HOSTED BY
ELSEVIER
CrossMark
Available online at www.sciencedirect.com
ScienceDirect
Defence Technology 12 (2016) 129–133

www.elsevier.com/locate/dt

Study of detonation wave contours in EFP warhead

Xu-dong ZU *, Zheng-xiang HUANG, Chuan-sheng ZHU, Qiang-qiang XIAO

School of Mechanical Engineering, Nanjing University of Science and Technology, Xiaolingwei 200, Nanjing 210094, China

Received 24 July 2015; revised 5 January 2016; accepted 6 January 2016

Abstract

An analytical model for calculating the propagation time of shock wave in a wave shaper is presented in this study. The calculated results show that the contours of three typical detonation waves, such as conical detonation wave, spherical detonation wave, and planar detonation wave, can be formed in the main charge by changing the thickness of wave shaper.

The results show that the planar detonation wave do better than the conical detonation and the spherical detonation wave in increasing the length–diameter ratio of explosively-formed projectiles (EFP) and keep the nose of EFP integrated. The detonation wave can increase the length–diameter ratio of EFP when the wave shaper has the suitable thickness.

Keywords: Explosion mechanism; Explosively-formed projectile; Wave shaper; Detonation wave contour

1. Introduction

Explosively-formed projectiles (EFPs) are used in numerous modern ammunition systems because of their advantages of effective stand-off and strong secondary effects after penetration. For the purpose of improving the penetration performance of warheads, one of the design goals of any designer is to obtain the most elongated and compact projectile with a high initial velocity [1]. Powerful explosives [2], detonation wave shaping [3], and the use of high-density and high-ductility liner materials are the main ways to achieve this goal [4]. The detonation wave shaping is considered to be the most efficient way of improving the penetration performance of warheads [5]. Embedding a wave shaper in charge is one of the ways to shape a detonation wave [6–8]. Weimann [1], Murphy et al. [6], and Men et al. [9] reported that the EFP length could be increased if a wave shaper is placed in charge. Zhang et al. [8,10] compared the performances of EFPs formed from warheads with and without wave shaper, and the results indicated that EFP formed from the warhead with a wave shaper has a higher velocity, larger length–diameter ratio, and higher penetration capability compared to that formed without a wave shaper. However, the researchers have not explored how to adjust the detonation wave contours shaped by the thickness of wave shaper on the formation of EFP.

An analytical model for calculating the propagation time of shock wave in the wave shaper is presented in this study. The time of the penetrating detonation wave reaching the liner and the time of the diffracted detonation wave reaching the liner can be determined. The calculated results show that the contours of three typical detonation waves can be formed in the main charge by changing the thickness of wave shaper. The effects of detonation wave contours on the formation of EFP were studied using the LS-DYNA software.

2. Analytical models

2.1. The initial parameters of shock wave in wave shaper

Given that the shock impedance of the Plexiglas is less than that of the explosive, the transmitted wave in wave shaper is a shock wave when the detonation wave impacts the wave shaper which is made of Plexiglas, whereas the reflected wave is a rarefaction wave. The initial parameters of the shock wave in wave shaper can be calculated by the following equation [11]

$$\left.\begin{aligned} u_x &= \frac{D}{\gamma+1}\left\{1+\frac{2\gamma}{\gamma-1}\left[1-\left(\frac{p_x}{p_{\mathrm{CJ}}}\right)^{\frac{\gamma-1}{2\gamma}}\right]\right\} \\ p_x &= \rho_{m_0}(a+bu_x)u_x \end{aligned}\right\} \tag{1}$$

Peer review under responsibility of China Ordnance Society.

* Corresponding author. Tel.: +8602584315649.
E-mail address: zuxudong9902@mail.njust.edu.cn (X.D. ZU).

http://dx.doi.org/10.1016/j.dt.2016.01.002
2214-9147/

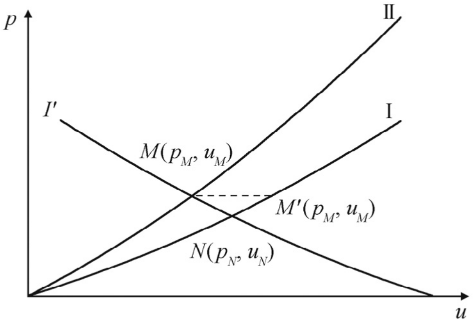

Fig. 1. u–p curves of Plexiglas and main charge.

where D is the velocity of detonation wave; P_{CJ} is the CJ detonation pressure; γ is the exponent in the polytropic equation of state for explosive; u_x is the particle velocity; p_x is the pressure of shock wave; ρ_{m_0} is the density of Plexiglas; and a and b are the material constants of Plexiglas.

2.2. Output parameters of shock wave in wave shaper

Given that the shock impedance of Plexiglas is less than that of the explosive, both the transmitted and reflection waves are the shock waves. The Hugoniot equations of Plexiglas and explosive are

$$p_1 = \rho_{01}(a_1 + b_1 u_x)u_x \tag{2}$$

$$p_2 = \rho_{02}(a_2 + b_2 u_x)u_x \tag{3}$$

As shown in Fig. 1, I and II represent the Hugoniot curves of Plexiglas and explosive, respectively, I' is the mirror curve of I about N, the pressure p_M and particle velocity u_M at the intersection point M are the initial parameters of shock wave in the main charge, M' is the mirror point of M about N, and the pressure p_N and particle velocity u_N at point N are the output parameters of shock wave in the wave shaper.

The criterion of shock wave initiating the explosive adopts the critical pressure criterion. If the critical pressure of the explosive p_c is known, $u_{M'}$ and u_M can be calculated by substituting $p_M = p_c$ into Eqs. (2) and (3). Given that M' is the mirror point of M about N, $u_N = (u_M + u_{M'})/2.0$. Finally, p_N can be calculated by substituting u_N into Eq. (2).

2.3. Critical thickness of wave shaper

Given that the attenuation of shock wave in inert medium is very complex, the attenuation law of shock wave in an inert medium can be expressed as an empirical formula [11]

$$p_x = p_0 e^{-\alpha x} \tag{4}$$

where p_0 is the initial pressure in the inert medium; α is the attenuation coefficient of the inert medium; x is the propagation distance of shock wave in the inert medium; and p_x is the pressure of shock wave corresponding to distance x.

The critical thickness of wave shaper h_c can be determined by substituting the initial pressure p_0 and output pressure p_N in Eq. (4).

2.4. Propagation time of shock wave in wave shaper

The velocity of shock wave in the wave shaper can be expressed as

$$u_s = a + bu_x \tag{5}$$

where u_s is the velocity of shock wave; and a and b are the constants of wave shaper material.

According to Eqs. (2), (4), and (5), the propagation distance x can be expressed as

$$x = -\frac{1}{\alpha}\ln\frac{\rho_{m0}u_s(u_s - a)}{bp_0} \tag{6}$$

A series of points (u_s, x) in the warhead can be obtained from Eq. (6), and the function of u_s about x can be obtained by fitting these points

$$u_s = A\left[(x - B)^2 + C^2\right] \tag{7}$$

The propagation time of shock wave in wave shaper can be written as

$$t = \int_0^h \frac{dx}{A\left[(x - B)^2 + C^2\right]} = \frac{1}{AB}\left(\arctan\frac{h - B}{C} - \arctan\frac{-B}{C}\right) \tag{8}$$

where h is the thickness of wave shaper; and A, B, and C are constants.

In the calculation, the 8701 explosive which consists of 95% RDX and 5% TNT was used as the subsidiary charge, with $\rho = 1.713\ \text{g/cm}^3$, $D = 7.98\ \text{mm/}\mu\text{s}$, and $P_{CJ} = 28.6\ \text{GPa}$ [12]. The material of wave shaper was Plexiglas with $\rho = 1.184\ \text{g/cm}^3$, $a = 2.572\ \text{mm/}\mu\text{s}$, and $b = 1.536$ [13]. The material of the main charge was an 8701 explosive with $\rho = 1.7\ \text{g/cm}^3$, $a = 2.95\ \text{mm/}\mu\text{s}$, and $b = 1.58$ [14]. The attenuation coefficient, α, of Plexiglas is 0.1186 [15]. The critical pressure of the 8701 explosive is 2.4 GPa [16].

Initial pressure p_0 and particle velocity u_0 in the wave shaper, output pressure p_n, particle velocity u_n, critical thickness h_c of wave shaper, and the constants in Eq. (8) can be determined according to the parameters mentioned above, which are $p_0 = 21.73$ GPa, $u_0 = 2.7194\ \text{mm/}\mu\text{s}$, $p_N = 1.9288$ GPa, $u_N = 0.49\ \text{mm/}\mu\text{s}$, $h_c = 20.4$ mm, $A = 0.0053$, $B = 25.7544$, and $C = 24.4835$.

3. Contours of three typical detonation waves

The configuration of EFP warhead with a wave shaper is shown in Fig. 2.

As shown in Fig. 2, two propagation paths for the detonation wave are created after the initiator initiates the subsidiary charge, where one path climbs the wave shaper and the other passes through the wave shaper. The detonation wave climbing the wave shaper is called the diffracted detonation wave, and the detonation wave passing through the wave shaper is called the penetrating detonation wave. The times of the diffracted and penetrating detonation waves reaching the liner vary with the change in the thickness of wave shaper. The contours of three typical detonation waves, such as conical detonation wave,