Optimization Design of Propellant Charge for a Medium and Large Caliber High Chamber Pressure Gun

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Abstract. Taking a medium and large caliber high chamber pressure gun as the object and a single charge as an example, the optimization design model of the propellant charge of high chamber pressure gun was established by using the optimization theory, and the trajectory parameters of 100mm gun were optimized, and the optimal trajectory design scheme satisfying the constraints is obtained. The results of this paper have some guiding significance for the optimal design of propellant charge for high chamber pressure gun.

1. Introduction

The propellant is the energy of weapon shooting, and the design of propellant charge is an important part of weapon and ammunition system design. Interior ballistic design is the basis of weapon design, and the accuracy of interior ballistic calculation can ensure the accuracy of propellant charge design [1]. For example, Wu,S.Q[2] optimized the design of different kinds of gunpowder charges based on the tactical and technical indexes of recoilless guns. Wang,J[3] established classical optimization model and two-phase flow optimization model to optimize the interior ballistic design of small caliber artillery. Although some scholars have studied the interior trajectory of high chamber gun [4], there is still a lack of effective simulation method for optimal design.

The charging design of 100mm high chamber gun was optimized, and the interior ballistic parameters were optimized to obtain a more reasonable and scientific charging design scheme in this paper. It is beneficial to the development of high chamber pressure artillery and further improve the combat ability of artillery units.

2. Optimization design model

The interior ballistic calculation model of this paper is based on literature.

The design of propellant charge should satisfy the tactical and technical requirements of weapon. However, these tactical and technical requirements are contradictory and mutually restrictive, so that a technical measure can only improve one part of the charge's performance and reduce some others. Optimization calculation is a fast and effective method in charge design. The mathematical model of optimal design is generally composed of objective function, design variable and constraint condition. Its mathematical expression is generally as follows:
\[
\min z = f(X) \quad \text{s. t. } g_i(X) \leq 0, i = 1, 2, \ldots, m
\]

Where \( X = [x_1, x_2, \ldots, x_n]^T \) is the design variable; \( f(X) \) is the objective function; \( g_i(X) \leq 0 \) is an inequality constraint.

Improving muzzle kinetic energy is the main goal pursued by charge designers, but it is necessary to control reasonable and stable chamber pressure while seeking for higher muzzle velocity. Too low chamber pressure can cause low muzzle velocity and make it difficult to reach the target, but too high chamber pressure can affect the mobility and safety of the gun. The relative end position of gunpowder is one of the criteria to evaluate the design of propellant charge, which refers to the ratio between the end position of gunpowder and the length of gun barrel. When the end position of the gunpowder calculated by theory is close to the muzzle, it is easy to cause some unburned gunpowder to fly out of the muzzle. This condition can not only lead to inadequate use of gunpowder energy, but also increase the generation of muzzle smoke flame. The objective function is to choose the muzzle velocity \( v_0 \), the maximum chamber pressure \( p_\text{m} \) and the relative position of gunpowder to the end of combustion: \( \eta_k \).

To determine the design variables, the designer must pay attention to the following principles: (1) the design variables are independent of each other; (2) design variables are those variables that have a contradictory impact and a greater impact; (3) design variables should be as dimensionless as possible and of the same order of magnitude. Charge weight \( \omega \), propellant web size \( 2e \) and propellant type \( i \) have great influence on ballistic performance, which can be set as optimization variable.

Considering the parameter requirements of the weapon system and the optimization of the interior ballistic system, the following conditions are determined as constraint functions:

1. Projectile muzzle velocity \( v_0 \geq v'_0 \), \( v'_0 \) is the minimum muzzle velocity achieved by weapon design and tactical requirements;
2. The maximum chamber pressure \( p_\text{m} \leq p'_\text{m} \), \( p'_\text{m} \) is the maximum chamber pressure limited in weapon design;
3. The relative position of the gunpowder at the end of combustion is \( \eta_k \leq \eta'_k \). In order to ensure that the gunpowder can finish burning in the chamber to maximize its effectiveness, according to experience, different guns are generally smaller than a specific value of \( \eta'_k \).
4. The charge weight of gunpowder is \( \omega \leq \omega' \), and \( \omega' \) is the rechargeable weight limited by gun.
5. Propellant web size \( 2e \) is related to the aspect ratio of gunpowder type, which is generally: \( 1.6c \leq D_0 \leq 1.8c \). In the formula, \( D_0 \) is the diameter of gunpowder; \( c \) is half of the gunpowder's length.
6. Propellant type \( i \geq 1 \), \( i \) represents the number of propellant types used in calculation.

Considering the requirements of weapon system parameters, an optimization model of propellant charge trajectory design is established:

The objective function \[
\begin{align*}
\max f_1(X) &= v_0(X); \\
\min f_2(X) &= p_m(X); \\
\min f_3(X) &= \eta_k(X)
\end{align*}
\]

s. t. \[
\begin{align*}
p_\text{m} &\leq p'_\text{m} \\
\eta_k &\leq \eta'_k \\
\omega &\leq \omega'
\end{align*}
\]

\[
1.6c \leq D_0 \leq 1.8c \\
i \geq 1
\]

The design variables \( X = (\omega, 2e, i)^T \)

3. Optimization results

According to the mathematical model established above, the high chamber pressure charge calculation software was used to carry out numerical simulation of the interior ballistic of 100mm gun.
First of all, the \( \ln(u) - \ln(p) \) curve was fitted in sections according to the results of the closed bomb chamber experiment, and the burning rate coefficient \( u \) and the pressure index parameters \( n \) of segmented results were obtained as shown in table 1.

| Pressure section | \( u \)/cm \( \cdot \) s\(^{-1} \cdot \) MPa\(^{-n} \) | \( n \) |
|------------------|---------------------------------|-------|
| \( p < 150 \text{MPa} \) | 0.80 | 0.70 |
| \( 150 \text{MPa} \leq p \leq 400 \text{MPa} \) | 0.31 | 0.85 |
| \( p > 400 \text{MPa} \) | 0.056 | 1.10 |

Specific constraints: \( v_0 > 1750 \text{m} \cdot \text{s}^{-1}; p_m < 593 \text{MPa}; \eta_k < 0.62; 2.43 \text{mm} < 2e_2 < 2.83 \text{mm}, \) variable step 0.02mm; \( 6500 \text{g} < \omega < 6800 \text{g}, \) variable step 10g; the propellant type \( i \) is cylindrical 19 hole powder, cylinder 7 hole powder, lace 19 hole powder, lace 37 hole powder or tubular powder.

The charging results satisfying the objective function after optimization are shown in Table 2.

| Number | Propellant type | \( \chi \) | \( \omega / g \) | \( 2e_2 / \text{mm} \) | \( p_m / \text{MPa} \) | \( v_0 / \text{m} \cdot \text{s}^{-1} \) | \( \eta_k \) |
|--------|----------------|--------|-------------|-----------------|-----------------|-----------------|--------|
| 1      | lace 19 hole powder | 0.7626 | 6610 | 2.81 | 592.2 | 1751.8 | 0.45 |
| 2      | lace 19 hole powder | 0.7626 | 6620 | 2.81 | 592.5 | 1753.1 | 0.46 |
| 3      | cylindrical 19 hole powder | 0.6787 | 6750 | 2.59 | 590.3 | 1750.3 | 0.58 |
| 4      | cylindrical 19 hole powder | 0.6791 | 6780 | 2.61 | 587.9 | 1751.4 | 0.60 |
| 5      | cylindrical 19 hole powder | 0.6791 | 6790 | 2.61 | 592.0 | 1755.0 | 0.59 |
| 6      | cylindrical 19 hole powder | 0.6794 | 6800 | 2.63 | 584.5 | 1751.0 | 0.61 |
| 7      | lace 37 hole powder | 0.7214 | 6610 | 2.79 | 586.9 | 1750.1 | 0.45 |
| 8      | lace 37 hole powder | 0.7214 | 6620 | 2.79 | 590.6 | 1753.2 | 0.44 |
| 9      | lace 37 hole powder | 0.7214 | 6640 | 2.81 | 584.6 | 1751.8 | 0.46 |
| 10     | lace 37 hole powder | 0.7214 | 6650 | 2.81 | 588.3 | 1754.8 | 0.45 |
| 11     | lace 37 hole powder | 0.7214 | 6660 | 2.81 | 590.8 | 1757.3 | 0.45 |
| 12     | lace 37 hole powder | 0.7214 | 6670 | 2.81 | 592.9 | 1759.4 | 0.45 |

In Table 2, \( \chi \) is the shape characteristic quantity of gunpowder.

Under the conditions of satisfying the muzzle velocity, maximum chamber pressure and relative end position of gunpowder, the interior ballistic design optimization system finally selected 12 design schemes of charging, and Scheme 6 is the calculation result of the existing charging scheme. The optimal design scheme 9 was selected to compare with the existing charging scheme. The comparison results are shown in Table 3.

| Scheme number | Powder type | \( \omega / g \) | \( 2e_2 / \text{mm} \) | \( p_m / \text{MPa} \) | \( v_0 / \text{m} \cdot \text{s}^{-1} \) | \( \eta_k \) |
|---------------|-------------|-----------------|-----------------|-----------------|-----------------|--------|
| 6             | cylindrical 19 hole powder | 6800 | 2.63 | 584.5 | 1751.0 | 0.61 |
| 9             | lace 37 hole powder | 6640 | 2.81 | 584.6 | 1751.8 | 0.46 |
The comparison of Table 3 shows that the initial velocity and maximum chamber pressure of the lace 37-hole powder in scheme 9 are similar to the original charge scheme, but the charge weight is reduced by 160g, which can slow down the ablative effect and improve the life of the weapon. In addition, scheme 9 significantly reduces the relative position of gunpowder at the end of combustion, with large charge utilization coefficient and high energy utilization efficiency of gunpowder. This is because compared with the cylindrical 19 hole powder, the combustion surface of the lace 37 hole powder increases more during the combustion process of the gunpowder, and there are fewer splits in the combustion stage of the reducing surface, so the charge weight is lower and the combustion end time of the gunpowder is shortened.

4. Conclusion
According to the classical interior ballistics theory and optimization theory, this paper established an optimization model of propellant charge trajectory design. An optimization scheme was designed for 100mm gun, and a relatively ideal optimal design result was obtained. According to the analysis results of the above optimization scheme, under the condition of satisfying the constraints, the optimization design of interior ballistic charge for high chamber gun could be realized, and a more reasonable and scientific interior ballistic parameter scheme could be obtained. The results obtained in this paper have some guiding significance for the optimal design of propellant charge for high chamber pressure gun.

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