$V_{jp2}\left(\frac{mm}{\mu s}\right)$	$V_{jc}\left(\frac{mm}{\mu s}\right)$	$T_{jp0}\,(\mu s)$	$T_{jp1}\,(\mu s)$
8.754	8.487	8.278	4.059	22.222	23.531

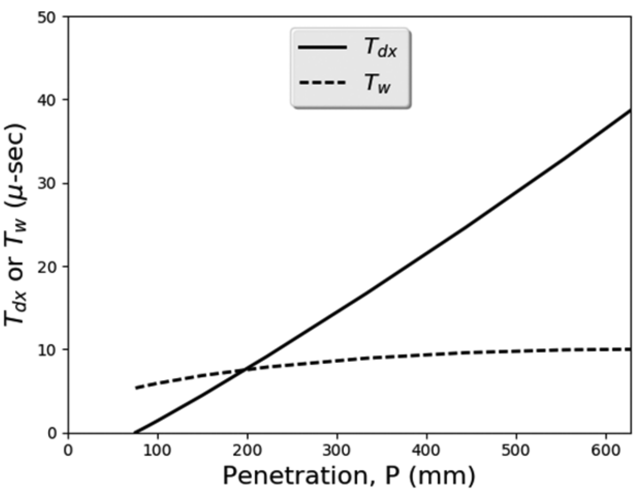

Figure 4. Variation of T_{dx} and T_w for different jet penetrations *P*.

wall of the expanding hole in the top plate at the same time at which the hole reaches its maximum diameter. The T_{dx} value for this penetration is $38.682\,\mu s$ and the T_w value is $9.989\,\mu s$. The formation of complete hole occurs in time $51.117\,\mu s$ after impact of jet on the top plate of the sandwich. Figure 4 shows that the detonation delay T_{dx} varies approximately linearly with target penetration and the jet shifting time T_w increases slightly with target penetration.

Once the insensitivity constant A_j of an explosive has been determined, the same analytical model described in this paper, can be used to calculate target penetration for any shaped charge jet by solving the equations in a different order. Such theoretical calculations would be very cost effective because the shaped charge warheads required to produce high velocity jets are very costly and conducting a large number of experiments for collection of jet penetration data becomes very expensive.

3.1 Theoretical Determination of Jet Penetration Across Sandwich having Explosive of Known Insensitivity Constant A_j

Suppose, having calculated the explosive insensitivity $A_j = 274411.323\,mm^6/\mu s^3$ as shown above, now one wants to calculate theoretically the penetration in the target due to a different shaped charge jet of tip velocity $V_{jpo} = 8.0\frac{mm}{\mu s}$. This jet is produced at virtual origin at time $t = 0$ and impacts the sandwich at a standoff distance $S_0 = 200\,mm$ obliquely at an angle $\theta = 60^0$.

The penetration in the target can be calculated using the following steps. Using parameters of sandwich, jet and target from Tables 1 and 2, one can solve for the various velocities V_p, V_{jp1}, V_{jx} and V_{jp2} using Eqns. (8) and Eqns. (11-13) and the arrival time T_{jp1} and time interval T_s using Eqns. (14) and (15) respectively. The detonation delay T_{dx} can be calculated from Eqn. (1) using the given explosive insensitivity A_j. In this case, the jet shifting time T_w is calculated using Eqn. (18) instead of Eqn. (23). Equation (18) is a quadratic Eqn in T_w and the positive root of this Eqn is the required solution for T_w. Eqn (6) is then used to calculate the tail velocity V_{jc} that exits the top plate before the jet becomes incoherent. If this tail velocity is less than $2\,mm/\mu s$, then a tail velocity of $2\,mm/\mu s$ is used to calculate target penetration. Using the standoff distance S_t from Eqn (4) allows one to calculate the target penetration using Eqn (3).

Tables 5 and 6 show the results of these calculations for the input parameters given in Tables 1 and 2 and a shaped charge jet of tip velocity $8\ .0\,mm/\mu s$ and a standoff distance $S_0 = 200\,mm$. The calculated value of detonation delay T_{dx} is $18.709\,\mu s$. The jet that penetrates the target has a tip velocity $V_{jp2} = 7.358\frac{mm}{\mu s}$ and a tail velocity $V_{jc} = 3.292\frac{mm}{\mu s}$. The calculated value of target penetration P for this example is calculated as 310.41 mm.

Table 5. Calculated values for $V_{jp0} = 8.0\,mm/\mu s$ and S_0 = 200 *mm*

$A_1\left(\frac{mm^4}{\mu s^2}\right)$	$B_1\left(\frac{mm^2}{\mu s^2}\right)$	γ_p	γ_x	$S_t\,(mm)$	$V_p\left(\frac{mm}{\mu s}\right)$	$T_s\,(\mu s)$
8.536	0.0641	0.936	0.415	228.0	1.50	1.136

Table 6. Velocities and arrival times of jet of tip velocity $V_{jpo} = 8.0\,mm/\mu s$ and S_0 = 200 *mm*

$V_{jp1}\left(\frac{mm}{\mu s}\right)$	$V_{jx}\left(\frac{mm}{\mu s}\right)$	$V_{jp2}\left(\frac{mm}{\mu s}\right)$	$V_{jc}\left(\frac{mm}{\mu s}\right)$	$T_{jp0}\,(\mu s)$	$T_{jp1}\,(\mu s)$	$T_{jc}\,(\mu s)$
7.782	7.544	7.358	3.392	25.0	26.473	54.827

4. Conclusion

This study proposed an analytical method of determination of detonation delay T_{dx} and insensitivity constant A_j of an explosive by measuring the depth of jet penetration in a target across the sandwich of the explosive. This method is convenient and has the potential to be reliable since it requires measurement of target penetration which is easy to measure accurately. Once the insensitivity constant of the explosive is known, the same analytical model presented here can be used to calculate target penetration for different shaped charge jets. This would be very cost effective since conducting experiments to determine jet penetration for different warheads is expensive.

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