Study on Prediction Technique for Fragments of Counterattack Projectiles for Active Protection

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Abstract. This paper aims to predict the distribution of mass and number of natural fragments based on the Payman method and using the fragmentation similarity relation and the correction relation of geometric factors that influence fragmentation. The results showed that the prediction accuracy of the fragment mass and number distribution was up to over 90%. The shape, explosive, material and heat treatment process of a projectile can be optimized through simulation tests to realize the reasonable matching of the projectile material, explosive and structure, thus shortening the development cycle and providing reliable technical means for improving the power of fragmentation munitions in China.

1. Introduction
Predicting projectile fragments is the basis to calculate the power of munitions. Over the past 40 years, Mott, Grady, Gilvarry, Payman and others have put forward some theoretical and experimental formulas¹⁻⁵ which can effectively express the fragment distribution and have been applied in the projectile design. However, results given by the Mott formula have a large deviation from experimental values in the large and small fragment areas; the Grady⁶ model has a large prediction error in terms of the number of small-mass fragments; the Gilvarry model is limited to the size prediction of small-mass and large-mass fragments⁷.

Since the 1990s, military powers of the United States and Europe have made great progress in the field of rapid prediction of fragment distribution by improving the above theoretical and experimental formulas. From the public literature, the Picatinny Arsenal Fragmentation (PAFRAG) modeling technology, the PAFRAG-Mott model⁸⁻¹² and its supporting prediction system, whose development are promoted by the U.S.Army RDECOM ARDEC, have been proved to be able to accurately reproduce the experimental fragment data. Numerics GmbH (Germany) developed the SPLIT-X
warhead design and analysis expert system for NATO. According to the official website and the theory manual of the system, the modified Grady model and Mott model \cite{13-14} are used for its natural fragment distribution model. From the official data, the analysis results are in good agreement with the measured values, and the prediction calculation can be done in seconds.

In China, the theoretical and engineering research in the field of natural fragment distribution prediction remains in its infancy. Conventional projectile design and development of new projectile materials follows the way of “drawing by designers, processing by factories and testing in shooting range”, which consumes a lot of manpower and material resources and has a long development cycle. Researchers have tried to solve this problem through theoretical analysis or simple experiments.

In this work, the Payman model was improved, and based on the similarity relation of cylindrical projectile fragmentation and the approximate correction relation of geometric factors, a simple simulation test was developed to predict the mass and number distribution of actual projectile fragments.

2. Theoretical and experimental basis

2.1. Establishment of the concept of per-unit-length modified Payman fragmentation parameter Cu

A large number of experiments have proven that there is a direct linear relationship between the logarithm of the cumulative mass percent of fragments and the mass of dimensionless fragments. By using the Payman\cite{1} mass, the following formula (1) is obtained:

$$\log_{10} P = - C_0 \left( \frac{m}{M_r} \right)$$  \hspace{1cm} (1)

Where m is the fragment mass; Mr is the total mass of recovered fragments, and when the recovery rate is very high, it is approximately equal to the metal mass M of the projectile; m/Mr is called the dimensionless fragment mass. In formula (1), P is the mass percentage of fragments with masses greater than m. The slope C0 of the line is defined as the modified Payman fragmentation parameter, which is a measure of projectile fragmentation. This parameter is obtained through the small cylindrical simulating projectile test. Theoretical analysis and experimental results showed that the modified Payman fragmentation parameter is directly proportional to the length of the projectile, namely:

$$C_u = \frac{C_0}{L}$$  \hspace{1cm} (2)

The proportional coefficient Cu is defined as the per-unit-length modified Payman fragmentation parameter, which has many advantages, especially keeping the same value for projectiles with the same material, explosive and diameter but different lengths.

2.2. Method for calculating the fragment mass and number distribution of any projectile with known Cu

According to formula (1), the total mass (g) of fragments in the range of m_i to m_j can be obtained by:

$$M_{ij} = (1 + \alpha)M \left( 10^{- \frac{C_{om}}{M}} - 10^{- \frac{C_{om}}{M_i}} \right)$$  \hspace{1cm} (3)
Where $M_i$ is the total mass of fragments with masses in the range of $m_l$ to $m_l$; $m_l$ and $m_l$ are the lower and upper limits of fragment mass groups, $m_l > m_l$; $M$ is the metal mass of each warhead unit; $Co$ is the modified Payman fragmentation parameter of the calculated projectile. As long as Cu is known, $Co$ can be obtained according to formula (2); $\alpha$ is the mass correction coefficient, which is selected according to the simulation test data.

The number of fragments in each mass range is:

$$N_{ij} = \frac{M_{ij}}{am_i + bm_j} \quad (4)$$

Where $a$ and $b$ are weighting coefficients, $a+b=1$, and their values are selected according to the simulation test data.

### 2.3. Projectile fragmentation similarity relation

In the study of the similarity relation at the early stage, it was confirmed that there is a linear relationship between the per-unit-length modified Payman fragmentation parameter Cu and the C/M ratio for given projectile materials and explosives, generally expressed as:

$$Cu = A + B \left( \frac{C}{M} \right) \quad (5)$$

Where $A$ and $B$ are the characteristic constants of a projectile material-explosive combination. Based on the test data of the small cylindrical simulating projectiles mentioned above, the C/M ratio of each simulating projectile, expressed by $x_i$, and the per-unit-length modified Payman fragmentation parameter $Cu$, expressed by $y_i$, are obtained. Then the linear fitting relationship of formula (3) is expressed as follows:

$$y_i = A + Bx_i + \epsilon_i (i = 1, 2, \ldots, n) \quad (6)$$

where $(x_i, y_i)$ is the i-th sample observation value of (C/M, Cu). By using the least square method, a straight line best reflecting the relationship between $Y$ and $X$ can be selected. Let $Q = \sum_{i=1}^{n} [y_i - (A + Bx_i)]^2$, where $Q$ reaches the minimum, and $A$ and $B$ are the least squares estimators.

### 2.4. Influence of projectile geometric factors on fragmentation and the correction relation

For the same material-explosive geometric combination, a tapered projectile and a cylindrical projectile which have the same average C/M ratio has the following relationship:

$$Cu(\text{tapered projectile}) = (1 - T_i \theta)Cu(\text{cylindrical projectile}) \quad (7)$$

where $T_i$ is the taper correction coefficient and $\theta$ is the surface taper. When the inner and outer surfaces are tapered, the average value is taken. This shows that the tapered projectile needs to be corrected according to formula (7).

The existence of end effect of the detonation point leads to fragmentation reduction. Compared with projectiles without end effect, the following relationship can be obtained.

$$Cu(\text{with end effect}) = Cu(\text{without end effect}) - T_2A \quad (8)$$
where $T_2$ is the correction coefficient of end effect, and the constant $A$ is the same as in formula (5). This shows that in the case of end effect, correction should be made according to equation (8).

3. Prediction method

According to the above theoretical and experimental basis, the prediction method of the fragment mass and number distribution of natural-fragmentation warheads is summarized as follows:

1. A certain number of small cylindrical simulating projectiles with the same material, heat treatment process and explosive are employed for static explosion tests. The per-unit-length modified Payman parameter $Cu$ is calculated. Then based on the linear relationship between $Cu$ and $C/M$ for a given material, heat treatment process and explosive, the characteristic constants $A$ and $B$ of the projectile material-explosive combination are calculated;

2. According to the warhead’s half longitudinal section and geometric characteristics, the calculation unit is selected, i.e., the warhead is divided into several segments;

3. The metal weight $M_i$ and explosive mass $C_i$ of each unit are calculated according to the geometric size of the unit and the density of the projectile material and explosive;

4. The mass ratio of explosive to metal $\left[ \frac{C}{M} \right]_i$ is calculated;

5. By substituting the $\left[ \frac{C}{M} \right]_i$ value of each unit into the known $Cu=A+B$ ($C/M$), the per-unit-length modified Payman fragmentation parameter $Cu$ of the cylindrical projectile with the same average $\left[ \frac{C}{M} \right]_i$ ratio of each unit is calculated;

6. The taper (angle) of each unit is calculated according to the size of each unit;

7. Based on the geometric characteristics of each unit, the fragmentation parameter $Cu$ of each unit is modified to obtain the fragmentation parameter $Cu_i$ of each unit;

8. The modified Payman fragmentation parameter $Co_i$ is obtained by multiplying the $Cu_i$ value of each unit by the length of the unit;

9. The fragment mass and number distribution are calculated;

10. The fragment mass and number of all units with the same mass range are added to obtain the fragment mass and number distribution of the entire warhead.

4. Realization of numerical calculation through software

In order to assist the research on the fragmentation of projectile materials, our institute independently developed the “Fragmentation Warhead Power Prediction System”. The system composition is presented in Figure 1. In the figure, fragment mass and number distribution prediction subsystem[15] is one of the core modules of the system, which mainly includes simulating projectile test management, live firing test management, fragment distribution prediction, prediction and verification management and other functions. The core class design is shown in Figure 1, and the prediction calculation interface is in Figure 2.
Figure 1. System composition and core classes of fragment mass/number distribution prediction subsystem.
As shown in Figure 2, the fragment mass and number distribution prediction subsystem fully realized the numerical calculation of the above prediction method, and the prediction calculation accuracy was higher than the design requirements. It can run on an ordinary PC computer with the i5 processor and above, and the prediction can be calculated in seconds.

5. Test verification

Take 130 mm gun howitzer with a given material and charge as an example (as shown in Fig. 3). The shell material is X steel and the density of iron is taken as its density, 7.8 g / cm³; the density of Y explosive is 1.67 g / cm³. The relationship between Cu and C/M is Cu=19.1+92.8 (C/M) (namely, A=19.1, B=92.8).

The following real ammunition fragmentation data are provided by the military test and training base, and the test data are compared with the prediction results: the average relative error between the effective fragment distribution prediction results and the historical experimental results is less than ±3%; the relative error between the lethal fragment distribution prediction results and the historical experimental results is less than ±1.9%, as shown in Table 1.
6. Conclusion

Based on the similarity relationship of projectile fragmentation and the influence of geometric factors on fragmentation, a prediction method of the fragment mass and number distribution was established. In this method, the characteristic constants A and B of a projectile material-explosive combination can be measured through only a small number of small cylindrical simulating projectile tests, and then by using the half longitudinal section of the projectile, the fragment mass and number distribution of any projectile can be calculated. Through the correction of geometric factors and the introduction of mass correction parameters and weighting coefficients, the accuracy of prediction results has been greatly improved, reaching over 90%. Therefore, in munition design, the shape, explosive, material and heat treatment process of projectiles can be optimized through simulation tests, so as to realize the reasonable matching of the projectile material, explosive and structure, thus greatly improving the power of munitions and shortening the development cycle, saving considerable research and development funds, and providing reliable technical means for improving the power of fragmentation ammunitions in China.

7. References

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