Detonation Velocity Deficit and Curvature Radius of Flexible Detonation Fuses

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Abstract: The detonation velocity deficit in bending flexible detonating fuses is studied, based on the detonation wave's corner effects and delay time phenomenon. A physical model and a theoretical mathematical equation of the detonation velocity deficit are established by using the dimensional analysis. Based on experimental data, a semi-empirical formula of the detonation velocity deficit for bending fuses in the same charge size is derived. It is shown that the detonation velocity deficit and the reciprocal of the curvature radius are in an exponential relationship.

Key words: detonation velocity deficit, flexible detonating fuse, curvature radius, delay time.

INTRODUCTION

Flexible detonating fuses are widely used to improve the performance of mild multi-point synchronous explosive circuits, which are components of multi-synchronous directional warheads and explosive trains. The more synchronous the detonation wave at the fuse output, the more effective the explosive circuit operation [1, 2]. According to some researches about explosively formed penetrator (EFP) warheads [3], when the synchronization error of detonation wave exhaustion from the fuses was more than 100 ns, the tail wing of such EFP warheads was obviously lopsided, which resulted in poor flight stability. In actual design of mild explosive circuits, the fuses are inevitably bent into various shapes to meet the requirement of warhead assembly. Some researches [4–6] showed that detonation fuse bending led to the detonation velocity deficit, which finally turned to errors in synchronization of mild multi-point synchronous explosive circuits. Therefore, the study of the detonation velocity deficits of bending flexible detonating fuses is not only an interesting issue, but also a lacked theoretical basis in the application of flexible detonating fuses.

PHYSICAL MODEL AND MATHEMATICAL EQUATION

Ye et al. [4] tested the action time of linear and bending flexible detonating fuses under various conditions. The results showed that the action time of bending fuses was longer than that of linear fuses, which was named the delay time phenomenon [7]. The essence of this phenomenon is detonation wave's corner effects [8, 9]: when the detonation wave passes along the corner of the bending fuse, there is a non-steady-state detonation period [10, 11], resulting in the detonation velocity deficit, which finally leads to the delay time phenomenon.

Figure 1 shows two fuses of an identical length: bending fuse (OA) and linear fuse (OB). Propagation of the detonation wave along the bending fuse OA can be considered as a process of propagation along continuous corners. The main factors affecting the detonation velocity deficit in the bending fuse are:

1. the bending fuse geometry (shell thickness Δ, shell density ρs, and curvature radius R);
2. performance parameters of the charge in the bending fuse (charge density ρ, charge diameter d, critical charge diameter dc, detonation velocity D of the linear charge, and coefficient of expansion of detonation products β).
Thus, the detonation velocity deficit for the bending fuse $\delta_D$ can be expressed on the basis of the dimensional analysis \[6, 12\] as

$$\delta_D = f(p_s, c_s, R, d_{cr}, \rho, d, D, \beta).$$

(1) Taking $d_{cr}, \rho,$ and $D$ as the scale parameters in Eq. (1), we obtain

$$\frac{\delta_D}{D} = f\left(\frac{d_{cr}}{d}, \frac{c_s}{c_s}, \frac{\rho}{\rho}, \frac{D}{D}, \frac{\Delta}{\Delta}, \beta\right).$$

(2) If the detonation fuse structure is fixed, the parameters $\rho_s/\rho, c_s/D, d_{cr}/\Delta,$ and $\beta$ can be regarded as constants; therefore, Eq. (2) can be further simplified to

$$\frac{\delta_D}{D} = \left(\frac{d_{cr}}{d}\right)^m f_1\left(\frac{d_{cr}}{D}\right).$$

(3) For the same-size detonation fuse, the shell material and charge parameters $d,$ $d_{cr},$ and $D$ are constant; therefore, Eq. (3) can be transformed to

$$\frac{\delta_D}{D} = n f_1\left(\frac{1}{R}\right).$$

(4) Here, $n$ is related to $d$ and $d_{cr}$. There are two boundary conditions for Eq. (4):

1. under the assumption that $R_{cr}$ is the critical curvature radius at which stable propagation of the detonation wave in the bending fuse it still possible, then the wave propagation process is terminated at $R < R_{cr}$ because the detonation velocity deficit becomes too large. Therefore, as $R \rightarrow R_{cr},$ the detonation velocity deficit tends to its maximum value and the term $nf_1(1/R)$ in Eq. (4) also takes the maximum value;

2. as $R \rightarrow \infty,$ the fuse can be regarded as a straight line without any detonation velocity deficit; in this case, the term $nf_1(1/R)$ in Eq. (4) is close to zero.

Based on the above-mentioned boundary conditions, we can assume that

$$nf_1\left(\frac{1}{R}\right) = a\left[1 - \exp\left(-\frac{b}{R}\right)\right], \quad a, b > 0.$$  

(5)

By virtue of Eq. (5), Eq. (4) can be written as

$$\frac{\delta_D}{D} = a\left[1 - \exp\left(-\frac{b}{R}\right)\right].$$

(6)

As $R \rightarrow R_{cr},$ we have $\delta_D/D = a \ (0 < a \leq 1)$ in Eq. (5); as $R \rightarrow \infty,$ we have $\delta_D/D \rightarrow 0,$ i.e., both cases are consistent with the boundary conditions given above. Therefore, the relationship between $\delta_D/D$ and $1/R$ is determined by $a$ and $b \ (0 < a \leq 1$ and $b > 0)$.

To obtain the values of $a$ and $b,$ we have to determine simultaneously the detonation velocity deficits for fuses with identical charge parameters, but different curvature radii, and then to solve Eq. (6) with data taken from the test. Then, a semi-empirical formula for bending fuses with identical charge parameters can be derived.

\section*{EXPERIMENT}

As the detonation velocity deficit is responsible for the delay time phenomenon, i.e., delay in the bending fuse action, as compared with the linear fuse of the same length, the velocity deficits for fuses with different curvature radii can be calculated on the basis of the known lengths and delay times of the fuses. Therefore, the relationship between the velocity deficit and the curvature radius can be found by using Eq. (6) through fitting the experimental data with a curve.

A “one into six” module was designed for these experiments \[4\]. After the input booster was initiated, the process could be started in several fuses simultaneously (Fig. 2). The detonation time in each fuse was determined by the explosive of the output booster. In our experiments, we used one linear fuse and five bending fuses with the curvature radii of 5, 10, 15, 20, and 25 mm, which formed a cylindrical surface with a corresponding radius. A sketch of the “one into six” explosive circuit and the actual product are shown in Figs. 3 and 4, respectively. In Fig. 3, the segments $AB, BC,$ and $CD$ present the input booster, input fuse, and intermediate booster, respectively. The point $D$ is the point of connection of six output fuses: $AO_1, AO_2, AO_3, AO_4, AO_5,$ and $AO_6.$ The main parameters of the fuses and boosters are listed in Table 1.

Usually, on-off target lines are used to test the action time of various explosive devices \[13\]; one target line was connected to the point $A$ to acquire the starting time, and other six target lines were connected to the points $O_1–O_6$ to acquire the ending time.