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Velocity axial distribution of fragments from non-cylindrical symmetry explosive-filled casing

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ABSTRACT

With the technical development of new warhead designs and explosive protection, theoretical research on the velocity distribution along the axis is important. The velocity distribution of fragments along the axis of 2 kinds of non-cylindrical casings, which were detonated at one end, was obtained and investigated in this paper with a flash-radiograph technique. The results of the experiments indicated that the rarefaction wave generated at 2 ends of the non-cylindrical casings was only related to the diameter of the explosive, instead of the filled ratio. According to the experimental conclusion, an "extended hard core" model was proposed, and its parameters were determined based on the analysis of the velocity distribution of different kinds of explosive-filled casings. This formula is able to directly obtain the velocity distribution of the non-cylindrical casing, which was detonated at one end, without needing experiments to determine unknown parameters. The formula is highly accurate and has a wide range of applications, which provides the basis for the new engineering design of diverse conventional warheads and explosive protection structure.

1. Introduction

The dynamic responses of the casing filled with an explosive charge, especially the velocity distribution, are typical issues in the field of warhead design, structure protection, and anti-terrorism technology. With the rapid development of irregular warheads and the higher requirements of variant explosives in the field of public security, analyzing the velocity of non-cylindrical casings has become increasingly important.

There have been many studies on fragment velocity distribution of explosive-filled casings. In addition, some formulas to calculate the fragment velocity have been established and demonstrated experimentally. Based on the conservation of energy, Gurney [1] proposed a typical formula to estimate the fragment velocity. His equation is based on the assumption that potential energy of the explosive before detonation equals to the kinetic energies of the detonation product gases and metal after detonation. The formula can be expressed as:

$$v_0 = \sqrt{2E}\cdot\sqrt{\beta/(1+0.5\beta)}, \tag{1}$$

where $(2E)^{1/2}$ is the Gurney constant of the explosive, v_0 is the Gurney velocity, and β is the filled ratio. The β can be expressed as $\beta = C/M$, where C is the mass of explosive and M is the mass of the metal casing.

In Gurney's model, the explosive in the casing is detonated simultaneously so the effect of propagation of detonation wave in the explosive is neglected. Thus, the fragment velocity distribution along the axis is consistent, that is, the fragment velocity axial distribution is free from effect of rarefaction waves coming from the casing ends and the influence of the angle between the detonation wave and the casing shell. However, in practice the fragment velocity axial distribution is effected by rarefaction waves and the incident angle of detonation wave. The dynamic response of the explosive-filled casing detonated at one end was recently studied numerically and experimentally [2–9]. König [10] studied the effect of rarefaction waves on the axial distribution of fragment velocity and its direction and then proposed a modified formula to estimate the velocity and ejection angle of fragments. Anderson et al. [11] further carried out numerical studies with different filled ratios and length–diameter ratios of cylindrical casings and explained how rarefaction waves affect the velocity and direction of fragments. Li et al. [12] established numerical models to study the effect of rarefaction waves, incident angle of detonation wave and eccentric initiation. The result shows that the axial distribution of the cylindrical casings is meanly affected by the rarefaction waves and incident angle of detonation wave. Grisaro and Dancygier [4] and Kong et al. [13] conducted numerical research on cylindrical casings with and without end caps, respectively. The numerical results indicated that the axial diffusion of explosive products caused the fragment velocity

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and ejection to be axially inconsistent.

Based on previous research, there are some modified empirical formulas to calculate fragment velocity. Hennequin [14], Randers-Pehrson [15] and Charron [16] proposed a correction formula, based on the Gurney formula, for the filled ratio according to a kind of geometric equivalence method. As shown in Eq. (2), the formula can calculate the fragment velocities distribution along the axis:

$$v_0 = \sqrt{2E}\cdot\sqrt{F(x)\beta/(1+0.5F(x)\beta)}, \tag{2}$$

where the correction formula can be expressed as $F(x) = 1-\min\{x/2R, 1, (L-x)/R\}$, x is the axial distance from the detonation point, and R is the radius of explosive.

After many experiments, Zulkouski [17] established a correction formula, $C_f(x)$, which is an exponential function that describes the influence of a rarefaction wave generated at 2 ends. The correction formula can be expressed as:

$$C_f(x) = (1 - e^{-2.3617x/d})(1 - 0.288e^{-4.603(L-x)/d}), \tag{3}$$

where x is the axial distance from the detonation point, and d is the diameter of explosive.

The correction formula demonstrates that the fragment velocity is distributed exponentially along the axis. It also implies that the rarefaction effect is only related to the diameter of explosive and the distance from the end. Huang et al. [18] experimentally investigated fragment velocity dispersal along the axis of the cylindrical casing using a flash-radiograph technique. The formula proposed by Zulkouski [17] was improved based on experiment results. The modified formula can be expressed as:

$$v_{0x} = (1 - 0.361e^{-1.111x/d})(1 - 0.192e^{-3.03(L-x)/d})\cdot\sqrt{2E}\cdot\sqrt{\beta/(1+0.5\beta)}, \tag{4}$$

where x is the axial distance from the detonation point, and d is the diameter of explosive.

In addition, a formula [19] was proposed to calculate the relationship of the expanding velocity of the casing with the expanding radius after many experiments. The model assumes that the casing breaks up when the radius expands several times larger than the initial radius, and the fragment velocity in this moment is regarded as the initial fragment velocity. This model is shown as follows:

$$v_0(x) = \frac{v_d}{16}\sqrt{\frac{\beta}{2+\beta}\left[1-\left(\frac{r_0}{r}\right)^4\right]\cdot\left[1+6\alpha(1-\alpha)+\frac{3}{2}\alpha\cdot\ln\frac{3-2\alpha}{\alpha} + 6\alpha(1-\alpha)(2\alpha-1)\cdot\ln\frac{3-2\alpha}{2(1-\alpha)}\right]}, \tag{5}$$

where α is the ratio of axial distance from the detonation point to length of charge, v_d is the detonation velocity of the explosive, r_0 is the initial radius of casing, and r is the expanding radius in one moment.

The equations mentioned above were developed considering the rarefaction waves at 2 ends, but there are still limitations in the formulas. On one hand, the calculated results of Eqs. (2), (4) and (5) were clearly different with experimental data, especially the velocity near ends. Therefore, the errors of the model are too large for application in practice [18]. Furthermore, the models mentioned above are only suitable to cylindrical casings.

Unlike cylindrical casings, the velocity distribution of non-cylindrical casings is related to rarefaction wave and it is also affected by the filled ratio. In this study, we carried out X-ray flash-radiograph experiments on various non-cylindrical casings to analyze the dynamic response of 2 kinds of non-cylindrical casings. The “extended hard core” model, which is established to estimate the initial fragment velocity of the cylindrical casing, is modified to expand the range of its application. In the modified model, the explosive volume is divided into an ineffective region (namely hard core) and an effective region in which the explosive product radial velocity is assumed to be linear. The new formula can be used to calculate the velocity distribution of non-cylindrical casings and does not require experiments to determine unknown parameters.

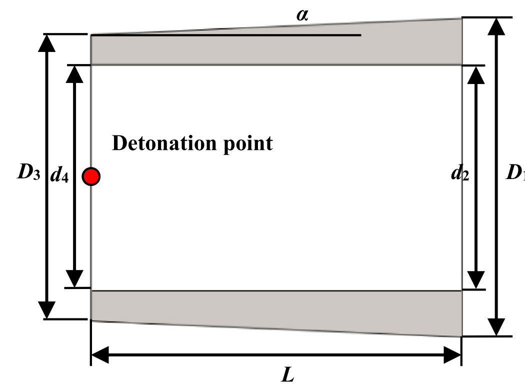

Fig. 1. Scheme for S-type casing.

2. X-ray experiments

2.1. Configuration design

The initial fragment velocities dispersing along the axis of non-cylindrical casings under interior blast loading were tested using the flash-radiograph technique. In addition, the experimental results of non-cylindrical casings were compared to those of the cylindrical casings. The casings with linearly changing shell thickness along the axis while the diameter of explosive stays the same were classified as S-type (see Fig. 1). The casings with linearly changing diameter of explosive along the axis while the thickness of shell stays the same were classified as C-type (see Fig. 2). The diameter of explosive and the shell thickness of these casings were the same at the detonation end for comparison.

In this paper, there were 4 experimental configurations: S1#, S2#, C1#, and C2#, according to the kind and change rate of each casing. For comparison, the experimental results of the cylindrical casings in Ref. [18] were also analyzed. Circumferential grooves were set uniformly along the axis on the outside of every casing to minimize the effects of mechanical properties of the shell, causing the casing to rupture more smoothly when the axial velocity gradient of the casing is high (see Fig. 3). The parameters of each configurations are listed in Table 1.

The analyses of the filled ratio of these explosive-filled casings were crucial, because the calculation in this study is based on the Gurney formula. The filled ratio of the cylindrical casings was 0.42, according to the parameters in Table 1. Unlike the cylindrical casings, the filled ratio of the non-cylindrical casings is a function of the axial distance

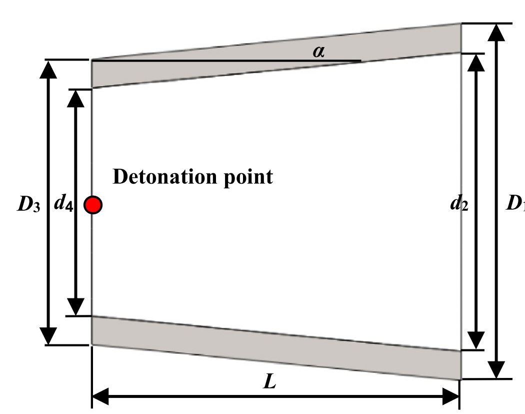

Fig. 2. Scheme for C-type casing.