Optimization design of shaped charge based on improved genetic algorithm

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Abstract. In order to improve the design efficiency of shaped charge, reduce the number of tests and shorten the development period, an improved genetic algorithm is introduced in the design process of shaped charge. Compared with the design scheme in the iterative process of traditional optimization design, the improved genetic algorithm introduces the multi-parent crossover operator, randomly selects N individuals, forms the subspace, and hybridizes N individuals in the subspace to form a new individual. Because of the number of individuals involved in the hybridization, it is easier to calculate the optimal solution, and has stronger optimization ability. Taking a shaped charge as an example, the structural parameters of shaped charge are optimized by the improved genetic algorithm. After the optimization, it is verified by the vertical static armor breaking test of shaped charge, The results show that the optimization design method of shaped charge structure based on the improved genetic algorithm is reasonable and feasible, and the operational and technical indexes of the optimization scheme meet the requirements.

1. Introduction
The appearance of shaped charge is cylindrical, one end is the initiation end, the other end is hollow, and the inner surface of the hollow is lined with a liner. After initiation, the detonation wave propagates at an extremely fast speed. When the detonation wave reaches the liner, the liner is crushed under the action of great detonation pressure, collides and closes on the axis, producing a metal jet with high energy density. On the one hand, it is used for anti tank, anti armored vehicle, anti airport runway, anti ship and anti submarine in military; on the other hand, it is often used for oil perforation, mining and jet cutting in civil use.

Genetic algorithm is a computational model simulating the natural selection and genetic mechanism of Darwinian biological evolution. It is an adaptive heuristic global search algorithm by simulating the natural evolution process to search for the optimal solution. It was first proposed by Holland in 1975 [1-3]. Compared with the traditional search algorithm, the first is that the genetic algorithm will replace the parameter search by the parameter space coding search; the second is that the search starts from multiple initial points; the third is that the search process only uses the target function information; the fourth is that the random transformation rules are used to guide the search. Genetic algorithm does not depend on the specific field of the problem, and has strong robustness to the types of problem solving. It has been widely used in optimization design, machine learning, automatic control, image processing and other fields.

2. Theory and method
2.1. Mathematical model

Shaped charge is the effective load of antitank missile, which is responsible for destroying the target. The main index for evaluating the penetration of shaped charge is the penetration depth of steel target\cite{4,6}. The design factors that affect the penetration depth of shaped charge mainly include charge diameter, charge height, top charge thickness, charge cover thickness, charge cover angle, diaphragm diameter, diaphragm height, etc. These factors constitute the aggregation of design variables. The mathematical model is as follows:

\[
\begin{align*}
\text{max } f(X), & \quad X = [x_1, x_2, \ldots, x_n]^T \\
g_u(X) & \leq 0, \quad g_u(X) \geq 0, \quad u = 1, 2, \ldots, a \\
h_v(X) & = 0, \quad v = 1, 2, \ldots, b
\end{align*}
\]

(1)

\(X\) is the set of design variables of shaped charge; \(f(X)\) is the objective function of shaped charge design; \(g_u(X)\) is inequality constraint function, \(a\) is the number of inequality constrained functions; \(h_v(X)\) is an equality constraint function, \(b\) is the number of equality constraint functions.

2.2. Objective function

In the process of shaped charge design, it is designed from the forward direction and the reverse direction respectively. Positive design refers to maximizing the power performance as the design objective, that is, maximizing the penetration of the shaped charge to the steel target as the design objective; Reverse design means to reduce the total mass of low molecular energy charge on the premise that the power performance meets the requirements of the index.

A large amount of kinetic energy is deposited on a relatively small area of the target by the high-speed flying metal jet. In the process of collision, a high pressure is generated between the metal jet and the target plate, resulting in the stress exceeding the yield strength of the material and forming a deep perforation on the target plate. Equation (2)~(6) is often used to evaluate the penetration ability of jet to target plate.

Equation (2) is the calculation formula of penetration depth of shaped charge jet into steel target.

\[
P(t) = V_0 \frac{V_j}{\gamma^{(1+\rho_j/\rho)}} - S
\]

(2)

\(P(t)\) is the penetration depth of jet in front of jet micro element; \(t_0\) is the time when the jet head reaches the target surface; \(V_0\) is the jet head velocity; \(\gamma\) is the density ratio of shaped charge jet to target, can be obtained from equation (3); \(S\) is the initial distance, can be obtained from equation (4); \(V_j\) is the velocity of jet micro element, can be obtained from equation (5).

\[\gamma = \sqrt{\rho / \rho_j}\]

(3)

\(\rho_j\) is the target density; \(\rho_j\) is jet density.

\[S = V_0 d_0\]

(4)

\[V_j = V_0 \csc \beta \cos(\alpha - \beta + \sin^{-1} \frac{V_0}{2U})\]

(5)

\(V_0\) is the pressing speed of the micro element of the liner, can be obtained from equation (6); \(\beta\) is the compression angle; \(\alpha\) is half of the top angle; \(U\) is the velocity of the detonation wave sweeping through the surface of the liner.

\[v_0 = \sqrt{2E} \frac{\beta'}{\sqrt{1 + 0.5 \beta'}}\]

(6)

\(\sqrt{2E}\) is the Gurney constant of explosive; \(\beta'\) is the warhead charge-weight ratio.
The total mass of shaped charge includes the sum of the mass of main charge, secondary charge, charge cover, partition and booster. The objective function of reverse design is as follows:

$$m(X) = \frac{1}{m_1 + m_2 + m_3 + m_4 + m_5}$$  \hspace{1cm} (7)$$

$m_1, m_2, m_3, m_4, m_5$ are the quality of the main charge, the secondary charge, the shaped charge liner, the partition and the booster charge respectively.

2.3. Constraint condition

Due to the overall limitation of the missile, the shaped charge is limited by the total mass, length and diameter in physical structure, as follows:

$$\begin{align*}
m(X) & \leq m' \\
L(X) & \leq L' \\
D(X) & \leq D'
\end{align*}$$ \hspace{1cm} (8)$$

$m'$ is the maximum total mass allowed for shaped charge; $L'$ is the maximum allowable length of shaped charge; $D'$ is the maximum allowable length of shaped charge and the maximum allowable outer diameter of shaped charge.

According to the classical jet formation theory, in order to form a condensed solid jet, the compression velocity of the liner is subsonic relative to the moving coordinate system.

$$v_0 < c_B$$ \hspace{1cm} (9)$$

$c_B$ is the sound velocity of the liner material.

3. Optimize the design process

The improved genetic algorithm is used in the optimization design of shaped charge. Compared with the traditional design scheme in the iterative process of optimal design, the improved genetic algorithm optimizes on the basis of a large number of design schemes; At the same time, the improved genetic algorithm introduces the multi parent crossover operator, randomly selects $h$ individuals to form a subspace, and hybridizes $h$ individuals to form new individuals in the subspace. As the number of individuals participating in the hybridization increases, it is easier to calculate the optimal solution and has stronger optimization ability, As shown in Figure 1.

In the process of shaped charge design, the traditional design method is to adjust and calculate the parameters of a few discrete schemes. On the one hand, the design efficiency is low, on the other hand, the design result is not optimal. In this method, the improved genetic algorithm is introduced into the design process of shaped charge, which improves the design efficiency and makes the design result an optimization scheme.
4. Example
The shaped charge has the characteristics of large penetration depth and strong armor breaking ability. The current designed armor breaking ability is more than 9 times of the charge diameter, which has strong damage ability to tank targets. But compared with hundreds or even thousands of fragment kill elements of fragment shaped charge, shaped charge has only one kill element. This requires the precise design and optimization of shaped charge under the constraints of the overall structural parameters of the missile.

4.1. Optimization design model
The typical shaped charge is mainly composed of main charge, secondary charge, partition, shaped charge liner and booster(Fig. 2). Table 1 shows main tactical and technical indexes. Limited by the existing conditions, the following initial restrictions are made. The material of the shaped charge liner is copper, and the material of the charge is JO-8.
1- secondary charge 2- booster 3- partition
4- main charge 5- shaped charge liner

Figure 2. Typical shaped charge structure.

Table 1. Main tactical and technical indexes.

| Design variable | Value range | Design variable | Value range |
|-----------------|-------------|-----------------|-------------|
| Mass m (kg)     | ≤8.0        | Elastic diameter D (mm) | ≤180        |
|                 |             | Length L (mm) | ≤300        |
|                 |             | Penetration depth P (mm) | ≥1000       |

Through analysis, the design variables are as follows:

\[ X = [D_C, H_C, L_0, \delta, \phi, D_G, H_G]^T \]  \hspace{1cm} (10)

\(D_C\) is the charge diameter, \(H_C\) is the charge height, \(L_0\) is the coating thickness, \(\delta\) is the thickness of the liner, \(\phi\) is the angle of the liner, \(D_G\) is the partition diameter, \(H_G\) is the partition height. The range of design variables is shown in Table 2.

Table 2. Variable value range.

| Design variable | Value range | Design variable | Value range |
|-----------------|-------------|-----------------|-------------|
| \(D_C\) (mm)    | [130,150]   | \(\phi\) (°)    | [40,60]     |
| \(H_C\) (mm)    | [130,225]   | \(D_0\) (mm)    | [94,110]    |
| \(L_0\) (mm)    | [26,75]     | \(H_G\) (mm)    | [20,50]     |
| \(\delta\) (mm) | [1,3]       |                 |             |

4.2. Optimization design results

Through MATLAB programming calculation, the optimized design parameters of shaped charge warhead are obtained, as shown in Table 3. It can be seen from table 3 that the performances of shaped charge meet the requirements of indexes.

Table 3. Optimization design results.

| NO. | Design parameters | result |
|-----|-------------------|--------|
| 1   | Charge diameter \(D_C\) (mm) | Φ145   |
| 2   | Charge height \(H_C\) (mm)    | 177    |
| 3   | Coating thickness \(L_0\) (mm) | 32     |
| 4   | thickness of the liner \(\delta\) (mm) | 2.2    |
| 5   | angle of the liner \(\phi\) (°) | 60     |
The test results of shaped charge show that the optimized design results are reasonable and can meet the technical requirements.

5. Conclusions
The improved genetic algorithm is introduced into the design process of shaped charge, the mathematical model of shaped charge optimization design is established, and the process of shaped charge optimization design is established. This method is used to optimize the design of a shaped charge, and the design results meet the requirements of technology indexes. At the same time, the optimization design scheme is tested and verified, and the test results meet the requirements. It shows that the improved genetic algorithm is reasonable and feasible in the process of shaped charge design. The method has strong robustness and improves the efficiency of shaped charge design.
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